4-10-78
1999

UCRL-50021-76

LASER PROGRAM ANNUAL REPORT — 1976

Prepared for U. S. Department of Energy
under contract No. W-7405-Eng-48

**LAWRENCE
LIVERMORE
LABORATORY**
University of California / Livermore

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

LASER PROGRAM ANNUAL REPORT -- 1976

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

1 *84*

A laser-driven implosion of a DT-filled hollow glass target photographed in the 1.5-keV x-ray band of light emitted by silicon. The image was formed by a grazing-incidence-reflection x-ray microscope, and then color-enhanced by computer to show details of the density distribution. The outer partial ring in the picture represents x radiation generated at the target wall at the start of the implosion. The bright central core represents a burst of x rays from the compressed target near the peak of the implosion. This experiment exemplifies hundreds of laser fusion experiments performed on the Janus and Argus laser systems in 1976.

LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California/94550

UCRL-50021-76

LASER PROGRAM ANNUAL REPORT — 1976

Scientific Editor: Philip E. Coyle

MS. Date: June 1977

Foreword

This issue of the LLL Laser Program Annual Report marks the fifth year in which we have formally summarized our yearly accomplishments. In 1972 and 1973, the report took the form of semiannual publications; since then, annual reports have been issued.

Our goal with these reports is to make accomplishments of the Laser Program understandable to technical readers in enough detail so that they can reproduce the results or know where to obtain full information. Accordingly, the document is organized in a manner paralleling the actual programmatic organization at Livermore. As in past years, you will find sections on solid state laser development, fusion experiments and diagnostics, and fusion targets, as well as advanced lasers, systems studies, and isotope separation. In addition, a new section, "Progress Towards Laser Fusion," summarizes the growing mass of analytical and experimental data that is helping us to understand the fundamental physics of laser fusion and to achieve specific scientific milestones. In the new section you will find descriptions of pre-experimental calculations, actual results obtained, and post-experimental analysis and interpretation. This design cycle is so integral to our day-by-day approach that this special section was devised to collect and summarize our results.

This year's annual report is an especially substantial volume so as to cover comprehensively the growing number of experimental results and new technical data produced by a dynamic, achieving program. To help locate specific materials, a Contents section in front summarizes the main headings in each major section. Line drawings symbolizing the program elements visually key the reader from the Contents to the major sections. A detailed,

article-by-article listing precedes each major section. We hope that the content and format will help the reader to follow and share in the rapid progress in laser applications research.

The accomplishments during 1976 are the result of hard work and dedication by all program personnel; these same people devoted extra time and effort to preparing this report. Each major section was organized by a section editor, who worked closely with individual contributors and the Program Leader responsible for that program element. At the end of each article appear the authors' names, together with those of coworkers who contributed significantly to that particular effort. At the end of each section we have included a list of program personnel and areas of expertise. With so many important contributions being made, it is not practical to acknowledge individual efforts in greater detail. Nevertheless, thanks are due to all participants in the Laser Program who contributed both to this report and to a year filled with outstanding achievements and advances.

The TID Publications staff headed by Paul Tanasovich and the TID Support staff headed by Jack King provided excellent support in editing, composition, artwork, layout, and printing the report. Special recognition for hard work is due Chuck McCaleb for his highly professional editing and for coordinating the overall report both in TID and with the Laser Program staff. Finally, this report might never have been published were it not for the sustained efforts of Jeanne Shrode in organizing and tracking some 200 individual contributions from first draft to final composition.

Philip E. Coyle
Scientific Editor

Section 1 – PROGRAM OVERVIEW	1-1
1-1 Program Resources	1-5
1-2 Program Facilities	1-6

Section 2 — SOLID STATE PROGRAM	. .2-1
2-1 Argus	2-8
2-2 Shiva	2-54
2-3 Shiva Nova	2-184
2-4 Optical Materials	2-235
2-5 Pulse Generation and Shaping	2-286
2-6 Theory and Design Analysis	2-324

Section 3 — FUSION EXPERIMENTS

PROGRAM	3-1
3-1 Experimental Facilities	3-7
3-2 Diagnostics Development	3-32
3-3 Optical Diagnostics	3-34
3-4 X-Ray Diagnostics	3-67
3-5 Particle Diagnostics	3-93
3-6 Real-Time Data and Control Systems	3-123

Section 4 — FUSION TARGETS 4-1

4-1 Laser Target Design and Analysis	4-6
4-2 Electron and Ion Beam Target Design and Analysis	4-44
4-3 LASNEX: Overview	4-51
4-4 Laser Plasma Theory and Simulation	4-59
4-5 Laser Light Absorption	4-61
4-6 Heated Electron Energies	4-83
4-7 Heat Transport	4-90
4-8 Other Studies	4-110
4-9 Target Fabrication	4-122

Section 5 — PROGRESS TOWARD

LASER FUSION	5-1
5-1 Exploding Pusher Targets:	
Janus-Clamshell System	5-6
5-2 Exploding Pusher Targets:	
Cyclops System	5-37
5-3 Exploding Pusher Targets:	
Argus System	5-51
5-4 Exploding Pusher Targets: D ³ He Fuel,	
Argus System	5-77
5-5 Exploding Pusher Targets: Summary . .	5-83
5-6 Super Liquid Density Targets:	
Janus-Clamshell System	5-126
5-7 Absorption and Transport Studies . .	5-146

Section 6 — ADVANCED LASERS6-1

6-1 Overview	6-3
6-2 Group VI-A Photolytic Lasers	6-6
6-3 Rare Earth Vapor (REV) Lasers	6-19
6-4 Metal Vapor Lasers	6-27
6-5 Rare Gas Oxide (RGO) Lasers	6-29
6-6 Raman Pulse Compression of Rare Gas	
Fluoride Lasers	6-40
6-7 Rare Gas Halide (RGH) Lasers	6-49
6-8 Developments in Theoretical and	
Computational Models	6-64
6-9 Photoionization	6-67
6-10 New Infrared Lasers	6-72
6-11 Electron Beam Physics	6-77

Section 7 — SYSTEM STUDIES AND APPLICATIONS	7-1
7-1 Overview	7-3
7-2 Fusion Reactor Studies	7-7
7-3 First-Wall Studies	7-14
7-4 Laser System Studies	7-25
7-5 Fusion-Fission Hybrids	7-36
7-6 National Security Applications	7-47
7-7 Long-Range Planning for Inertial Confinement Fusion	7-50

Section 8 — LASER ISOTOPE SEPARATION PROGRAM	8-1
8-1 Overview	8-3
8-2 Atomic Uranium Laser Spectroscopy	8-9
8-3 Photon Dynamics	8-20
8-4 SPP-II Test-Bed Facility	8-29
8-5 Copper-Vapor Lasers	8-33
8-6 Dye Amplifiers	8-36

Section 1

PROGRAM OVERVIEW

Contents

Section 1 — PROGRAM OVERVIEW . . .	1-3
1-1 Program Resources	1-5
1-2 Program Facilities	1-6
High Energy Laser Facility	
(Building 391)	1-6
Main Laser Bay	1-6
Target Room	1-6
Energy Storage	1-7
Laboratory Area	1-7
Building Support Systems	1-7
General Plant Project (Building 161) . .	1-9
New Trailer Complex	
(Trailers 3725 and 3726)	1-9
Future Plans	1-9

Section 1

PROGRAM OVERVIEW

1976 was a year of transition for the Livermore Laser Fusion Program. During the year we moved from an era of basic physics experiments with relatively modest facilities to high-yield, high-density experiments on high-power laser systems. In June 1976, Argus reached full operation, and soon thereafter delivered more than 2 TW of laser power on target. This achievement was doubly significant in that the measured performance closely matched predictions from earlier theoretical calculations. In conjunction with this, well-calibrated and sensitive laser diagnostic techniques were developed and proved. By year's end, improvements were incorporated in Argus including an inventive new beam relay system that uses a hard aperture, increasing the fill factor to 0.85 and resulting in nearly 5 TW on target in short pulses.

The Shiva laser system was completely designed, and development began of the beta, gamma, and delta amplifiers. A prototype of the Shiva automatic alignment system was tested on Cyclops while the full-scale alignment system was being fabricated and assembled. A new oscillator and oscillator control first developed for Argus were incorporated in the Shiva design.

Plans for a Shiva system upgrade, called Shiva Nova, culminated in completion of the first phase of a CP&D study showing that a tenfold improvement over Shiva performance could be realized in the early 1980's. Related studies on new optical materials, laser glasses, and crystals, as well as measurements of nonlinear and thin film damage, all promise to extend the capabilities of future solid state laser systems.

Solid state laser component design and engineering reached full production levels for Shiva, and our understanding of rod and disk amplifiers, oscillators, and pulse shapers was translated into hardened commercial practice.

Our efforts begun in 1975 to transfer this technology to outside markets through and in cooperation with industry reached success in 1976. As the result of a symposium held in December

1975 and followup activities during 1976, several firms have become more proficient as suppliers of advanced solid-state laser components and sub-systems, and one company successfully bid on and delivered a complete high-power laser system to the United Kingdom.

Day-to-day fusion experiments on both Janus and Argus produced many valuable new results. In particular, we achieved and diagnosed record-breaking thermonuclear conditions with exploding pusher targets in a series of experiments on Argus. Neutron yields were increased by two orders of magnitude over our 1975 best, to more than 10^9 neutrons at DT ion temperatures of 8 keV and densities of about 0.2 g/cm^3 . Our best experiments resulted in DT gains of 10^{-2} , never before attained in fusion laboratory experiments. To support these and other experiments, our Fusion Target Fabrication Group fabricated and assembled hundreds of exploding pusher and other low- ρ targets to exacting tolerances, under quick-turnaround pressures.

The analytical and theoretical basis for fusion target design advanced considerably in 1976. We completed designs for intermediate- and high-density targets that should be capable of compressing DT to 100 times liquid density with Argus and a factor of 10 or more times liquid density with Shiva. These designs point to a family of reactor-class targets that greatly relax the laser and target fabrication requirements for power reactors. Our LASNEX computer code was improved to run at lower cost, and we continued our previously demonstrated ability to calculate specific results before they are achieved. This powerful design tool is unique in controlled fusion research and provides part of the strong theoretical foundation in plasma physics that is so necessary for rapid progress in ICF research.

Measuring the performance of fusion lasers and fusion microexplosions requires diagnostic techniques with tight resolution in both time and space. Today's targets are microscopic in size and function

Table 1-1. Laser program costs and effort

	Fiscal Year							
	70	71	72	73	74	75	76	77
Operating costs (millions of dollars)								
Laser fusion	1.9	6.5	9.5	13.5	18.4	19.9	22.2	29.9
Laser isotope separation	—	—	—	—	0.74	4.8	7.2	8.1
Manpower								
Laser fusion	43	124	156	232	223	230	244	281
Laser isotope separation	—	—	—	—	23	70	90	94
Equipment (millions of dollars)								
Laser fusion	0.1	0.4	0.9	1.1	1.17	2.0	2.4	2.8
Laser isotope separation	—	—	—	—	0.13	0.7	1.5	2.4

Table 1-2. Laser fusion program costs and effort by budget category

Budget category	Fiscal year			
	1976		1976T	
	Manpower	Cost (thousands of dollars)	Manpower	Cost (thousands of dollars)
Nd: glass laser development	82	10,330	62	2,460
New laser development	28	2,025	30	355
Pellet design and fabrication	52	4,309	76	1,660
Target interaction experiments	57	3,655	75	2,000
Diagnostics development	23	1,535	28	400
Reactor systems studies	2	270	4	110
Total	244	22,205	275	6,985

Table 1-3. Laser isotope separation program costs and effort by budget category

Budget category	Fiscal year			
	Manpower	Cost (thousands of dollars)	Manpower	Cost (thousands of dollars)
Laser development	20	2,060	20	710
Separation experiments	45	3,095	44	900
Supporting technology	26	1,995	25	500
New concepts	1	100	1	25
Total	92	7,250	90	2,135

on picosecond time scales, and we require time, space, and energy-resolved measurements of each target. We now can measure time-integrated x-ray energies from 50 keV to 100 eV and time-resolved x-ray energies from 30 keV to 100 eV. We have developed time-resolved x-ray diagnostics capable of taking streak pinhole camera pictures of the moving radius of emitted x rays from laser fusion targets with resolution to less than 6 μm in space and 15 ps in time. Much of our target and laser data are being acquired, digitized, scaled, and printed by computer-interfaced online systems.

Our Advanced Laser Program, while funded at effectively less than 1972 levels, conceived and evaluated several new options for future high-efficiency, high-repetition-rate lasers. We completed extensive laboratory experiments to measure the cross sections and excited state lifetimes of a wide variety of candidate systems. In particular, we studied rare earth molecular vapor laser systems, both electron-beam and optically pumped, and defined the operating parameters of such systems; we completed a prototype design of a 1-kJ iodine laser and analyzed its scaling to high energies; and we investigated Group VIa gas lasers pumped by photodissociation of simple polyatomic molecules containing oxygen, sulfur, or selenium. These and other candidates are being evaluated for development to the higher energies required for commercial-scale laser fusion reactors.

Our Laser Isotope Separation Program catalogued a broad range of spectroscopic data using new and more accurate techniques. We defined and developed a number of major subsystems and components for uranium LIS and put into operation a testbed facility for evaluating process options under conditions analogous to those in a full-scale enrichment process.

Finally, our Systems Studies Group developed reactor prototypes of several novel laser fusion concepts and completed a significant effort to map the military applications of laser fusion technology.

1-1 Program Resources

The LLL Laser Program in its present form began with 20 scientists and an operating budget of about \$1 million. From that beginning, the program has grown into two major elements — Laser Fusion and Laser Isotope Separation (LIS) — with 375 workers and combined FY 1977 operating budgets

of \$38 million. Table 1-1 chronicles Laser Program costs and effort for FY 1970-1977. The manpower numbers reflect all personnel in direct support of the program: scientific, technical support, non-technical, and craft support. A breakdown of the Laser Fusion and Laser Isotope Separation programs by budget category for FY 1976 and the transition quarter (FY 1976T) is given in Tables 1-2 and 1-3. Major line item projects, such as the currently funded Shiva and proposed Shiva Nova, are costed separate from the operating budgets. Shiva, funded at \$25 million, had an average staff of 30 LLL personnel in 1976. For peak construction and assembly periods on projects such as this, extensive use is made of outside temporary manpower. Shiva in 1977 will use more than 40 outside personnel during the laser system assembly stages. Shiva Nova is projected to use outside personnel 2:1 over LLL personnel during the design and construction life of the projects.

Since its inception, LLL has been committed to the goal of obtaining program milestones by involvement and effective utilization of industry, universities, and other outside agencies wherever possible. A direct outgrowth of the policy is reflected in Fig. 1-1. The LLL Laser Program has spent less than half its funding on internal manpower costs. More than half goes for outside fabrication, development contracts, and research, a large fraction of this being spent outside the ERDA complex. This trend is expected to continue until about FY 1980, when the anticipated ratio is about one-third internal expenditure and two-thirds outside the Laboratory. In addition to the operating budgets, large projects such as Shiva and the proposed Shiva Nova further the goal of outside involvement. On these projects the ratio approaches 9:1; that is, for every dollar spent inside the Laboratory, nine dollars are spent outside. Effecting such a goal requires lots of planning and resolve by all program personnel. Technology transfer seminars, continuous contact with suppliers, and presentations at industry conventions are some of the methods used to inform the commercial sector about the role it can play in developing inertial confinement fusion technology. To date, the response and results have been encouraging. The LLL Laser Program has made considerable progress toward developing both the mechanisms and the system for interacting on a large scale with outside industry and university organizations.

Fig. 1-1. Operating costs and wage expense by fiscal year for (a) the laser fusion program and (b) the laser isotope separation program.

1-2 Program Facilities

High Energy Laser Facility (Building 391)

The LLL High Energy Laser Facility (HELFF) is a project dedicated to demonstrating laser-driven compression and thermonuclear burn of DT fusion pellets. It consists, in all, of the 20-beam Shiva laser system, target system, diagnostics arrays, and the building that encloses and supports these systems. The building (structure) was completed in 1976; beneficial occupancy was taken in July 1976 to begin installation of the framework that supports the many components and subassemblies making up the full system.

HELFF is a \$25 million project funded by ERDA and administered by its San Francisco Operations Office. Of this total, \$8.8 million is allocated for building design and construction, the balance going for the Shiva laser and target system.

The building's gross area is approximately 66 000 ft², divided about equally between a main floor and a basement. Personnel access is through a lobby on the south side and an entrance at the west end, both at ground level. A ramp provides basement-level access for freight and personnel on the north side. The exterior architecture (Fig. 1-2) includes elements of cast-in-place concrete, precast concrete, and painted steel panels over steel framing, each element being appropriate to the technical requirements within.

The HELFF building encloses five major space elements (see Fig. 1-3): a main laser bay, a target room, an energy storage area, a laboratory area, and building support systems. Each element has unique requirements reflected in unique features.

Main Laser Bay. The configuration of the Shiva laser and its supporting space frame indicated the need for a long, high room with a bridge crane for handling components. The first-floor laser bay is 50 ft wide by 160 ft long, 30 ft high under the crane. In addition, the laser's need for high mechanical stability and class 10,000 cleanliness resulted in a 12-in.-thick concrete floor supported above the basement on 48 steel columns. An air conditioning system circulates 440 000 ft³ of air per minute, with temperature controlled to $\pm 1^\circ\text{F}$. The required cleanliness is assured by vertical laminar air flow from high efficiency particulate (HEPA) filters in the ceiling to a perforated raised floor that creates a return-air plenum in the space below. The laser bay is framed and sheathed in steel, with sealed and painted gypsum board on the inside surfaces.

Target Room. The geometry of the incident laser beams and target diagnostics indicated the need for a room 60 ft square and 65 ft high under a second bridge crane, with its floor at basement level. The anticipated neutron yields of Shiva targets mandate substantial radiation shielding, which is optimized by constructing the room with 4-ft-thick concrete walls and a 2-ft-thick ceiling. The target chamber and its supporting space frame require the target room to have the same environmental control as the

laser bay. An identical system circulates 225 000 cfm/min of filtered, temperature-controlled air.

Energy Storage. 22 MJ of electrical energy to fire the laser's flashlamps and rotators will be stored in 7350 capacitors which, with their charging power supplies, will occupy 19 000 ft² of the basement directly under the laser bay. This satisfies the primary requirement that cables connecting the capacitors to the laser must be as short as possible. Comfort-level air conditioning is provided with an additional feature permitting 100% outside air to be introduced for smoke removal.

Laboratory Area. Laboratories, an entrance lobby, a control and diagnostics room, and a clean room are located at ground level in a single-story wing on the south side of the laser bay and target room. The clean room has 3 000 ft² of class 100 environment for assembly of laser components. Adjacent air handlers circulate 170 000 cfm of air in vertical laminar flow from HEPA filters in the integrated ceiling to a raised, perforated floor. The diagnostics and control room has a raised computer floor and shuttered windows overlooking the laser bay. All incoming diagnostic and outgoing control signals are optically transmitted to maintain the room's electrical isolation from the rest of the building. Other elements of the laboratory area will be used for target fabrication laboratories and for traffic circulation. These elements are characterized by standard finishes and comfort-level air conditioning.

Building Support Systems. Heating, ventilating, air conditioning, and power distribution equipment are located in a 38 000-ft² equipment room in the basement. The power substation, located outdoors adjacent to the equipment room, provides 4000 kVA of building utility power, 3750 kVA of intermittent power for capacitor charging, and 500 kVA of "clean" instrument power.

Fan lofts extending the full length of the building's north side shelter the vaneaxial fans, chilled water coils, and prefilters for the laser bay and target room air conditioning systems. Other air-handling systems are outdoors at various locations around the building.

Although temperature control and high air velocity are dominant air conditioning requirements in a large part of the building, the system is nevertheless energy-efficient. A significant portion of the vaneaxial fans' total 775 hp is dissipated as heat to the airstream. Chilled water coils remove the excess heat; the chillers recover it for redistribution to the rest of the building. Only a small boiler is needed, to make up the space-heating deficit occurring on very cold days.

Design and construction of the HELF building have been executed by the phased construction technique. Construction was accelerated by permitting a start on excavation and foundation work before the building superstructure design was completed. We engaged a professional construction manager who administers all construction subcon-

Fig. 1-2. LLL High Energy Laser Facility (HELF), Building 391.

Fig. 1-3. Building 391 space is divided into five major elements.

tracts and is responsible for construction scheduling and cost control. Norman Engineering Company of Los Angeles is the architect-engineer and the construction manager for HELF. At year's end 1976, the building was physically complete, with only a small number of acceptance inspections outstanding.

General Plant Project (Building 161)

In December 1976, a new Laser Isotope Separation Development Laboratory building was physically completed and ready for activation. It provides five new laboratories for research in uranium molecular spectroscopy, metal-vapor atomic spectroscopy, excited-state atomic and molecular collision processes, and electron-beam source diagnostics.

The new building is wood frame with a stucco exterior, concrete slab floor, comfort-level air conditioning, and standard laboratory utilities and fixtures. At 6 000 ft² gross, its total budgeted cost is \$385,000. Careful cost analysis and optimization yielded nearly the maximum laboratory space obtainable at current construction costs and within statutory limitations of the general plant project budget.

We anticipate construction of another general plant project in FY 1977 to house a major process experiment for laser isotope separation. Within the next two years, we anticipate that new LIS light laboratories will have to be housed in portable buildings.

New Trailer Complex (Trailers 3725 and 3726)

Laser Program office space falls into two extremes: high-quality, permanent quarters in the laser fusion laboratory (Building 381), which includes Argus and its associated light laboratories, or obsolete and barely adequate trailers. About half the program's professional staff have offices in Building 381. To replace obsolete office trailers, two new trailer complexes, each 15 000 ft², are under construction. These will house professional personnel in the Laser Isotope Separation and the Advanced Quantum Electronics groups. The new trailers will consolidate all professionals in or near Building 381 and provide an office environment of comparable quality.

Future Plans

While no line item construction is authorized within the next two years, two major projects have been submitted for which construction would start in FY 1979. Shiva Nova includes a 95 000-ft² laboratory addition to Building 391 and a new office building for 200 people. It would be completed in early 1982. The Laser Isotope Separation Facility would have about 50 000 ft² of laser-qualified laboratories, with offices for 175 professionals. Completion would be late in 1980.

Until a major line item is completed, the Laser Program will have to rely to an increasing extent on temporary facilities funded from its own equipment and operating resources.

Section 2

SOLID STATE PROGRAM

Contents

Section 2 — SOLID STATE PROGRAM	2-5	Quality Control	2-100
2-1 Argus	2-8	Technology Transfer	2-101
2-2.1 Overview	2-8	2-2.6 Disk Amplifier Contamination	
2-1.2 Achievements	2-11	and Damage	2-101
2-1.3 Staging and Small-Scale Instabilities	2-13	Contaminants	2-101
Laser Staging	2-13	Clean Assembly Rooms	2-105
Spatial Filtering	2-13	Amplifier Cleaning and Assembly	2-107
Time-Averaged Power	2-13	2-2.7 Spaceframe	2-108
Time-Resolved Power	2-15	Construction	2-109
Filling Factor	2-18	Stability	2-111
2-1.4 Performance Improvements through		Beam Splitters and Folding Mirrors	2-112
Image Relaying	2-19	Cradles	2-112
Beam Propagation with Sequential		Gas System	2-113
Spatial Filters	2-23	2-2.8 Power Conditioning	2-113
Low-Pass Filtering	2-23	Staging and Layout	2-115
Fully Relayed System	2-27	Pulse Power Grounding	2-119
2-1.5 Subsystems	2-28	Fault Protection	2-121
Facilities	2-28	Capacitor Bank Assembly	
Laser Control	2-29	and Testing	2-123
Power Conditioning	2-30	Preionization Lamp Check (PILC)	2-125
Laser Components	2-32	Controls and Diagnostics	2-125
Component Train	2-37	System Design and Prototype Tests	2-128
Chain Optics	2-39	Pockels Cell Drivers	2-134
Component Alignment and Beam Line		Flashlamps	2-136
Stability	2-40	2-2.9 Control System Architecture	2-138
Laser-Target Isolation	2-42	Front End Processors	2-139
Instrumentation for Beam Diagnostics		Intermediate-Level Processors	2-140
and Laser Alignment	2-42	Supervisory Monitoring, Analysis, and	
2-1.6 Performance Highlights	2-46	Control (SMAC)	2-140
2-1.7 Schedule and Cost Summary	2-50	Intersystem Communication	2-141
Construction and Operation	2-50	2-2.10 Beam Alignment	2-141
Cost/Manpower	2-53	Oscillator-Preamplifier Alignment	2-142
2-2 Shiva	2-54	Main Chain Input Pointing	2-142
2-2.1 Overview	2-54	Spatial Filter Pinhole Positioning	2-143
Technical Status	2-54	Centering on Focusing Lens	2-143
Project Management	2-56	Pointing at Target	2-144
Schedule	2-56	Focusing on the Target	2-144
2-2.2 Performance Highlights	2-56	Target Viewing and Exchange	2-145
2-2.3 Shiva Laser Components	2-66	Alignment Controls	2-145
Disk Amplifiers	2-73	2-2.11 Alignment Control Subsystem	2-147
Amplifier Design Summary	2-79	Front End Processors	2-148
Spatial Filters	2-79	Alignment Control from	
Electro-optical Isolators	2-85	Control Room	2-151
Turning Mirror Gimbals	2-89	Products Designed to Support FEPs	2-151
Pockels Cells	2-90	2-2.12 Beam Diagnostics	2-155
2-2.4 Optical-Pulse Generation and		Data Acquisition and Control	2-156
Synchronization	2-94	Oscillator and Preamplifier	
2-2.5 Optics Procurement	2-97	Diagnostics	2-158
Glass Storage and Inventory Control	2-99	Chain Diagnostics	2-161

Incident Beam Diagnostics	2-162	2-4.6 Other Studies of Laser Glasses	2-263
Reflected Energy	2-168	Fluorescence Sensitization	2-263
Prepulse Measurement	2-168	Saturation Fluence	2-266
Amplified Spontaneous Emission		Fluorescence Line Narrowing	2-268
Monitor	2-169	Fluorescence Quenching	2-271
2-2.13 Target Chamber	2-169	Multiphonon Relaxation	2-272
Focal Spot Size of 10-Beam Clusters	2-170	2-4.7 Faraday Rotator Materials	2-274
Target Positioner	2-175	2-4.8 Lens/Substrate Materials	2-276
Lens Positioner	2-177	2-4.9 Oscillator Crystals	2-277
Centering Screen	2-177	2-4.10 Laser-Induced Damage	2-278
2-2.14 Target Diagnostic System	2-181	Antireflective Coatings for Shiva	
2-3 Shiva Nova	2-184	Amplifier Rods	2-279
2-3.1 Overview	2-184	Pulse-Duration Dependence on	
Project Strategy and Scope	2-184	Surface Damage	2-279
Construction Planning and		Other Studies	2-281
Design (CP&D)	2-186	2-4.11 Nonlinear Optics	2-282
2-3.2 Laser Chain Design	2-186	Refractive Index Nonlinearity	2-282
2-3.3 Optics	2-189	Facilities	2-284
2-3.4 Mechanical Systems	2-189	2-5 Pulse Generation and Shaping	2-286
2-3.5 Power Conditioning	2-190	2-5.1 Overview	2-286
2-3.6 Alignment and Controls	2-192	2-5.2 Actively Mode-Locked and	
2-3.7 Target Chamber	2-192	Q-Switched Oscillator	2-289
2-3.8 Activation and Shielding		Theory	2-289
Considerations	2-194	Experimental Development	2-291
2-3.9 Buildings	2-198	Electronic Switchout	2-298
2-3.10 Design Procedures	2-202	2-5.3 Regenerative Amplifier	2-300
Laser System Design and		Theoretical Considerations	2-301
Analysis	2-203	Experimental Apparatus	2-302
Cost-Optimum Design of		System Operation	2-303
Laser Amplifiers	2-222	2-5.4 Passive Pulse Shaping by	
Optimum Amplifier Aperture	2-233	Coherent Pulse Addition	2-308
2-4 Optical Materials	2-235	Pulse Stretching with a Fabry-Perot	
2-4.1 Overview	2-235	Interferometer	2-308
2-4.2 Fluoride Glasses	2-239	Double-Etalon Pulse Shaper	2-309
Fluorophosphates	2-239	Polarizing Beam-Splitter Stacker	2-313
Fluoroberyllates	2-241	2-5.5 Active Pulse Shaping	2-316
Fluorozirconates	2-247	Example of Pockels Cell Active	
2-4.3 Gain Coefficients of Neodymium-Doped		Pulse Shaping	2-317
Laser Glasses	2-247	System Requirements for Active	
Experimental Measurements	2-247	Pulse Shaping	2-318
Comparison Between Theory and		Optical Risetime Measurements of	
Experiment	2-250	KD*P Pockels Cells	2-318
Compensation for Flashlamp and		Stripline Optical Modulators and	
Fluorescent Decay	2-251	Other Techniques	2-320
2-4.4 Neodymium Laser Glass Data	2-253	Summary	2-321
Computerized Spectroscopy Facility	2-253	2-5.6 Metallic-Coated Apodizing Apertures	2-322
Absorption Efficiency Calculations	2-253	2-6 Theory and Design Analysis	2-324
2-4.5 Glass Development Program	2-256	2-6.1 Overview	2-324
Procurement	2-259	2-6.2 ARTEMIS: A Diffraction Model for	
Equipment	2-259	Laser Light Propagation	2-326
Quality	2-259	Program Description	2-326

Generalized Fitting Scheme	2-327	Detailed Description	2-346
Phase and Amplitude Changes	2-328	MALAPROP Example: Efficacy	
Additional Features	2-329	of Filtering	2-353
Code Limitations	2-329	2-6.6 MCHARTSC: A Milestone Chart	
Program Verification	2-333	Constructor	2-357
2-6.3 Fast Lumped-Element Computer Analysis		Capabilities	2-359
of Laser Systems	2-333	Output Devices	2-359
Program Input	2-333	2-6.7 MATHSY: An Interactive Language	
Propagation	2-334	for Mathematical	
Spatial Filtering	2-337	Operations	2-359
Program Output	2-338	Background and Motivation	2-360
2-6.4 Bespalov-Talanov Ripple Growth		Interaction	2-360
Calculations in Laser		Array Processing	2-360
Systems	2-339	Special Functions	2-361
Ripple Growth	2-339	Graphics	2-361
Amplifier Gain	2-340	Programming	2-361
Program Input	2-341	MATHSY Examples	2-361
Calculation	2-341	Torus	2-363
Program Output	2-343	2-6.8 DLOGE: A Procedure for Interpreting	
2-6.5 MALAPROP: Light Propagation in		Optical Densitometer Records	2-364
a Nonlinear Medium with			
Stochastic Perturbations	2-344		

Section 2

SOLID STATE PROGRAM

The Solid State Laser Program is responsible for developing the large Nd:glass laser systems for LLL's target implosion experiments. These systems—Janus, Cyclops, Argus, Shiva, and Shiva Nova—are designed and constructed on a time scale paced by technological innovations and program resources. Figure 2-1 shows the overall plan. In addition to the major system activities, the Solid State Program is responsible for system upgrading, advanced laser technology, and special laser technology for target experiments.

In 1976 the program's major accomplishment was

completion of the Argus laser (see Fig. 2-4). This laser system achieved an output power of 2 TW in June 1976, 3.5 TW in November, and recently more than 4.5 TW due primarily to an innovation in system design. In September 1976, an Argus target experiment yielded a fusion energy output equivalent to 3×10^{-5} of scientific breakeven, as projected and shown in Fig. 2-1.

With completion of the Shiva building, construction began this year on the Shiva laser system. This work has been the major activity of the Solid State Program. Subsystem designs have been frozen and

Fig. 2-1. Succession of laser irradiation facilities planned for LLL's laser-fusion program. Performance is shown in terms of pellet gain, the ratio of thermonuclear energy output from the target pellet to laser energy input. Pellet gain levels corresponding to the various milestones set for the program are shown at the left. (Shading indicates facilities not funded.)

Fig. 2-2. The building and space frame for Shiva were completed in 1976, and construction of the laser system had begun by year's end.

Table 2-1. Accomplishments in LLL's solid-state laser program during 1976

<u>Argus:</u>	2.0 TW June . 3.5 TW November . 4.6 TW December .
<u>Shiva:</u>	Building finished. All system designs frozen. Procurements and assembly begun. Laser and target frame installed. High-gain, clean amplifiers designed. Ultraclean assembly techniques developed. Shiva pulse-power digital control system prototyped. Automatic pointing and centering systems prototyped. Generalized Shiva control systems designed.
<u>Material Development:</u>	New laser, substrate, and Faraday rotator materials identified. ERDA/LLL materials program begun.
<u>Laser physics:</u>	Coherent and electro-optic pulse shaping demonstrated. High-reliability oscillator developed and implemented. Regenerative pulse-shortening demonstrated. Beam relaying and high-fill-factor apodization demonstrated. Detailed theories of self-focusing developed.
<u>System design:</u>	Saturated, B-limited system design methodology developed. 10X Shiva Upgrade (Nova) study performed.

assembly has started (see Fig. 2-2). Laser performance greater than 20 TW at 100 ps and target performance approaching 1% of scientific breakeven are expected. Many new concepts in control, propagation, and pulse generation are being implemented for the first time on Shiva. These new concepts promise to increase the utility of this laser substantially by increasing its reliability, versatility, and level of automation. In fact, without the new features of digital control and automatic alignment,

a system as complex as Shiva would be extremely difficult to use for real target experiments.

Finally, work on Shiva upgrades has progressed to the point where it now appears technically and financially feasible to commit large resources to a several-hundred-terawatt Shiva Nova laser and be assured of success.

Table 2-1 summarizes accomplishments of the LLL Solid State Laser Program in 1976. This year was remarkable because so many technologies have

Fig. 2-3. A brief history of solid-state laser technology in the LLL program. Solid boxes indicate reasonable understanding or well-developed technology; dashed boxes indicate incomplete understanding. On each of the five horizontal technology lines important examples are given. Each technology strongly affects other parts of the graph. The reliability and stability questions, in late 1974, arose from the problems that occurred when the Janus target experiments began. At this time the cost in manpower and schedule delay due to amplifier deterioration, beam wander, electrical failure, etc. became overbearing, prompting enhanced efforts in amplifier design and cleaning, auto-alignment, digital control, and development of new oscillators. In 1976 successful solutions to many problems were obtained. Questions arose which showed that additional work was required to completely understand propagation performance of future long-pulse (>1-ns) lasers.

come to fruition. Solutions to many outstanding problems associated with laser design, propagation, reliability, and pulse generation have been worked out or the foundation has been set for satisfactory solutions in the near future.

Figure 2-3 outlines the progress of technical development in the Solid State Program. An attempt is made to set solid-state technology in perspective by showing known and unknown quantities in solid and dashed ovals, respectively. In 1972 the need for a Shiva-class laser system for key laser fusion experiments was fully appreciated. It was also recognized that a major R&D effort would have to be initiated to develop the technology for such laser systems. In 1972 and 1973 basic laser materials and nonoptimized individual components were in hand; the major problem lay in organizing them into a system. By the end of 1974, optimized laser components were developed, and most laser problems were identified and their solutions proposed.

But new problems associated with target experiments arose as the Janus target system went into operation. Previous concerns over reliability, prepulse, alignment stability, and especially beam breakup due to self-focusing became experimental fact as the irradiation of actual laser-fusion targets began. These problems were recognized, and many solutions were developed which were incorporated into the design of the Argus laser system. Probably the most important of these was the use of multiple spatial filtering. In 1975 many satisfactory solutions to laser and laser-target problems were defined, and in 1976 they were implemented. In particular, ultraclean laser design and manufacturing techniques, ultrareliable oscillators, coherent pulse shaping, digital control and automatic alignment were developed to support the Shiva laser system. These

improvements have been applied where possible to existing systems; as an example, the new oscillator system is now operational on the Argus laser.

In 1976 propagation physics, materials science, and system design advanced markedly. These advances led to a twofold increase in beam power on Argus and provided the technical basis for upgrading Shiva. This upgrade, called Shiva Nova, will achieve on-target laser power of 200-300 TW and be capable of demonstrating the scientific feasibility of laser fusion by producing high-gain microexplosions.

In summary, solid-state laser technology has advanced to a level where we have a reasonable understanding of the constraining physics and engineering of glass laser systems. We have compiled an extensive data base of technical and cost information which is useful to outside industry via technology transfer and which is useful internally for a wide range of activities, including costing of new fusion-laser systems. Technical improvements will continue to result in significant laser performance increases; a notable example will be advances in thin film technology. Management and manufacturing technology will improve to enhance the execution of Shiva Nova-level projects. The successive goals of the national laser fusion program — 100× compression, significant thermonuclear burn, 1000× compression, scientific breakeven, and scientific feasibility—are attainable with the technology discussed in this report. In the following sections the activities of the Solid State Program are presented for the year 1976.

Authors

J. F. Holzhrichter

T. J. Gilmartin

2-1 ARGUS

2-1.1 Overview

Argus is the third in the LLL series of high-power Nd:glass laser systems designed for laser-fusion experimentation. Figure 2-1 illustrates the several primary motivations for its construction. First, the

fusion energy yield from Argus targets was intended to be large enough to measure the time of flight of the neutrons directly, thus spectrally confirming their thermonuclear origin. Second, Argus was to provide an operational demonstration of the efficacy of sequential spatial filtering in enhancing

short-pulse power performance. Third, Argus was to be the driver for implosion experiments to achieve target compression of 100X liquid density.

At present, yields on the order of 2×10^9 neutrons have allowed direct time-of-flight neutron energy measurements on several target experiments; laser performance has exceeded projections, thus proving the baseline design of the larger Shiva system, and the 100X compression experiments are under way. Finally, Argus is providing an ongoing experimental data base for laser-plasma interactions and laser physics at previously unrealizable multi-terawatt and multi-kilojoule levels. During 1977, Argus will achieve significant laser-fusion advances,

emphasizing high-density and high-temperature implosions.

The Argus laser (Fig. 2-4) is a twin-beam, 20-cm-output-aperture, Nd:glass solid-state laser capable of delivering greater than 4 TW of power to laser fusion targets. Its general layout parallels other master-oscillator/power-amplifier laser systems. A weak pulse possessing the requisite temporal profile is generated by the master oscillator on the center table. The pulse traverses small optical components that amplify it, modify its spatial profile, and split it into two pulses of equal intensity. Each of these pulses then undergoes further amplification as it travels through a sequence of amplifiers of

Fig. 2-4. The Argus laser pulse is initiated at the oscillator (square-edged blue box near far end of center table) and travels toward the near end of the center table through various small optical components that amplify and spatially shape the beam, then split it into equal-intensity pulses that branch to left and right. These pulses are turned 90° again at the corners of the long outer "side-arm" tables and travel up the tables through identical sequences of amplifiers, Faraday isolators, and spatial filters of progressively increasing size on their way to the target chamber, behind the open doors in the far end wall. The 25-mm-aperture rod amplifier chassis appears on the cross-arm table in the foreground. Disk amplifiers along the side-arm tables are blue with white cable covers in place. Spatial filters are in the white tubes located at intervals along each side-arm table.

Fig. 2-5. Schematic cross-section view of the Argus target chamber and final $f/1$ focusing optics used during 1976.

increasingly larger aperture. The amplification process culminates in two 20-cm-diameter beams, each providing more than 2 TW of focusable power. The pulsed beams are aimed at the target by two dielectric turning mirrors, and are focused on the target by $f/1$ aspheric lenses, as shown in Fig. 2-5. Arrival simultaneity is adjusted by 45° - 45° - 90° retro prisms on the oscillator table shown in Fig. 2-4.

In the following articles, the accomplishments of Argus to date, in terms of focusable power enhancement,¹ neutron yields, and general performance, are summarized. The laser staging strategy is discussed, first in terms of the effectiveness of multiple, sequential spatial filters in suppressing small-scale instability growth, and then in terms of

performance evolution as image relaying was introduced and the amplifier filling factor was increased. It is shown that the imaging effects of the lens pairs that comprise a high-power vacuum spatial filter must be taken into consideration, both in accounting for the performance of Argus and in designs for future laser systems. Next a description of the subsystems and components that are the essential parts of the Argus facility is given; these include the power conditioning, mechanical support structure, beam diagnostics, and laser-target isolation subsystems, as well as the active beam-line components. Finally, Argus laser performance, the cost, and the schedule of fabrication through 1976 are summarized. The target chamber, the targets, and their performance and diagnostics are discussed

in great detail in other sections of this report. Cost-effective upgrades for Argus to increase its output to 10 TW have been identified but will not be pursued during 1977.

Author
W. W. Simmons

2-1.2 Achievements

Argus began dedicated, one-sided target irradiations in June 1976. At that time, the north arm was fully defined and operational, while the south arm was in a hardware-complete checkout phase during

characterization. Two-beam experiments started in mid-July and are still continuing. Figure 2-6 shows the evolution of Argus' power with time and the close time coordination between performance improvements and confirming yield enhancement from selected target neutron experiments.

Of particular interest are the time points in mid-September, when the beam profile was modified (from a filleted-quadratic profile) to a flatter-topped profile with filling factor of about 0.5, and in November, when the filling factor was increased still further (to about 0.7) by a partial implementation of the image-relaying technique described later. Dramatic focusable power improvements resulted in each instance.

Briefly, Argus has, during 1976, met and exceeded its programmatic short-pulse goals; these were¹ 1.5 TW of focusable power per beam for pulse durations between 30 and 100 ps.² Neutron

Fig. 2-6. Argus performance through 1976. Full up operations commenced at midyear. The laser has experienced two substantial upgrades in power capability during the year. Note neutron yield from target shots follows upgrade implementation closely in time.

yields exceeding 10^9 per shot in selected target experiments have dramatically confirmed this performance.³ Target-plane beam diagnostics, which spatially and temporally analyze both incident beams on each shot, give us further confirmation that focusable power (i.e., beam power incident on the target) is regularly and reliably in excess of 2 TW per beam, or 4 TW. Single-beam brightness

evaluation, carried out with equivalent plane-beam diagnostics described below, shows that the Argus beams exceed 10^{18} watts/cm²·sr their planes of best focus (see Fig. 2-7).

During 1977, Argus will be dedicated to performing target experiments that require temporally shaped/stacked pulses⁴ of up to 1-ns duration. At these longer durations, new problems confront us as

Fig. 2-7. Summary of single-shot performance analysis of Argus north arm representative of September 1976. Total beam energy (64.6 J) is measured with the incident beam calorimeter. Temporal power (lower left) is recorded with a streak camera in the plane equivalent to 100 μm in front of best focus. The array camera described in Section 3 takes equivalent plane time-averaged photographic data which, when reduced, enables us to plot enclosed energy contour trajectories (upper right) and energy distribution in equivalent planes; distribution in the best focus plane is shown at lower right. The image radius of the final spatial filter pinhole is shown as well; very little energy appears outside this circle. In the upper left corner, we show the magnified best-focus-plane beam profile; the circle surrounding it enclosed 90% of the beam energy. Moderate astigmatism is evident but is not severe. By combining time-resolved and time-averaged data, we arrive at a beam brightness of $1.5 \times 10^{18} \text{ W/cm}^2 \cdot \text{sr}$.

this more energetic beam traverses the laser amplifier; specifically, damage to optical coatings and closure of spatial filter pinholes will provide new performance limits that are not as yet experimentally defined. These potential constraints are presently being explored using the Argus laser chain. At present, energy in excess of 1.1 kJ at 0.9 to 1.0 ns has been obtained from a single beam.

2-1.3 Staging and Small-Scale Instabilities

Laser Staging

Argus is the first laser to incorporate multiple, sequential spatial filtering as a deliberate check on the exponentiation of small-scale beam breakup and filamentation.⁵ Early experimental work using the ILS⁶ and Cyclops⁷ laser systems at LLL confirmed the nature and origin of small-scale beam instabilities and established both a need and a design criterion for spatial filters in a multi-component amplifier chain. Succinctly stated, the incremental beam-breakup integral ΔB must be less than three for any section of the amplifier. (An amplifier section is that part of the optical train lying between sequential spatial filter pinholes; ΔB measures the approximately exponential growth of the fastest growing instabilities on the beam profile,⁸ and is defined by $\Delta B = k\gamma \int_{NL} Idl$, where the on-axis intensity integral counts all of the material in the amplifier section.) Using this criterion, the ground rules previously stated⁹ (namely, two 20-cm output aperture chains employing disk amplifiers already performance-proved on Cyclops and Janus systems) and methodology described elsewhere,¹⁰ the baseline single-arm beam design shown schematically in Fig. 2-8 was developed.¹¹ The parameters shown are beam diameter, beam power in GW at the exit of each section, ΔB in nepers (for each section), and the accumulated nonlinear phase retardation in radians along the beam centerline at the exit of each section. The numbers indicated are for a design-center 1.5-TW shot, with a nominal filling factor of 0.4, and for realized performance at these progressively larger filling factors (0.35, 0.50, and 0.70).

There are differences between initial design and actual chain performance.¹² The initial design assumed a gain of 2.0 per three-disk C-amplifier, and a spatial filter pinhole transmission of unity. A gain of 1.8 per C-amplifier was realized, and we observed that spatial filter transmission roll-off with increasing input power is more gradual but initiates at lower power levels than was previously assumed. Table 2-2 compares these differences in terms of single-arm power and gain performance for various sections.

Spatial Filtering

The success of multiple spatial filters (SF) in countering the detrimental effects of small-scale breakup is best evidenced by performance comparisons between one arm of Argus and a similarly staged laser system without multiple spatial filters (Cyclops). For similar filling factors (0.50) and for short pulse operation, maximum power obtainable from Argus is about 1.6 TW; essentially all of this power is focusable on target. Cyclops is able to reach 1.0 TW, but only 60 to 80% of this power is focusable¹³; the remainder is contained in high frequency spatial "noise" that misses the target and in high intensity filaments that may damage optical components as well. Figure 2-9 shows near-field time-integrated output photographs of the two beams for qualitative comparison.

Time-Averaged Power

To characterize laser performance, transmitted energy through the second, third, fourth, and final spatial filters was measured as a function of beam input power to the 4-cm rod amplifier. In each instance, as input power is increased, progressive roll-off of the data points from the appropriate straight-line gain curves becomes apparent. The effect is attributed to small-scale beam breakup rather than gain saturation, which is inconsequential for pulses less than about 100 ps. In fact, the data (as shown, for example, in Fig. 2-10) correlate well with various simple phenomenological models depending explicitly upon the breakup integral ΔB .

Several laser amplifier simulation codes have been developed to analyze laser system performance (§ 2-6.3); each depends upon this correlation, and upon data obtained from other laser systems, for normalization. One of these codes, SPACE-R, is

Design center

Power at 100 ps, GW	4.1	40	120	800	1560	1500
Breakup integral ΔB , Np	0.5	0.7	1.1	2.0	2.2	2.0
Whole beam phase B, rad	0.5	1.2	2.3	4.3	6.5	8.5

Realized, F = 0.35

Power	4.5	49	157	770	1257	1110
ΔB	0.7	0.9	1.7	3.1	2.8	2.4
B	0.7	1.6	3.3	6.4	9.2	11.6

Realized, F = 0.50

Power	7.9	85	273	1300	1990	1685
ΔB	0.7	0.9	1.7	3.3	2.9	2.4
B	0.7	1.6	3.3	6.6	9.5	11.9

Realized, F = 0.70, relay in

Power	10	110	350	1675	2650	2330
ΔB	0.7	0.9	1.7	3.2	2.7	2.3
B	0.7	1.6	3.3	6.5	9.2	11.5

Table 2-2. Argus single-arm performance; design and realized section gains and losses

		Rod amplifiers	B-disk	B-booster	C-amplifier	C-booster	Output
Power out (GW)	Design	4.1	40	120	800	1500	1500
	Realized	7.1	75	240	985	1525	1435
ΔB (neper)	Design	0.73	0.81	1.26	2.9	2.9	3.3
	Realized	0.88	1.08	1.85	3.1	2.2	2.3
T_{sf}	Design	1.0	1.0	1.0	1.0	1.0	—
	Realized	0.98	0.98	0.95	0.84	0.92	—
Gain	Design	—	9.8	3.0	6.6	1.9	—
	Realized	—	11	3.4	5.2	1.7	—

used as a vehicle to discuss the overlying ideas and to illustrate its reasonable agreement with Argus experiments. This code was primarily developed for the analysis of Shiva Nova point designs; it is discussed in general terms in the Nova design section (§ 2-6.3).

Given a fixed component arrangement, input beam-intensity profile, and pulse duration, SPACE-R calculates (saturated) gain, B-contribution, and output power of each component sequentially for a number of equal-area radial zones of the laser beam. Zones are assumed to "propagate" independent of each other through the chain elements. SPACE-R simulates the effects of diffraction (discussed below) and self-focusing by subdividing each zone into two subsections with intensities $I \pm \Delta I$. This procedure allows us to approximate the growth of large- as well as small-scale ripples due to whole-beam B effects. Input zone intensities are chosen to simulate input beam profiles. Initial noise, represented by ΔI_0 , corresponds in a crude sense to the radial distribution of imperfections in the input beam. This noise component is assumed to grow as $(1 + 2B^2)$, the average growth rate for large ripples.¹⁰

The spatial filter (SF) transmission function is approximated by

$$T_{SF} = \frac{1}{1 + \Delta e^{2\Delta B}}, \quad (1)$$

where Δ represents the fractional spatial noise power present at each SF output, and ΔB measures the exponential growth of small-scale noise in the amplifier section preceding the SF. In using Eq. (1), one makes the implicit assumptions 1) that each SF, by stripping away small-signal noise, forces small-signal exponentiation to restart in following components (in effect, B is "reset" to zero for each amplifier section), 2) that residual small-scale noise referred to the section input is the same for all sections, and 3) that SF's discriminate perfectly; that is, the entire beam passes each pinhole, whatever its diameter, while all small-scale noise is rejected. Despite these restrictions, reasonable agreement has been found with the data for the parameter value $\Delta = 0.02\%$, for all spatial filters. Calculations based on this model are shown, for example, as the solid curves underlying the data points in Fig. 2-10. ΔI_0 has been chosen to be 0.3%.

SPACE-R has also been used to calculate the tabular values shown in Fig. 2-8 and in Table 2-9.

Time-Resolved Power

Since small-scale instabilities grow at the expense of beam intensity, one expects the temporal pulse center to be progressively "eaten away" by the spatial filters as the beam traverses the amplifier chain. One rough measure of optimal power performance for Argus (or any other large solid-state laser) is the existence of a very slight temporal "dip"

in the equivalent plane streak camera record. For shot 10 depicted in Fig. 2-11, this dip is absent; the pulse peak is, instead, somewhat flattened relative to the front-end temporal profile. Note the difference in FWHM pulse durations between input and output pulses, which is related to this flattening.

The system, of course, can be overdriven; the output then exhibits a distinctive temporal dip.^{7,14}

Processed streak camera records for such an event are shown in Fig. 2-12 by way of example, and illustrate how *not* to operate the laser amplifier. Beam power is not efficiently coupled to the target and, in addition, the spatial filter pinholes are very heavily flux-loaded (and sometimes damaged).

By correlating temporal measurements of the output beam with the above calculations, we can

Cyclops

Argus

15 cm

$P_{OUT} = 640 \text{ GW}$

$B = 6.2$

17 cm

$P_{OUT} = 1500 \text{ GW}$

$B = 11.5$

Fig. 2-8. Comparative near-field beam profiles with (Argus) and without (Cyclops) multiple spatial filtering. Top, polaroid exposures through 6.3, 0.6, 1.0, and 2.0 neutral density filters; bottom, 1Z plate exposures. Note that the high spatial frequencies and high intensity filaments characteristic of an unfiltered beam are absent in the Argus profiles.

Fig. 2-10. Time-averaged power output vs power input for two filling factors. The dashed lines at $\Delta B = 2.5$ and $\Delta B = 3.0$ indicate the desired operating conditions for maximum power output without significant temporal distortion. Time-averaged power out is defined by the ratio of energy into the diagnostic calorimeter divided by the temporal FWHM of the pulse as measured with the output array streak camera. Lines underlying the data points are generated by the code SPACE-R using the SF transmission model discussed in the text.

Fig. 2-11. Overlays of the data reduced from an equivalent plane streak camera photograph and a Gaussian representation of the (same shot) pulse as recorded with a Reticon-equipped streak camera located at the oscillator. The ordinate is normalized to beam power by setting the area under the micro-densitometered curve equal to the measured pulse energy. Right, normal shot. Left, overdriven shot, illustrating that temporal distortion arises predominantly from beam-breakup. In each case, $F \approx 0.5$.

Fig. 2-12. Illustration of severe temporal "dip" distortion that signifies a heavily over-driven amplifier. $F = 0.35$. Most of the beam power has been converted to small-scale power, then stripped away by the spatial filters.

characterize the onset of temporal "flattening" and temporal "dip" regimes of amplifier operation with ΔB for the C-amplifier section equaling 2.5 and 3.0, respectively. These results are consistent with our prior experience with other lasers, and serve as useful rules of thumb in discussions to follow.

Filling Factor

The efficiency with which energy and/or power can be extracted from a given aperture is measured by the filling factor F , which is defined by the relation(s)

$$F = \frac{\int_0^a I(r) 2\pi r dr}{I_{\max} \pi a^2} = \frac{\text{average intensity}}{\text{peak intensity}}, \quad (2)$$

where $I(r)$ is the beam intensity at the radial position r of a circularly symmetric profile, and a is the clear aperture radius. For most (but not all) situations of interest, $I_{\max}$ occurs at $r = 0$; thus, calculations of the B-integral based upon the on-axis intensity generally represent the region of the beam where small-scale growth is fastest.

For Argus, as for other laser systems at LLL, we have generated propagating beam profiles by illuminating a metallic (or photographic) apodized aperture mask¹⁵ with the central portion of the spatially Gaussian pulse from the oscillator. The resulting beam, characterized initially with a smooth intensity profile given by $I(r) = I_{\text{Gauss}}(r)T(r)$ with $T(r)$ the mask transmission function, traverses the remaining amplifier sections with no further deliberate spatial truncation. Neglecting diffraction and nonlinearities for the moment, geometrical ray projection then predicts that F is constant for every chain element. As examples of this (over) simplification, Fig. 1-11 shows time-averaged power output vs chain input for two initial profiles and corresponding filling factors $F = 0.35$ (June through September) and $F = 0.50$ (September through October). The former, conservative choice, formed by a transmission function $T(r)$ that is a filleted quadratic with $F = 0.41$, allowed for significant increases in focusable power to be achieved simply by increasing the (nearly) free parameter F .

Experiments have shown that F does not change significantly with propagation during normal (i.e., not overdriven) laser operation, for $F \leq 0.5$. When initial fill factors are larger than 0.5, F can be expected to vary substantially from element to element throughout the chain. In Fig. 2-13, we show overlaid input and output beam profiles from three different input beam shapes; the edge of the output beam departs noticeably from its input slope in the highest filling factor case. In Fig. 2-14, we show time-averaged output power curves for three input profiles; one of these is a "hard" aperture profile (a 21-mm-diam washer). It is difficult to distinguish, either from these curves or output beam profiles, which initial input profile was used.

To account more quantitatively for variations in the profile as the beam traverses the laser, we took into account diffraction, self-focusing, and the aperture stop effects of the spatial filter pinholes. The latter inevitably soften the profile edge by removing higher transverse spatial frequency components and simultaneously introduce intensity modulation upon the beam. The signature of a spatially filtered beam in the near field is the appearance of irregular rings at the SF cutoff frequency. To illustrate this point, Fig. 2-15, center, shows a typical scan through the diameter of a near-field beam photograph taken at moderate laser power (thus deemphasizing self-focusing effects). For comparison,

top and bottom curves are computer profiles generated by ARTEMIS,¹⁶ a computer code that effectively models beam propagation through large laser systems. To obtain the output results shown here, a cosinusoidal radial modulation at the SF cutoff frequency was superposed upon the beam at the chain input; this modulation represents in a simple way the spatial noise generated by optical imperfections in the rod amplifier section. Excellent agreement with the data is obtained for the reasonable peak-to-peak modulation depth of 10%.

These and other similar comparisons convinced us of the ability of our models to account for whole-beam distortions. In the next sections, we discuss more completely the ideas behind this modeling approach.

2-1.4 Performance Improvements Through Image Relaying

Implementation of spatial filters has resulted in almost complete suppression of the effects of small-scale instabilities, thus allowing experimental access to the details of whole-beam behavior at high power levels. As a result of comparisons between observed beam profiles and theoretical predictions concerning nonlinear propagation, an entirely new high-power beam-propagation philosophy, which we call "image relaying," has emerged.

The goal central of image relaying is to maintain a smooth intensity profile through finite aperture components as the beam traverses the amplifier. Diffraction and nonlinear phase distortion work together to degrade this smoothness in a conventionally staged (i.e., non-spatially filtered) amplifier.* If, however, a (phase distorted but otherwise smooth) beam passes through a confocal lens pair, the emerging beam profile remains a smooth, reasonably close approximation to the incident beam profile throughout a well-defined downstream distance terminating at the input lens

*Aberrations and surface imperfections in components through which the beam passes obviously influence beam smoothness as well. Image relaying produces a small benefit here too, but discussion of this point is deferred to a later section.

- (a) Moderate power shot
 $P \approx 0.70$ TW
 Input filling factor = 0.33
 Output filling factor = 0.37

- (b) High power shot
 $P = 1.6$ TW
 Input filling factor = 0.50
 Output filling factor = 0.58

- (c) High power shot*
 $P = 2.8$ TW
 Input filling factor ≈ 0.85
 Output filling factor ≈ 0.67

*Energy to C-head flashlamps
 larger by 44%

Fig. 2-14. Time-averaged performance points for several apodized aperture input functions, including a "hard" aperture. Only slight performance differences can be discerned.

Fig. 2-15. Beam profiles in cross section, illustrating agreement between experiment (center) and propagation code calculations (top and bottom). It is clear that the experimental profile exhibits maximum modulation at the SF cutoff frequency. The code runs are, of course, left-to-right symmetric. In the calculations, an input spatial noise function, $A \cos(kr)$, was superposed upon the input beam intensity. Top, $A = 0.05$; bottom, $A = 0.03$. The experimental modulation depth (averaged) lies between the two code calculations.

image plane (see Fig. 2-16). Diffraction and nonlinear phase distortion partially compensate each other throughout this so-called "imaging space."

The ideas behind image relaying as applied to long chain amplifiers are twofold; the smooth beam profile originating in a well-defined "object" plane (for a prime example, the plane of the profile-defining apodized aperture) is imaged in the input plane of a second confocal lens pair. The process is repeated with a third lens pair, etc., thus "relaying" the apodized aperture smooth beam image from plane to plane throughout the amplifier. Spatial filters, conveniently, constitute such confocal lens pairs if their spacing is correct. Amplifiers, Faraday isolators, etc., are then located in the "imaging spaces" between lens pairs where intensity gradients are minimal.

The payoff obtained by following this recipe is significant. First, one can realize a larger effective filling factor, thus using the amplifier clear apertures more efficiently. Second, the smaller modulation depth inherent to the technique implies smaller intensity gradients and lower local intensities for a given power level; this, in turn, implies greater focusable power output from a fixed hardware system. When elaborating upon these benefits in the following paragraphs, we establish beam brightness as the significant measure of laser performance.

We have partially implemented image relaying in the Argus laser chain; results of key experiments are discussed. In any real system, such as Argus, the necessarily finite SF pinhole diameters (which must be small enough to strip away substantially all small-scale beam noise) influence the whole beam to

Fig. 2-18. The combination of diffraction and nonlinear phase distortions produces large intensity gradients. With further propagation in a nonlinear medium, self-focusing enhances these gradients, reducing effective filling factor and, ultimately, focusable power. The use of a two-lens combination reduces diffraction effects as shown in the lower figures, thereby minimizing the growth of intensity gradients due to nonlinear phase distortions. Effective filling factor is maintained for component placement through a post-relay distance of $2f$.

a significant extent; this effect is examined qualitatively. This section concludes with a projection of the power capability of a fully relayed chain using Argus components and staging. Assuming "perfect" components (i.e., negligible Seidel aberrations), the brightness can exceed 10^{20} W/cm²·sr.

Beam Propagation with Sequential Spatial Filters

For a given peak intensity and clear aperture, the power and/or energy scales linearly with the previously defined filling factor F . Obviously, the most efficient fill factor is unity. However, the optimum fill factor is not so obvious when diffraction causes an initially smooth beam to acquire intensity fluctuations that are then amplified by nonlinear effects arising from the intensity-dependent refractive index. If a beam with a large F (that is, $F > 0.5$) is propagated through the optical amplification train and no attempt is made to minimize diffraction and nonlinear effects, the beam focusability will be seriously degraded. These detrimental effects can be greatly reduced through application of image relaying,¹⁷ which we now discuss in some detail.

The fact that an SF is an imaging system has two very important consequences in reducing self-focusing effects: (1) Diffraction effects can be minimized, thereby reducing the magnitude of the near-field source terms for small-scale self-focusing, and (2) the perturbing effect of whole-beam phase distortion on the near-field intensity profile is reduced. A direct result of these properties is that the ratio of peak-to-average intensity is reduced. Clear amplifier apertures may then be used more effectively for higher output power from any stage.

To illustrate these points, the free-space propagation properties of an idealized but aberrated beam have been calculated¹⁶ both with and without a spatial filter. Figure 2-16 shows the improvement in beam propagation characteristics achieved solely by the imaging properties of a lens pair (an SF with a very large pinhole diameter). The input beam in these calculations is described by the radial intensity distribution,

$$I(\rho)/I_0 = e^{-28\rho^2} e^{-6.91\rho^{100}} \quad (3)$$

and the phase distortion,

$$\xi_D = 0.5 I(\rho)/I_0, \quad (4)$$

with ρ the normalized radial beam coordinate.

The combined effects of diffraction and self-focusing are evident on the non-spatially filtered beam at all downstream distances. Notice in particular a pronounced shoulder near the edge of the beam, with a resultant increase in the ratio of peak-to-average intensity, and the fine grained "ripple" spread throughout the beam profile. Both of these characteristics are absent in the imaged beam. Figure 2-17 shows experimental verification with a beam of moderate intensity and comparable profile to the theoretical calculations.

If an amplifier with an intensity-dependent index of refraction is placed in the path of these beams, the phase distortion accumulated by the non-imaged beam will thereby develop significantly larger gradients than those possessed by the beam that has been imaged. Furthermore, these larger phase gradients (in the non-imaged beam) will result in enhanced growth of the intensity fluctuations (relative to the imaged beam) upon further propagation.

The preceding discussion can be extended to encompass a sequential set of spatial filters. The combined system will then behave as an optical relay line—relaying, with minimal distortion, a complex wave form from a (object) position prior to the first SF to a specific (real image) position past the final SF. To demonstrate the efficiency of the relay technique, both in improved beam quality and increased focusable power, we have implemented it in the first few stages of the LLL Argus laser system.¹⁸

In Fig. 2-18 we show schematically a portion of the laser optical chain and near-optimal power performance levels through the 85-mm clear aperture amplifier stages; both with and without the first relay lens pair. Figure 2-19 illustrates the high power, near-field beam profile at the entrance to the final SF. More than 90% of the beam energy was transmitted through this SF (300- μ m pinhole, 85-cm focal length lens), corresponding to a peak focusable power of 400 GW at this aperture.

Low-Pass Filtering

We now discuss the effects of spatial filter pinholes on the propagating beam. As has been

noted, pinholes are used to "strip off" high-frequency-intensity fluctuations before they can grow by means of nonlinear amplification to significant power content. The maximum transverse spatial frequency passed by the filter is obtained from the expression

$$K_{\max} = \frac{2\pi N}{a} \quad (5)$$

where

$$N = \frac{D}{4\lambda f}, \quad (6)$$

where D is the diameter of the pinhole, λ the wavelength of the laser light and f the f-No. of the spatial filter lenses. Hence, for a given f-No., the scale length of the intensity fluctuations on the transmitted beam is determined by the diameter of the pinhole. The most important factors that must be taken into consideration when choosing the pinhole diameter are the nonlinear growth curve for intensity perturbations and the noise sources that create the perturbations. Both of these quantities are difficult to measure experimentally and only incomplete understanding of them is known theoretically. However, a simple relationship does exist that compares input and output beam quality.

Fig. 2-17. Low power beam profiles taken with (top) and without (bottom) and first relay element. The photos were taken in the plane B-B in Fig. 2-18. Notice particularly the diffractive rings appearing in the bottom photo. At higher power levels, these serve as nucleation "ripples" for nonlinear growth with further propagation through downstream amplifiers.

Fig. 2-18. Optical schematic showing the portion of an Argus chain between the AA and the final 85-mm clear aperture spatial filter. Typical short pulse power is shown, both with and without the relay lenses.

Fig. 2-19. High power beam profile taken at the entrance to the third SF shown in Fig. 2-21. The initial peak-to-average ratio of this configuration is 1.4; $F = 0.7$. Observe that self-focusing effects are moderate even at this power level. 90% of the beam passes through the SF pinhole.

Fig. 2-20. The effects of SF pinholes on beam propagation. Top: a pinhole that is too small results in an intensity ripple on the output beam. The radial spatial frequency is at the SF cutoff frequency. The relative amplitude is proportional to the square root of the fractional beam energy lying outside the pinhole in the focal plane of the input lens. Center: The amplitude of modulation from a localized disturbance on the input beam is decreased by passage through the SF. The amplitude of the perturbation in the image plane is proportional to the square root of the fractional energy in the perturbation passing through the pinhole, and the scale length is determined by the pinhole diameter. Bottom: Intensity fluctuations distributed throughout the beam profile, and having a characteristic spatial frequency above the SF cutoff frequency are not transmitted.

This quantity, the rms amplitude fluctuation of the output beam relative to the input beam, is

$$\Delta\psi_{rms} = \sqrt{\frac{\int |\psi_{in} - \psi_{out}|^2 dx dy dt}{\int |\psi_{in}|^2 dx dy dt}} \quad (7)$$

$$\frac{\Delta\psi_{rms}}{\psi_{input}} = \sqrt{1 - T} \quad (8)$$

where ψ is the electric field and T is the ratio of the output energy to the input energy.

Equations (7) and (8) present a paradox in pinhole selection. If the input beam is smooth, the pinhole will cause the output beam to have amplitude fluctuations; an estimate of the magnitude of these fluctuations is given by Eq. (7), and their characteristic scale length (corresponding to the cutoff frequency of the SF) is given by Eqs. (5) and (6). Conversely, if the input beam possesses amplitude fluctuations, then Eq. (8) tells us that the pinhole will reduce the magnitude of these fluctuations.

Figure 2-20 summarizes the filtering properties of a low-pass SF and its effect on beam propagation. Computer calculations give the bounds for the parameter N in Eq. (3) as

$$5 \leq N \leq 10$$

for beam diameters ranging between 2 and 20 cm. In practice, the exact pinhole size must be obtained by experiment; the correct pinhole diameter is that which produces the smoothest output beam with the largest fill factor. Experiments with a variety of pinholes have led us to select 300 μm for the rod-B SF (a 250- μm -diam pinhole clips the main beam hard enough to impose significant bandpass "noise" upon it, while a 400- μm pinhole admits a significantly larger amount of noise generated by optical imperfections in earlier amplifiers).

Fully Relayed System

In concluding this discussion, it is useful and informative to project an estimate of maximum power and brightness performance from one fully relayed

Argus amplifier chain. We have used the ARTEMIS code to make detailed computer simulations of this system, using the following assumptions:

- Spatial noise originating in the rod section (i.e., prior to the first SF) is no worse than presently exists; hence, the first vacuum SF pinhole diameter is fixed at 300 μm .
- Static aberrations are zero (since ARTEMIS does not treat astigmatism or coma). Thus, focal spot blurring and beam brightness are influenced only by nonlinear phase distortions. This assumption causes negligible effects on focusable output power in the sense that we have used the term.*
- Small-scale transmission of each spatial filter is unity. Phenomenological corrections based on ΔB may be inserted at any time. ARTEMIS does, however, include energy/power loss at each pinhole due to focal plane clipping of the whole beam. This loss, too, becomes suddenly catastrophic when the drive power is too large.
- An input filling factor $F = 0.85$ is introduced at the apodized aperture, and perfectly homogeneous amplifier gain is assumed. Thus F is maintained, at low power throughout the entire amplifier.

With these (ground rule) assumptions, a number of code runs were made with varying pinhole diameters at the second, third, fourth, and fifth vacuum SF focal planes. The best of these "optimization" calculations is presented in Fig. 2-21. One concludes that a fully relayed Argus arm should be capable of delivering focusable power in excess of 3 TW. Of equal importance, *theoretical* beam brightness at this power level is well in excess of 10^{20} W/cm²·sr. As is discussed at length elsewhere in this report, measured brightness is of order 10^{18} W/cm²·sr; we conclude that passive aberrations enhanced by nonlinear phase distortion are primarily responsible for focal spot enlargements.

It is fortunate that Argus can, in fact, be converted to a fully relayed system by (1) making minor front-end modifications and (2) converting existing rod-B and B-B-C spatial filters from $f/10$ to $f/20$ optical systems. These modifications are underway; Argus will be converted during the first half of 1977.

*"Focusable output power" means that the output beam has passed through the terminating spatial filter in the chain.

Fig. 2-21. (a) Beam profiles at maximum projected power output, assuming a fully relayed Argus amplifier chain, with spatial filters having the pinhole diameters shown in (b). (b) Focal plane intensities at each pinhole (log scale). These projections have been generated with the ARTEMIS simulation code. Beam brightness in the final SF focal plane is estimated at $\sim 3 \times 10^{15}$ W/cm²-sr.

2-1.5 Subsystems

Facilities

Argus is in the high bay of Building 381, which is specifically designed for laser operation and has a number of unique environmental control features

summarized in Table 2-3. The laser/target support structure is a single reinforced concrete floor 3 ft thick, supported independently by many reinforced concrete pillars. Laser components are rigidly mounted to steel-reinforced concrete tables, which in turn are grouted to the floor. This structure forms a singularly stable optical platform for the laser.

Table 2-3. "Laser-qualified" high bay environment

Working dimensions	180 X 60 X 28 ft high
Air flow	Downward laminar
Capacity	100,000 ft ³ /min
Average velocity	7.6 ft/min
Temperature	Ambient 72° ± 2°F max (day operations)
Humidity	40-50%
Airborne particulates	<1500 particles larger than 0.5 µm/ft ³
Vibration	<2 X 10 ⁻⁶ in. peak-to-peak
Long-term laser pointing stability	<50 µrad

Laser and target areas are physically and electrically separated for maximum diagnostic noise immunity, as well as for personnel safety. The capacitor banks are housed in the basement, directly under the laser, and are fully interlocked and alarmed. Disk amplifiers are cooled by a bimodal, centrally controlled, dry nitrogen manifolding system. The nitrogen system also has the capacity for prechilling the nitrogen flow to the disk cavity of each disk amplifier for faster thermal recovery of the system. Flow rates are pressure-controlled and amount to about 10 ft³/min per amplifier head (fast flow). Disk amplifier and flashlamp cavities are mutually sealed and have their own independent nitrogen cooling flow.

Laser operations are centralized in the control room (shown in Fig. 2-22 and described below). For full system shots, the laser bay and bank rooms are cleared of personnel and swept with the TV surveillance subsystem pictured here. Banks are then charged, the oscillator and switchout shutters are opened, and the status of all components is assessed by the operator. When satisfied, he pushes a button (central console rack) to initiate the firing sequence, which first opens all camera shutters, next clears streak camera reticons, then commences a timed series of flashlamp and rotator discharges culminating in the next oscillator pulse (last event in the sequence). For maximum reliability, the oscillator runs continuously at a repetition rate of 0.5 to 5 pps. Immediately following the shot, the banks are crowbarred and all shutters are closed. Forty-five seconds later, the high-flow nitrogen disk cooling cycle initiates, lasting for 45-60 min. Flashlamp integrity is validated at the operators' discretion by

pulsed ionization lamp check (PILC). Personnel access to the laser bay is then opened, concluding the hot event sequence.

Laser Control

Figure 2-22 shows the control room for the Argus laser. The two left-most racks contain all the circuit breakers, housekeeping/interlock indicators (red LED means "made up", green means "not"), cross-connect panels, liquid flow indicators for rod amplifiers and cw alignment laser (brighter red lights midway up rack A02), and autocontroller for nitrogen flow to disk amplifiers (red, yellow, and green LEDs indicate for each amplifier, respectively, flow on, flow standby, and flow-off manual-control mode). Four TV monitors (top of center back racks) enable the operator to monitor activities in the laser, target, and basement bays. Racks A03 and A04 contain all the power supply controllers for voltage settings on the Argus capacitor banks. Racks A05, A06, and A07 contain the various trigger delay generators (TDG) for ensuring a properly timed lamp and rotator firing sequence. Rack A08 contains the master patch panel, which allows various waveforms and signals to be monitored by oscilloscopes in the control room. The operator console (foreground) contains, from left to right, audio communication links; zoom, pan, tilt, and channel select for the TV monitors (note the oscillator pulse train display on the small left monitor); master charge and fire control, and at-voltage display panels (red means "ready to fire," yellow means "ready to charge," and green "deselected" here); PILC charge, fire and

Fig. 2-22. Argus laser control.

summary panels, Faraday rotator fault detector panel, and master system clock (the latter drives the TDGs mentioned above); and camera shutter control (orange lights), SF vacuum, emergency power, and flow fault alarms. The HP 9830 (at extreme right) processes all the calorimeter signals and returns their energy readings after each shot. The digital voltmeter on the console top records switched-out pulse energy system shots.

Power Conditioning

We gained a lot of operating experience in powering the Argus laser during the past year. With 3.5 MJ of active energy storage, this system presented some new problems in the areas of bank staging and fault isolation. In addition, the pulsed ionization lamp check (PILC) circuitry was implemented for the first time on a large scale. A brief review and

critique of the power conditioning system (PCS) is therefore appropriate. (For a detailed discussion of the Argus PCS, see Ref. 19.) Table 2-4 lists system energy requirements and other operational energies.

The system is configured around the basic capacitive energy storage module shown schematically in Fig. 2-23. Each capacitor-inductor fuse combination in the parallel arms of this configuration forms an isolated energy storage module that provides the necessary trigger voltage and pump energy for a series pair of flashlamps. These modules are charged from a common power supply and switched from a common size "D" ignitron switch unit.²⁰ This approach results in a cost-effective, reliable system. These modules are installed in Argus as shown in Fig. 2-24.

The number of modules sharing a common switch is limited by the peak current and maximum coulomb transfer capability of the size "D"

Table 2-4. Energy requirements for Argus

Active element	Bank storage capacity at 20 kV (MJ)	Glass volume (liter)	Energy stored at 1.6 μ m (kJ)	Focusable energy extracted		
				At 100 ps (kJ)	At 400 ps (kJ)	At 1.0 ns (protected) (kJ)
4 Rods	0.05	0.7	0.5	—	—	—
18 B-disks	0.43	5.4	2.6	0.040	—	—
12 C-disks	<u>1.09</u>	<u>22.6</u>	<u>8.4</u>	<u>0.2</u>	<u>0.5</u>	<u>1.2</u>
Single-arm totals	1.57	28.7	11.5	0.2	0.5	1.2
Two-arm totals	3.14	57.4	23	0.4	1.0	2.4
Miscellaneous bank storage requirements						
4 C-rotators	0.30					
4 B-rotators	0.04					
Other	<u>0.02</u>					
Total Argus bank storage capacity	3.50					

ignitrons. Experience indicates that these tubes will operate reliably with a maximum peak current of 120 kA and a total coulomb transfer of 60 C. This corresponds to a limit of 32 parallel modules, or a maximum energy of about 600 kJ per switch.

For the Argus B-amplifier and C-amplifier sections, a single power supply (100-kVA capability, see Fig. 2-25) charges two fully loaded switch modules. Because the output terminals of the supply are common to both switch modules, a fault in excess of 1 MJ is possible. To minimize the effects of this potentially destructive fault mode, isolating diodes and fuses were included as shown in Fig. 2-23. In the event an ignitron should prematurely self-trigger, either during bank charge or while the banks are at voltage, the diodes prevent the discharge of energy from both switch modules through a single switch. Should a fault occur within the power supply, the fuses will clear before large-scale damage occurs. Both of these fault modes have in fact occurred during operation of the laser. The isolating diodes and fuses performed as anticipated.

Other fault modes exist within the 32-segment

flashlamp energy storage module. The most probable fault occurs when a capacitor in any given segment shorts while the banks are charged. In this case, the fuse in the faulty segment clears before significant energy can be transferred from the other segments. This has occurred a number of times during the past year. In every case, the fuses have limited the energy in the fault to values below 25 kJ, thus avoiding catastrophe.

Since flashlamps consume most of the Argus PCS power, Faraday rotators must also be energized (see Table 2-4). Again, rotator banks for a particular aperture are charged from a common 100-kVA supply. In the case of the "C" rotators, separate ignitron switches are provided for each rotator magnet. In the event of a magnet fault, high current fuses in each circuit prevent catastrophic energy dumping. Two 5-kA fuses are wired in parallel for each individual magnet circuit; we exercise care to avoid mutual inductive coupling between fuses. Subsequent to early troubles involving faulty ignitron switches, these circuits have worked reliably and well.

Fig. 2-23. Modular staging as implemented on Argus power conditioning system. Each capacitor-inductor-fuse combination in the parallel arms of this configuration forms an isolated energy storage module that provides the necessary trigger voltage and pump energy for a series pair of flashlamps. High voltage diodes and fuses isolate switch modules from power supply when a number of modules are charged by a single power supply.

Pulsed ionization lamp check (PILC)²¹ was implemented on a large scale for the first time on the Argus laser. PILC diagnoses defective flashlamps in the laser amplifiers in a nondestructive manner. Failure to detect defective lamps generally results in catastrophic failure of the lamps within the amplifier with attendant severe damage to optical components.

The lamps are checked by applying a full voltage, low energy pulse to them from the PILC circuitry. Current flow in the lamps is applied in the reverse direction; this procedure allows for diode isolation of PILC and bank circuitry. PILC energy is limited to approximately 1% of nominal pulse energy. This is sufficient to produce an end-to-end streamer arc along the lamp wall, but not to ionize the full volume of the lamp. Current transformers in the ground return leg for each lamp pair allow the PILC current pulses to be monitored and checked for correct pulse height. A summary of these monitors

is displayed in the control room as shown in Fig. 2-26(a). Should PILC find a fault, lamp location is displayed on the detailed panel display located in the laser bay [Fig. 2-26(b)]. Figure 2-27 shows the PILC circuitry as implemented with the Argus banks.

PILC has proved to be a very effective diagnostic tool. Since its final implementation on the Argus system, no flashlamp explosions have occurred in the amplifiers. Several defective lamps have, however, been detected and replaced before catastrophic failure occurred.

Laser Components

2.5-cm Rod Amplifiers. Each of the two arms of Argus uses a chassis-mounted, three 2.5- by 25-cm rod amplifiers aligned in optical series, as shown in Fig. 2-28, upper left. This amplifier chassis provides adequate protection from spurious intercomponent

Fig. 2-24. Segment of the 3.5-MJ energy storage bank for Argus, showing several racked capacitor-inductor modules.

Fig. 2-25. Full complement of Argus bank charging power supplies, located in Building 381 basement.

oscillations by incorporating two Faraday isolator units. Each 2.5-cm rod amplifier exhibits a gain profile homogeneous²² to within 5% using a non-index-matched sodium nitrite immersion solution. Including passive attenuation losses, each triple-rod chassis has a nominal small signal net gain of 600X.

4.0-cm Rod Amplifiers. The 4- by 25-cm rod amplifiers have gain profiles homogeneous to within $\pm 2\%$ and a small signal net gain of 7.1X. These amplifiers feature (1) samarium-doped shield glass of dimensions selected to exclude parasitic whisper modes from the rod volume, (2) silvered elliptical flashlamp reflectors, and (3) saturated ZnCl_2 ($n = 1.53$) immersion fluid. Both the 2.5- and the 4-cm rod amplifiers use anti-reflection-coated 0° rod faces in order to eliminate dispersive steering errors and to make use of the available apertures. Like the 2.5-cm rod amplifier, the 4-cm rod amplifier uses six 1.3-cm-bore, 300-Torr, 20-cm arc length xenon flashlamps. Figure 2-29, lower left, shows an assembled 4-cm rod amplifier.

Table 2-5 summarizes the Argus rod amplifier characteristics.

B-75 Disk Amplifier. Three B-75 disk amplifiers are used per arm on Argus. The internal B-75 design features (1) complete absence of any threaded fasteners (to eliminate abrasion contaminants), (2) electropolished stainless steel metal rails and disk holders, (3) split shield-glass assembly, (4) clip-on laser disk retainers, and (5) solid edge-clad laser disks. Figures 2-29, and 2-28, upper right, show some of these features. Each B-75 disk amplifier has a net pulsed gain of 3.6X for an input energy of 144 kJ. The 16-lobe silvered flashlamp reflectors have a segment curvature radius of 1.9 cm with the reflector displaced 1.3 cm from the axis of each flashlamp. The resulting gain profile is homogeneous to within $\pm 5\%$ of the axis gain.²³

Eight circuits (two flashlamps per circuit), each having a capacitance of 90 μF and an inductance of 450 μH , produce an approximately critically damped flashlamp pumping pulse of $3\sqrt{LC} = 600\text{-}\mu\text{s}$

(a)

(b)

Fig. 2-26. (a) PILC control and summary panels in Argus control room. (b) PILC individual lamp-circuit fault-display panel in Argus laser area.

Table 2-5. Specifications for Argus rod amplifiers

Rod amplifier (cm)	Rod length (cm)	Laser glass	Na ⁺⁺⁺ Doping (wt%)	Small-signal gain	Pulsed gain	Input energy (kJ)
2.5	25	Ed-2	1.0%	10.9	8.4	6
4.0	25	Ed-2	0.8%	9.9	7.1	12

Fig. 2-27. PILC circuitry as implemented with the Argus banks. PILC and main bank discharge paths are of opposite polarity; thus the two functions are isolated by the steering diodes.

duration. The 1.5-cm-bore, 112-cm arc-length, cerium-doped flashlamps are filled with 300 Torr of xenon and feature encapsulated electrodes.

C-75 Disk Amplifier. Each arm of Argus has four C-75 disk amplifiers comprising the 20-cm aperture output stages. In general, the design features of the C-75 amplifiers parallel those of the smaller B-75 amplifiers, with the exception that the C-75 disk holder assemblies were originally designed to accept either liquid²⁴ or solid-disk edge claddings (the former was intended for suppression of parasitic modes within the laser disks).²⁵ Recent progress in the development of index-matched solid-edge claddings has made the use of liquid-clad disks on Argus unnecessary. In changing from liquid to solid-edge cladding, we were able to remove the organic "O" rings from the internal optical pump-

ing cavity of the C-75 disk amplifier, thereby eliminating this serious source of contamination.

As reported previously,²⁶ extensive design efforts directed at optimizing the cleanliness of both the B-75 and C-75 disk amplifiers were undertaken to reduce damage and enhance amplifier radiance. The originally unclad C-75 laser disks have been returned to the manufacturer for application of an index-matched solid-edge cladding. Currently, solid-edge-clad "C" disks from Cyclops are being used in the south arm. Table 2-6 summarizes the Argus disk amplifier specifications.

Spatial Filters. The Argus laser system employs five sizes of spatial filters deployed along each amplifier chain in order of increasing entrance aperture. The smallest of these, No. 1 in Table 2-7, is shown in Fig. 2-28, lower right; the largest, in Fig.

Fig. 2-28. Components designed for the Argus laser system — clockwise from upper left: 2.5-cm rod amplifier chassis, 8.5-cm disk amplifier (J75), red-B spatial filter, and 4-cm rod amplifier.

Fig. 2-29. Inner assembly of the prototype of the B75 disk amplifier.

2-30. Because of the very high optical flux present in the vicinity of the SF focal planes, all the Argus spatial filters are evacuated to a pressure of less than 10^{-6} Torr. The focal plane aperture (generally a diamond wire die) is positioned at the input lens focus using a manually operated three-axis manipulator. The output lens of each unit is adjustable in focus and centering to permit, respectively, collimation and minimal aberration adjustments.

Internal vacuum is maintained below 10^{-6} Torr on each spatial filter assembly using ion holding pumps having a speed of 25 litre/s. Two pumps are used on each spatial filter in order to prolong pump lifetime and reduce the risk of excessive gas pressure buildup inside the spatial filters.

Table 2-7 summarizes the optical elements of each of the five spatial filters on Argus.

The output spatial filter on Argus (No. 5 element in Table 2-7) is specially modified to accept the amplified spontaneous emission (ASE) shutter²⁷ for target protection from the substantial optical flux generated by amplified fluorescence in each amplifier chain.

Component Train

Figure 2-31 presents pictorially the arrangement of the optical components in one Argus arm, in somewhat more detail than shown in Fig. 2-8. The functions performed by each component have been discussed previously,²⁸ with the exception of the relay lens pair shown in Fig. 2-31(b). These lenses image the apodized aperture (AA) in the vicinity of the first SF input lens, as has been discussed earlier.

Table 2-6. Specifications for Argus disk amplifier

Amplifier	No. of disks	Disk size (cm)	Nd doping (wt%)	Disk thickness (cm)	Small-signal gross head gain	Net pulsed small-signal gain	Glass type
B75	6	10.0 X 18.4	3.0	2.35	3.8	3.6	ED-2
C75	3	21.0 X 39.8	2.7	2.6	1.9	1.8	LSG-91H ^a
		(present north arm)	2.0	3.0	—	1.84	LSG-91H
		(present south arm)	2.0	2.5	—	1.7	LSG-91H

^aLiquid-clad disks.

Table 2-7. Specifications for Argus spatial filter

No.	Spatial filter	Input lens			Output lens			Output beam
		Diam (cm)	Clear aperture (cm)	Focal length ^a (cm)	Diam (cm)	Clear aperture (cm)	Focal length ^a (cm)	
1	4-cm rod to B	5.3	4.0	39.13	9.8	8.5	83.65	collimated
2	B to B	9.8	8.5	83.65	9.8	8.5	83.65	collimated
3	B to collimating lens	9.8	8.5	83.65	9.8	8.5	135.19	diverging
4	Collimating lens	22.0	20.0	516.86	—	—	—	collimated
5	C to C	22.0	20.0	195.82	22.9	20.0	195.82	collimated

^aFocal lengths measured at 0.633 μ m.

Fig. 2-30. C-C spatial filter for Argus amplifier chain. Device has a clear aperture of 20 cm, an overall length of 4.2 m, and incorporates two 200-cm focal length plane-aspheric lenses as optical elements and vacuum windows. Ion holding pumps (on top of the SF barrel) maintain a vacuum of 10^{-6} Torr. Note rigid clamp-down to table slots.

Figure 2-32 shows the north arm C-amplifier sections [see Fig. 2-31(e)]. Nitrogen flow controllers are also shown (against the wall).

A listing of components and their pertinent properties, in the order in which the beam encounters them starting from the apodized aperture, is given in Table 2-8.²⁹ From the tabulated values, simulation calculations³⁰ can generate performance curves similar to those shown in Fig. 2-10. One such calculation, representing present component arrangement, $F = 0.7$, and near maximum power

output, is included for illustration and reference in Table 2-9 (it is always useful to be able to refer to ΔB and B values at various interchain points).

Chain Optics

High-power beam focusability is affected by static aberrations arising from the cumulative effect of the 140-odd optical surfaces in a single Argus amplifier chain. With close optical tolerances on individual components, and careful mounting and

Fig. 2-31. Argus components. (a) Oscillator and switchout sections. (b) Beam profiling, splitting, and path equalization for the selected pulse. The dye cell is mounted kinematically for target shots. Positioning for the relay lens pair is indicated. (c) Each beam traverses rod amplifiers; power and beam diameter are shown where appropriate. (d) Next the beam traverses the B-disk amplifier section. (e) Finally, the beam traverses four amplifiers, three SFs, and two isolators in the C-disk section. Ultimately, the beam arrives at the target chamber via two turning mirrors (not shown).

Fig. 2-32. C-amplifier sections of Argus north arm [see Fig. 2-31(c)]. These amplifiers comprise the critical high power stages of the laser.

alignment, cumulative chain aberrations are held to less than 1 wave.³¹ Table 2-10 summarizes the optical characteristics of Argus.

Component Alignment and Beam Line Stability

The optical system comprising the incident beam diagnostics, described below, also serves for single-chain spatial-filter alignment. Once the SF lenses are accurately centered on the original (surveyed) beam line, the telescope/TV viewing system located at the end of each chain is used to image the cw alignment beam. In this way, all SF focal planes are imaged simultaneously. The positioning of the five pinholes, each in x, y, and z (focus), is done sequentially, using the beam position of the TV screen as fiducial reference. For highest power shots, the pinholes are moved upstream by precalculated

amounts, to compensate for focal "zoom" due to whole-beam self-focusing.

Once aligned, the system is stable in alignment to within 15 μ rad (limit on our measurement) for periods of hours, (probably for days, but we have not had occasion to check). Following a full system shot, beam pointing recovers after about 2 hr; thermal aberrations recover in 3-4 hr.

Turbulence, once a problem with large aperture systems,³² has been essentially eliminated through the use of sealed metallic intercomponent couplings that minimize random air flow into the beam path. The excellent air flow and temperature control systems in the laser facility help prevent stratification of the beam tube air; we observe no beam bending attributable to this source.

Good correlation has been found between the appearance of the cw beam (as viewed with several imaging systems) and the high-power pulsed-beam

Table 2-8. Properties of Argus laser components

Element	Beam diam (cm)	Thickness (cm)	Pulse gain	Angle (deg)	Refraction index	Nonlinear index ($\times 10^{-13}$ esu)
Rod section						
Apodizer	2.500	2.000	0.800	0	1.507	1.246
Polarizer	2.500	0.700	0.980	56.43	1.507	1.240
Turn prism	2.500	6.000	0.980	0	1.507	1.240
Rod, 25 mm	2.500	25.40	5.000	0	1.556	1.410
Rod, 25 mm	2.500	25.40	9.500	0	1.556	1.410
Polarizer	2.500	0.700	0.980	56.43	1.507	1.240
Polarizer	2.500	0.700	0.980	56.43	1.507	1.240
Rotator	2.500	1.250	0.960	0	1.678	2.000
Rod, 25 mm	2.500	25.40	9.500	0	1.556	1.410
Polarizer	2.500	0.700	0.980	56.43	1.507	1.240
Polarizer	2.500	0.700	0.980	56.43	1.507	1.240
Rotator	2.500	1.250	0.960	0	1.678	2.000
Pockels KD*P	2.500	5.000	0.850	0	1.470	1.000
Pockels BK7	2.500	0.800	1.000	0	1.507	1.240
Pockels oil	2.500	0.200	1.000	0	1.500	10.00
Polarizer	2.500	0.700	0.980	56.43	1.507	1.240
Polarizer	2.500	0.700	0.990	56.43	1.507	1.240
Diver lens	2.500	0.500	0.990	0	1.507	1.240
Rod, 40 mm	3.800	25.40	5.300	0	1.556	1.410
SF, 40 mm	4.000	0.800	0.990	0	1.507	1.240
B-amplifier section						
SF, 85 mm	8.500	0.950	0.990	0	1.507	1.240
Polarizer	8.500	1.200	0.980	56.43	1.507	1.240
Polarizer	8.500	1.200	0.980	56.43	1.507	1.240
Rotator	8.500	2.500	0.960	0	1.678	2.000
Disk, 85 mm	8.500	14.10	3.650	57.27	1.556	1.410
Disk, 85 mm	8.500	14.10	3.650	57.27	1.556	1.410
Polarizer	8.500	1.200	0.980	56.43	1.507	1.240
Polarizer	8.500	1.200	0.980	56.43	1.507	1.240
Rotator	8.500	2.500	0.960	0	1.678	2.000
SF, 86 mm	8.500	0.950	0.990	0	1.507	1.240
B-boost section						
SF, 85 mm	8.500	0.950	0.990	0	1.507	1.240
Beam split	8.500	2.200	0.970	45.00	1.507	1.240
Astigmatic lens	8.500	1.260	0.990	0	1.507	1.240
Astigmatic lens	8.500	1.260	0.990	0	1.507	1.240
Disk, 85 mm	8.500	14.10	3.650	57.27	1.556	1.410
SF, 86 mm	8.500	0.950	0.990	0	1.507	1.240
C-amplifier section						
SF, 85 mm	8.500	0.950	0.990	0	1.507	1.240
Recol lens	20.000	2.000	0.990	0	1.507	1.240
Polarizer	20.000	2.400	0.970	56.43	1.507	1.240
Rotator	20.000	3.100	0.950	0	1.678	2.000
Polarizer	20.000	2.400	0.970	56.43	1.507	1.240
Disk, 200 mm	20.000	7.950	1.840	57.27	1.556	1.410
Disk, 200 mm	20.000	7.950	1.840	57.27	1.556	1.410
Rotator	20.000	2.700	0.950	0	1.610	1.700
Disk, 200 mm	20.000	7.950	1.840	57.27	1.556	1.410
SF, 200 mm	20.000	2.000	0.990	0	1.507	1.240

Table 2-8. (Continued)

Element	Beam diam (cm)	Thickness (cm)	Pulse gain	Angle (deg)	Refraction index	Nonlinear index ($\times 10^{-13}$ esu)
C-booster section						
SF, 200 mm	20.000	2.000	0.990	0	1.507	1.240
Disk, 200 mm	20.000	7.950	1.840	57.27	1.556	1.410
SF, 200 mm	20.000	2.000	0.990	0	1.507	1.240
Target optics section						
SF, 200 mm	20.000	2.000	0.990	0	1.507	1.240
TGT lens	20.000	6.000	0.960	0	1.507	1.240

photographs.³³ As a result, targets can be aligned and shot with a high degree of confidence. Very little pulse-beam energy misses the target (<1.0%) as monitored by calorimeters on the far side of the target chamber. This performance feature is a direct consequence of the presence of the output spatial filters.

Successive shots, separated by hours and by minor realignment activity, have occurred for which all data (laser and target) were indistinguishable within a few percent. Generally, shot-to-shot reproducibility has been limited by the reproducibility of the switched-out oscillator pulse (typically 20% in power and time duration, 10% in energy). This will improve dramatically with the integration of the KAMO model-locked oscillator³⁴ in January 1977.

Laser-Target Isolation

Premature damage to targets by prepulses and amplified spontaneous emission (ASE)^{35,36} is controlled in Argus by a bleachable dye cell at the output of the 12-mm-diam preamplifiers and by a Pockels cell in each arm at the output of the 25-mm-diam rod amplifiers. The bleachable dye cell, which contains Eastman Kodak 9740 dye, suppresses both the remnants of the rejected oscillator pulses that leak through the optical gate in the switchout during its closed time and the interpulse noise that is switched out with the pulse to be amplified during the 8-ns open time. For most targets, the optimum small-signal transmission of this dye cell is about 10^{-4} . With typical relative values of $<10^{-3.5}$ for both

the switchout extinction and the oscillator interpulse noise, this transmission gives a pulse contrast ratio of greater than 10^7 .

The Pockels cells at the 25-mm rod output suppress ASE originating in the small diameter rod amplifiers at the front of the amplifier chain. The Pockels cells are 25-mm diameter and have a measured extinction ratio between crossed polarizers of less than 10^{-3} ; this has been adequate to prevent damage to most targets. The Pockels cell gate time (100 ns) is narrow enough to ensure that the ASE energy transmitted during the open time is small compared to the total leakage during the closed time.³⁷ The gate length allows reliable laser-triggered sparkgap switching using the rejected pulse train from the oscillator switchout. The criterion used to establish acceptable ASE levels is based upon aligned target survival in the focused beam, from a full amplifier flashlamp firing shot, with only the oscillator switchout disabled (the 25-mm Pockels cells are switched in their normal manner). Under these conditions, the single-chain ASE energy is 80 μ J.

Instrumentation for Beam Diagnostics and Laser Alignment

Present laser fusion targets are difficult and time-consuming to fabricate because of their small size and strict uniformity requirements. The alignment of the beams on the target and the setup of the diagnostics are also time-consuming, sometimes taking several hours. The Nd:glass laser is the most reliable type of high-power pulsed laser in operation

Table 2-9. Single-shot power performance of Argus

Input power	2 MW
Pulse duration	0.1 ns
Saturation flux	3.24 J/cm ²
Laser wavelength	1.064 μ m
Input profile	20
Large-scale noise fraction	0.3%
Small-scale noise fraction	0.02%
No. of radial zones	10

Element	Gain	Saturated gain	Power (GW)	ΔB (neper)	B-Total (rad)	Flux (J/cm ²)	Fill factor
Rod	4.60	4.54	9.1	0.37	0.37	0.13	0.71
SF	0.99	0.99	9.0	0.02	0.39	0.10	0.71
		1.00	9.0	0.39 ^a			
SF	0.99	0.99	8.9	0.00	0.39	0.02	0.71
Polarizer	0.96	0.96	8.5	0.01	0.40	0.02	0.71
Faraday rotator	0.96	0.96	8.2	0.02	0.42	0.02	0.71
Disk	3.65	3.63	29.8	0.10	0.52	0.07	0.71
Disk	3.65	3.59	106.8	0.36	0.88	0.27	0.71
Polarizer	0.96	0.96	102.6	0.10	0.98	0.27	0.71
Faraday rotator	0.96	0.96	98.5	0.20	1.18	0.26	0.71
SF	0.99	0.99	97.5	0.05	1.23	0.25	0.71
		1.00	97.0	0.84 ^a			
SF	0.99	0.99	96.1	0.05	1.28	0.24	0.71
Splitter	0.97	0.97	93.2	0.09	1.36	0.24	0.71
Lens	0.98	0.98	91.3	0.12	1.48	0.24	0.71
Disk	3.65	3.48	317.6	1.11	2.59	0.80	0.71
SF	0.99	0.99	314.4	0.16	2.74	0.82	0.71
		0.99	310.7	1.52 ^a			
SF	0.99	0.99	307.6	0.16	2.90	0.81	0.71
Lens	0.99	0.99	304.5	0.06	2.96	0.15	0.71
Polarizer	0.97	0.97	295.4	0.06	3.01	0.14	0.71
Faraday rotator	0.95	0.95	280.6	0.14	3.15	0.14	0.71
Polarizer	0.97	0.97	272.2	0.05	3.20	0.13	0.71
Disk	1.84	1.82	496.5	0.29	3.49	0.24	0.71
Disk	1.84	1.81	899.4	0.52	4.01	0.44	0.71
Faraday rotator	0.95	0.95	854.4	0.32	4.33	0.45	0.71
Disk	1.84	1.79	1530.5	0.92	5.26	0.76	0.71
SF	0.99	0.99	1515.2	0.32	5.58	0.79	0.71
		0.95	1433.1	2.84 ^a			
SF	0.99	0.99	1418.7	0.31	5.88	0.76	0.70
Disk	1.84	1.76	2495.7	1.62	7.50	1.32	0.70
SF	0.99	0.99	2470.8	0.58	8.08	1.42	0.70
		0.94	2320.3	2.50 ^a			
Lens	0.95	0.95	2204.3	2.17	10.24	1.36	0.67
Total		1102.15	2204.3		10.24		
				Final fill factor	0.666		
				Max. noise ratio	0.730		
				Modulation	0.525		

^aNumbers are cumulative ΔB in nepers for the preceding section.

Table 2-10. Optical parameters of Argus

No. of optical surfaces (each arm)	141
Beam divergence	Collimated through all sections except 4-cm rod amplifier
Target lenses	f/1 aspheric
Spatial filter lenses	f/10 plano-aspheric
Single-element aberration specification; <85-mm components	<1/20 wave at 1.06 μm
200-mm components	<1/10 wave at 1.06 μm
Cumulative static aberrations (each arm)	0.5-1.0 waves at 1.06 μm
Passive aberration compensation (in 1976)	Up to 3 waves of astigmatism; no spherical or coma correction capability
Optical path length in glass	~ 280 cm
Total optical path length (apodized aperture to target)	~ 60 m
System recovery time (limited by thermally aberrated C-disks)	~ 2 hr minimum

today. Nevertheless, it falls short of the requirements for repeatable experiments. These factors combine to make complete monitoring of the laser output necessary on each shot in order to interpret target irradiation experiments meaningfully.

As a result of these considerations, diagnostics were set up to characterize the laser pulse input into the amplifier train, the laser amplifier train operation, and the output beam parameters of interest for target irradiation experiments. Figure 2-33 is a schematic drawing of Argus showing the location of the beam diagnostic stations serving these purposes and listing data to be taken at each station. A fast photodiode and oscilloscope digitizer monitor the oscillator and switchout operation by recording the rejected pulse train at the single-pulse switchout. An integrating photodiode monitors the switched-out pulse energy. A calorimeter measures the pulse energy after it has been amplified by the 12-mm-diam rod preamplifier; and a Reticon-equipped streak camera records the pulse duration after it has passed through the (prepulse suppressing) dye cell. These diagnostics characterize the laser pulse input into the amplifier train.

At two intermediate locations along each laser train, the beam energy is measured with a calorimeter and a near-field photograph of the

beam is taken. The calorimeter data allows setting the flashlamp voltages on the front end of the laser to obtain the intended output power and to balance the output from the two arms. It is also used in conjunction with the output calorimeter to monitor the gain of each amplifier train on each shot. The near-field photographs are taken with Eastman Kodak IZ spectroscopic plates or with various types of Polaroid film. These photographs provide permanent records of system alignment and of accumulated dirt and damage in the optical train. On high power shots, they indicate as well the operating conditions at which self-focusing instabilities become significant. The diagnostic beam at the 25-mm rod output is taken through a 96% reflectivity turning mirror; the diagnostic beam midway in the amplifier chain is taken in reflection from a 2% reflectivity beamsplitter located at the input to the B-B-C spatial filter. In addition to the listed beam diagnostics, Pockels cell operation, selected amplifier flashlamp current waveforms, and Faraday rotator current waveforms are all recorded on oscilloscope traces, which monitor relative timing and proper electrical operation of these components.

The output beam parameters that are significant for target experiments are: the energy incident on the target; the temporal and spatial shape of the

beam at the target; and prepulse or ASE energy that might prematurely damage the target. A small fraction of the output beam from the laser is transmitted through the final turning mirrors to provide the source for these diagnostics. This low power beam is brought to a magnified (50X) focus using a Galilean telescope lens pair. Spatial and temporal measurements are made in planes in front of this focus at distances optically equivalent to target planes in the f/1 lens focus of the main beam. The optical system to accomplish this is described in detail in Section 3. In addition to these diagnostics, a fast photodiode-oscilloscope combination monitors for prepulses of energy greater than $50 \mu\text{J}$ that may precede the laser pulse by more than 0.5 ns. Finally, a volume-absorbing calorimeter measures a known fraction of the beam to determine the laser output energy.

In addition to focusing the beam for the equivalent plane diagnostics, the Galilean telescope and ir-sensitive television camera in the incident beam diagnostics package also provide an optical system for the alignment of the spatial filter pinholes in the laser. Figure 2-34 shows the optical system used for the pinhole alignment. Alignment is started by moving the negative lens in the Galilean telescope to focus the $\lambda = 1.064\text{-}\mu\text{m}$ cw-alignment laser beam in the plane of the crosshair as viewed with the relay lens and TV camera. The turning mirror at the front of the laser is rotated to center the focused beam on the crosshair. These adjustments correct the steering errors in the beam and image the best focus position of the five spatial filters on the TV camera. The diffuser is placed in the beam to illuminate the pinholes, and each

Fig. 2-33. Argus schematic, top view, showing locations for beam diagnostics that are discussed in the text.

Fig. 2-34. Optical schematic of the Argus laser amplifier, showing the SF and component alignment optics and TV vidicon location.

pinhole is adjusted in x, y, and z until the edges of the image are sharp and the pinhole is centered on the crosshair. If any displacements are necessary to precompensate for whole beam self-focusing, these are made after the best focus position is established. We find that both beam and pinhole alignment are very stable; only minor adjustments for centering and focus are needed from day to day. Only on occasions where major system modifications are done is it necessary to hunt to acquire the beam on the TV system. Using this technique, complete beam alignment, including the five pinholes in each laser chain, may be accomplished in about 15 min.

2-1.6 Performance Highlights

The output power from Argus has been progressively increased during the year by increasing the filling factor of the beam in the amplifier apertures. As mentioned earlier, the system was initiated with an $F = 0.41$ filleted quadratic aperture which, when folded with the spatial profile of the input beam, gave a 0.35 initial input fill factor. With this input beam, the maximum power obtainable from the north arm was about 1.1 TW. By increas-

ing the diameter of the beam filling the apodizer and by changing the apodizer profile to an $N = 10$ super-Gaussian, F was increased to 0.5. With these changes, maximum output power from the north arm increased to 1.7 TW. In early December, a series of experiments was performed with $F = 0.6$ and $F = 0.7$ apodizers and with a hard aperture which, when folded with the input beam profile, yielded an input fill factor of 0.85. In the course of these experiments, the relay lens-pair [described above and shown in Fig. 2-31(b)] was implemented. Output power performance from the three sets of experiments was similar (see Fig. 2-14), with the hard aperture performing slightly better than others. Figure 2-35 summarizes the time-averaged power performance for 1976. Record focusable power of 2.8 TW was obtained from a north arm shot with this aperture when the C-disk amplifier flashlamp voltage was increased to 23 kV (from the usual firing voltage of 20 kV). This beam-defining-aperture-plus-image-relay system is currently being used as the "standard" Argus configuration.

Every effort has been expended in building the Argus laser to produce the best possible beam quality. Highest quality optical components were used, and the surface finish and wavefront distortion of all elements were carefully controlled to

Fig. 2-35. Time-averaged data for one arm of the Argus laser system, illustrating the direct proportionality between optimum power output and aperture filling factor. The lower curve is obtained with hand calculations using a SF transmission algorithm similar to that used by SPACE-R. The upper two curves are obtained by linearly scaling the lower curve by the measured output filling factor. Agreement is quite reasonable.

minimize optical distortion of the beam (see Table 2-10). As a result, the passive beam quality of the Argus laser is less than $2\times$ diffraction limited. At high power, however, the beam quality is significantly degraded by self-focusing instabilities. Figure 2-36 shows qualitatively the changes in the near-field beam as laser output power is increased. (These photographs were all taken with the near-field camera described in Section 3, when the partially relayed laser input beam was defined by the 21-mm hard aperture.) As the output power increases from 0.9 to 2.8 TW, a noticeable increase in the beam filamentation is evident. Beam high-frequency content is considerably reduced by the cascaded spatial filters (see Fig. 2-9), but a noticeable structuring of the beam at wavelengths longer than the bandpass of the output spatial filter is evident.

A similar correlation between beam quality and output power is observed in the array camera photographs taken of the beam in an equivalent target plane. To illustrate this, Fig. 2-37 shows array camera photographs from the three shots shown in Fig. 2-36. These images are taken and analyzed in a plane equivalent to a position $117\ \mu\text{m}$ ahead of the focus of the north $f/1$ target chamber lens. The overall symmetry of the distribution shows that Seidel aberrations (i.e., astigmatism and coma) are well controlled. This symmetry is essential in obtaining a symmetric implosion from laser irradiated

targets. As power is increased, the beam at the target becomes progressively more structured. Without spatial filters, the high power beam would be broken up into smaller, more intense filaments; most of the energy in this small-scale filamentation would miss the target. The cascaded spatial filters in Argus have succeeded in controlling this filamentation; thus, nearly all of the laser output energy arrives on the target. Even with spatial filters, however, the relatively smooth focused beam at low power develops significant large-scale structure as the power approaches 2.5 TW.

Output calorimeter data and the equivalent plane streak camera photographs are analyzed by computer to determine the power on the target vs time. Figure 2-38 gives typical data from a recent (December 1976) Argus shot. Output from the north arm was 2.5 TW with very little evidence of beam breakup. Output from the south arm on this same shot was about 1.7 TW, with the pronounced temporal dip characteristic of an overdriven amplifier. The dotted curves in each case were constructed from the measured input pulse width, the measured input energy into the 4-cm rod amplifier, and the (previously) measured low power gain of each amplifier train. It was assumed that the input temporal pulse is Gaussian. The filamentation loss in the south arm is more severe than in the north arm and is the result of more badly pitted disks in

the south C-amplifiers. These pits serve as noise sources for small-scale growth and filament formation. In addition, the south C-amplifiers exhibit a 30% lower gain (due primarily to disk thinness). We have attempted to compensate for the lower gain by raising the voltage on the south C-disk amplifier

flashlamp banks, and by increasing the beam power input into the south C-amplifiers; neither of these strategies has proved satisfactory. The situation will improve with arrival of newly edge-clad disks in early FY 1977.³⁸

Brightness measurements of the laser output beam have been made by combining the power measurements described in the previous paragraph with array camera photographs of the beam in the plane of best focus. The size and energy distribution in the spot at best focus is done in the same way as described in the analysis of the equivalent target plane photographs. A radial average of the intensity distribution is calculated; from this average, peak intensity and beam brightness are extracted. Data from shots for which this analysis has been done are given in Table 2-11. The shot exhibiting the maximum brightness was obtained when the laser was configured with $F = 0.5$; this was *not* the most powerful shot analyzed. Even though the laser output power was later increased significantly (from 1.7 to 2.8 TW), beam brightness actually decreased. It is not presently known whether or not this has an impact on target yields to date.

The array camera with which these data were taken is located in a beam split-off from the main beam at the first turning mirror. The main beam must still pass through a thick $f/1.0$ lens and vacuum window before coming to a focus. Significant beam breakup and focal spot spreading can result from passage through these optics. To simulate this effect in an array camera photograph, a thickness of high quality glass approximately equal to the axial thickness of the focusing lens (about 8 cm) was placed in the beam immediately in front of the first turning mirror. The resulting array camera photographs were similar to previous photographs; however, the filament size recorded in the planes ahead of focus was smaller, while contrast was enhanced. The diameter of the best focal spot was considerably enlarged; brightness was decreased by about a factor of two. From these experiments, we conclude that array cameras give an excellent qualitative picture of the focal spot in the target chamber, but care must be taken lest quantitative results be taken too literally.

0.9 TW

1.9 TW

2.8 TW

Fig. 2-36. Argus beam profile photographs, illustrating progressive near-field distortion at the final SF bandpass spatial frequency, as the output power increases. For all three shots, the hard apodized aperture and relay optics were installed.

Fig. 2-37. Argus equivalent plane photographs and scans. Each corresponds to the near-field photographs of Fig. 2-36. Depth of modulation has increased significantly over that shown in the near field (Fig. 2-36) due to self-focusing.

Fig. 2-38. Comparison of Argus power on target vs time. Shot 36120910, input pulse, FWHM, 28 ps.

Table 2-11. Argus beam brightness

Shot No.	Fill factor	Energy (J)	Pulse duration FWHM (ps)	Peak power (TW)	Beam brightness ($\text{W}/\text{cm}^2\cdot\text{sr}$)
36093004	0.5	65	39	1.7	1.5×10^{18}
36100114 ^a	0.5	56	38	1.5	6×10^{17}
36121004	0.85	90	31	2.8	9×10^{17}

^aSimilar to shot 36093994 but with extra glass in output beam path to simulate the focusing lens.

2-1.7 Schedule and Cost Summary

Construction and Operation

The Argus laser facility was conceived, designed, fabricated, and activated in the extremely short time of 17 mo (January 1975 through May 1976). It

represents a synergistic effort involving hundreds of individuals. Figure 2-39 shows those activities that were central to its completion. The following items connected with this effort are of particular interest:

- Sufficient electrical systems, banks, and controls were installed to accommodate an upgrade to four arms (6.9-MJ storage capacity) if desired at some future date; 3.5 MJ of this capacity is actually used for the present two-arm operation.

Fig. 2-39. Development schedule for Argus.

Fig. 2-40. Costs and manpower loading for Argus.

- The C-amplifier modules were designed and built with the capability of accommodating either solid or liquid disk-edge claddings. This provides flexibility in choice of C-disks for future operations.

- Beam characterization and target shot ac-

tivities have proceeded in parallel for the past 7 mo. Close coordination between these two activities has resulted in a remarkable sequence of near-simultaneous laser performance improvements and record neutron yields per target shot.

Table 2-12. Argus cost breakdown (in thousand dollars)

	FY 1975	FY 1976	FY 1976T	FY 1977	Project
Major procurements	39	1290	27	0	1356
Minor procurements	38	369	40	6	453
Contract labor	0	117	7	1	125
Facility	5	207	23	8	243
Other supplies and expenses	1	184	7	3	195
Subtotal expenses	83	2167	104	18	2372
FTE (man-years)	(2.2)	(20.3)	(1.5)	(0.2)	(24)
FTE manpower costs	95	843	64	11	1013
Subtotal expenses	178	3010	168	29	3385
Capital expenditures	0	192	0	0	192
	178	3202	168	29	3577

Table 2-13. Argus procurement and activation (in thousand dollars)

Electrical systems (Energy storage and control, flashlamps)	1207
All optical components (Disks, lenses, turning mirrors, polarizers, rotators, rods)	565
Facilities (N ₂ , tables, beam tubes, J-boxes, etc.)	120
Mechanical systems (Amplifier heads, spatial filters, miscellaneous mounts)	672
Total hardware	2564
Fabrication and assembly FTE	420
Activation FTE	593
Total Argus fabrication	3577

Cost/Manpower

Argus laser costs and manpower loading followed closely the S-shaped curves characteristic of most projects; these are shown graphically in Fig. 2-40. Two major procurement items were still outstanding at the close of the Argus fabrication project. These are index-matched edge-clad C-disks (\$100,000) and optical aberration compensation units (about \$30,000). Both are expected to contribute significantly to further laser performance improvements during 1977.

Table 2-12 lists the total cost breakdown for the Argus laser fabrication. Not included in the table are portions of the costs associated with major beam diagnostic optics, target chamber, target diagnostics/electronics, target data acquisition system (ADAS), and ancillary facilities (e.g., the neutron time-of-flight facility). These portions were funded from the Argus operating budget once the system was operational.

Table 2-13 shows an alternate way of representing costs. Here we have divided all hardware (parts) costs, major and minor, into four categories; and we have (retroactively) assigned full-time-equivalent (FTE) manpower to the separate tasks of (1) fabrication and assembly and (2) laser system activation. The latter includes such subtasks as component alignment, amplifier and rotator timing, systems integration and debug, diagnostic calibration. As shown, the cost of these latter activities is significant.

In summary, the Argus laser system was built over a 17-mo time span, at a cost of \$3.6 million, through the efforts of more than 100 technical LLL personnel. Argus was realized at about 1.1 TW per million dollars and provides a significant data point in terms of cost estimation for future systems.

References

1. E. S. Bliss, J. T. Hunt, P. A. Renard, G. E. Sommargren, and H. J. Weaver, "Effects of Nonlinear Propagation on Laser Focusing Properties," *IEEE J. Quant. Electron.* QE-12, 402 (1976).
2. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), pp. 75-81.
3. *Business Week* (November 15, 1976), pp. 125, 127.
4. See § 2-5.4 of this report.
5. W. W. Simmons, G. A. Allen, W. S. Neef, and E. P. Wallerstein, "Design, Construction, and Initial Performance of Argus," *OSA/IEEE CLEOS Technical Digest*, p. 58 (1976); W. W. Simmons, *Argus Laser System at Livermore*, Lawrence Livermore Laboratory, Rept. UCRL-78634 (1976).
6. E. S. Bliss, D. R. Speck, J. F. Holzrichter, J. H. Erkkila, and A. J. Glass, "Propagation of a High-Intensity Laser Pulse with Small-Scale Intensity Modulation," *Appl. Phys. Lett.* 25, 448 (1974).
7. W. W. Simmons, F. Rainer, S. Guch, and J. E. Murray, "A High Energy Spatial Filter for Removal of Small Scale Beam Instabilities in High Power Solid State Lasers," *IEEE/OSA CLEA Technical Digest*, p. 30 (1975).
8. V. I. Bespalov and V. I. Talanov, "Filamentary Structure of Light Beams in Nonlinear Liquids," *JETP Lett.* 3, p. 307 (1966).
9. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50017-74 (1975), p. 53.
10. J. A. Glaze, "High Energy Glass Lasers," in *Proc. SPIE 69, Laser Systems*, 45 (1975) and J. B. Trenholme, "Optics in Laser Fusion," in *Proc. SPIE 69, Laser Systems*, 158 (1975).
11. Reference 9, pp. 52-55 and Ref. 3, p. 77.
12. D. R. Speck and W. W. Simmons, "Argus Laser Fusion Facility," *Bull. Am. Phys. Soc. II*, 21, 1173 (1976).
13. Reference 3, pp. 244-245.
14. J. F. Holzrichter and D. R. Speck, "Laser Focusing Limitations from Nonlinear Beam Instabilities," *J. Appl. Phys.* 47, 2459 (1976).
15. Reference 2, pp. 138-140.
16. P. A. Renard and J. T. Hunt, "ARTEMIS: A Diffraction Model for Laser Light Propagation," Lawrence Livermore Laboratory, Rept. UCID-17381 (1977); see also § 2-6.2 of this report.
17. J. T. Hunt, Lawrence Livermore Laboratory Patent Disclosure IL-6200, November 1976.
18. J. T. Hunt, P. A. Renard, and W. W. Simmons, "Improved Performance of Fusion-Lasers Using the Imaging Properties of Multiple Spatial Filters," *Appl. Opt.* 16, 779 (1977).
19. Reference 2, pp. 166-172.
20. G. R. Allen, *Switches and Switching Methods Suitable for Use in the 1-kJ Amplifier Chain*, Lawrence Livermore Laboratory Internal Memo, SSL 73-189, July 1973.
21. J. Fugit and W. Gagnon, Lawrence Livermore Laboratory Patent Disclosure IL-6142, August 17, 1976.
22. S. M. Yarema, Lawrence Livermore Laboratory Internal Memo AD 77-07, February 1977.
23. G. J. Linford, Lawrence Livermore Laboratory Internal Memo SSD 76-119, August 1976.
24. S. Guch, Jr., "Parasitic Suppression in Large Aperture Disk Lasers Employing Liquid Edge Claddings," *Appl. Opt.* 15, 1453 (1976).
25. J. A. Glaze, S. Guch, and J. B. Trenholme, *Appl. Opt.* 13, 2808 (1974).
26. W. D. Fountain, W. F. Hagen, and G. J. Linford, "Design of Disk Laser Amplifiers for Laser Fusion Applications," *OSA/IEEE CLEOS Technical Digest*, p. 60 (1976).
27. Reference 2, p. 178.
28. Reference 2, pp. 78-79.
29. See § 2-6.3 of this report.
30. See § 2-3.10 of this report.
31. Reference 2, p. 72.
32. R. Baltzer and W. D. Fountain, Lawrence Livermore Laboratory Internal Document SSD 76-11.
33. D. R. MacQuigg and D. R. Speck, "Beam Diagnostics on Argus," *Bull. Am. Phys. Soc. II*, 21, 1174 (1976) (abstract only), and Lawrence Livermore Laboratory, Rept. UCRL-78447 (1976), submitted to *J. Opt. Soc. Am.*

34. See § 2-5.2 of this report.
35. J. F. Holzrichter, D. R. Speck and J. E. Swain, *Plasma Development in Low-Z Laser-Fusion Targets*, Lawrence Livermore Laboratory, Rept. UCRL-75979 (1974).
36. Reference 2, pp. 371-374.
37. Reference 2, pp. 249-251.
38. G. J. Linford, S. C. Roberts and S. M. Yarema, "Evaluation of New Index Matched Edge Coatings," Lawrence Livermore Laboratory Internal Memo AD 76-10, December 1976.

Authors

W. W. Simmons
W. F. Hagen
J. T. Hunt
W. L. Gagnon
G. J. Linford
C. B. McFann, Jr.
D. R. Speck

2-2 SHIVA

2-2.1 Overview

Shiva is the fourth solid-state laser system in a series of increasingly more powerful LLL lasers designed to accomplish major laser-fusion goals. The planning for Shiva began in 1972 when it was recognized that a 10-kJ, high-power laser irradiation source was required for advanced laser-fusion experiments. The primary scientific objectives of Shiva are to achieve a significant thermonuclear burn, defined as a thermonuclear yield greater than 1% of the laser light input, and to demonstrate fuel compression to 1000 $\times$ liquid density. Recent experiments on Argus have shown that Shiva will provide the promised laser performance of 10 kJ in a subnanosecond pulse. In this section the progress made in 1976 in building the Shiva laser facility is discussed.

The past year was a period of accelerating activity on the Shiva laser. The successful performance of the Argus laser system verified the staging model used for Shiva. Detailed designs were completed on the major components, and procurement was initiated for all long-lead-time items and the bulk of the high-dollar-value items. The building to house Shiva, Building 391, was ready for occupancy on July 26, 1976, and the Shiva project moved into the hardware fabrication and installation phase.

Technical Status

Early in 1976 it was decided to adopt a target illumination system composed of two clusters of 10 beams, instead of the previously planned icosahedral geometry. In the new geometry, shown on the Shiva system model in Fig. 2-41, two oppos-

ing bundles of 10 beams each are focused onto the target with f/6 singlet lenses. Individual beams within a cluster are arranged on the corners of two concentric pentagons with their polarization vector directed radially outward. This geometry will allow continuity between early Shiva target experiments and ongoing two-sided irradiation experiments with Janus and Argus.

Only relatively minor changes have been made in the laser staging described in the 1975 Annual Report (UCRL-50021-75). Since the new target geometry uses f/6 lenses, which are much thinner than the previously planned f/1.6 lenses, the resultant decrease in nonlinear ripply growth allowed a reduction in the output beam diameter from 30 cm to 20 cm. This change permitted a collimated beam to propagate through the δ amplifier stage, and it also allowed the addition of a window on the target chamber and the removal of the atmospheric pressure load on the focus-lens translation mechanism. Other changes include the conversion of the reflecting polarizers in the δ amplifier stage to 1-cm-thick transmitting polarizers, the reduction of the δ rotator thickness from 1.4 cm to 1.0 cm, the addition of an isolation stage and beam-expanding telescope to go with each of the four β rod amplifiers in the beam splitter array, and the conversion of the beam-expanding telescope between the α rod amplifier and the β rod amplifier to a beam-relay spatial filter.

The mechanical subsystems have progressed markedly during 1976. One of the most spectacular accomplishments was the fabrication and installation of the 600,000-lb space frame for the laser bay and target chamber. This was completed ahead of schedule, exceeded the specified tolerance, and demonstrated the predicted stability. The design of

the target chamber has been completed and the focus-lens translation mechanism has been prototyped. The design and award of contracts for the β disk amplifiers, the γ disk amplifiers, the δ disk amplifiers, the α rod amplifiers, the β rod amplifiers, the five different sizes of spatial filters, and the optical cradles are completed. Many of these components have been delivered and are now being assembled and installed. Hundreds of other mechanical parts have either been designed or are nearing design completion.

A significant effort has been directed toward better and more efficient methods of cleaning and assembling the laser disk amplifiers. Shiva has 100 disk amplifiers which must be as clean as possible to provide better system reliability and less maintenance. Faster cleaning and assembly techniques have reduced the time to build the amplifiers in-

itially and will provide more rapid recleaning of used amplifiers. Sophisticated cleaning techniques have also been extended to the laser chain's nitrogen purge and cooling system. To minimize "dirt," the piping and valves used to distribute the nitrogen are carefully selected, precleaned, and cleaned again following installation.

The largest total dollar procurements in 1976 were for optical components. Contracts were awarded for the neodymium-doped disks and rods, the rotator glass, the Pockels cells, the spatial filter lenses, the focus lenses, the small polarizers, and the beam splitters. Contracts for coating and finishing of large polarizers and turning mirrors are being awarded in 1977. In general the optical elements are being procured as finished components with a single vendor responsible for the optical blanks, finishing, and coating. However, for the large lenses,

Fig. 2-41. Model of Shiva laser, complete with all amplifiers, space frames, target chamber, and capacitor bank. Scale is indicated by man in foreground. Twenty laser chains are mounted on four vertical walls of the laser spaceframe, and forty turning mirrors are located on the target spaceframe. The system is about 200 ft long.

Fig. 2-42. Plan schematic of the Shiva laser system. The central portion of the figure shows pulse generation and preamplifier stages along with the oscillator alignment and pulse synchronization systems. The splitters and automated pointing gimbals to the left of the figure divide the beam into 20 amplifier channels. The output beam, from each channel is directed to the target with an automated system of image sensors, pointing gimbals, and focusing lenses.

polarizers, and turning mirrors, separate contracts have been awarded for the raw glass, the finishing, and the coating. This arrangement affords better control and reduces the cost associated with the risk of breakage on these difficult, expensive optical elements.

As reported last year, the Shiva laser system will have a distributed minicomputer control system. The four functional computer subsystems are for power conditioning, beam diagnostics, alignment, and target diagnostics. Each of these subsystems can operate independently and interact with the other subsystems through a central computer. A vendor has been selected to provide the computer hardware. The computer control system for power conditioning has been successfully prototyped and tested in the severe environment of electromagnetic interference typical of large pulsed power supplies. The control system, power supplies, and capacitor banks are now in various stages of fabrication and installation. All the capacitor racks have been installed. Capacitor modules are being assembled, tested, and installed in the racks. The remaining 5 MJ of high density capacitors, required for Shiva, have been ordered.

A series of electro-optical systems has been designed to facilitate the alignment of the Shiva laser and the fusion target. Separate systems control (1) oscillator alignment, (2) spatial filter alignment, (3) chain input pointing, and (4) target pointing, focusing, and centering. The two latter systems (3 and 4) were developed by Aerojet's Electro Systems Division under contract to LLL. All these systems have been successfully prototyped on the Cyclops laser and are now being manufactured. They will be integrated into the Shiva digital-control system.

Project Management

The Shiva Project has been organized as an independent team in the Solid State Program, with a project manager, subgroups, and separate reporting and management systems. This management organization has evolved over the life of the Shiva project and is continually improving in effectiveness.

In 1976 it became clear that the actual manufacturing of the Shiva system would severely tax the capabilities of the Laboratory. As a result several new arrangements were developed with Laboratory management. These include a procurement tracking

system to handle nearly \$10 million worth of procurements in 1977. A detailed report, which is updated weekly, provides projected costs, actual costs, delivery schedules, procurement schedules, etc. for program management.

An expedited receiving and inspection system was also established to ensure the timely and proper handling of vendor-supplied items when they are delivered. In addition a separate source was set up for supplying Shiva parts that are the same as those regularly stocked in the LLL stores. Since Shiva requires such parts in much greater numbers than are normally stocked by the LLL stores, separate supplies of these parts are procured for use in Shiva, so that their prompt delivery is assured and so that Shiva requirements will not disrupt the normal usage rates and restocking practices.

Schedule

In summer 1977 the first beam of Shiva will be tested. In fall 1977 the entire Shiva system is expected to begin operation, and the first target experiments are expected in winter 1977-1978. The Shiva system will provide >20 TW to conduct the significant thermonuclear burn experiments and >10 kJ to conduct the 1000× compression experiments.

Authors

R. O. Godwin

J. A. Glaze

2-2.2 Performance Highlights

Several important modifications were incorporated in Shiva during 1976. Figure 2-42 shows an updated plan schematic of Shiva. The central portion shows the master oscillator and preamplifier sections along with a cw oscillator for alignment and a cw mode-locked oscillator for equalizing the optical path lengths to the target for the 20 chains. The β rod amplifier stages preceding the beamsplitter array have been modified to include Faraday rotators for prelude isolation and beam-expansion telescopes for improved uniformity of illumination over the apodizing aperture. Other changes include modifications of the spatial filter between the β rod

Table 2-14. Components and parameters for Shiva amplifier chain. Clear aperture refers to that portion of the optical element that meets optical finishing specifications. Beam diam refers to the 10^{-3} intensity points. Small-signal-gain values include insertion losses

Element	Clear aperture (mm)	Nominal beam diam (mm)	Thickness or length (mm)	T_p^a	T_s^b	Small-signal gain/loss ^c	Nominal output power at 0.1 ns (GW)	Beam breakup contribution at 0.1 ns	Nominal output power at 1 ns (GW)	Beam breakup contribution at 1 ns
Debris shield	190	190	3	0.99	0.99	0.99	1537		746	
Vacuum window	210	185	15	0.99	0.99	0.99				
Target focusing lens (EFL = 1.2 m)	210	202	15	0.99	0.99	0.99		0.57		0.25
2nd turning mirror	?	202		d	d					
1st turning mirror	270	202		d	d	0.98				
3 β disks	208	202	32	0.96	0.3	0.98	1820	1.02	811.2	0.48
Polarizer	218	202	10	0.97	10^{-2}	0.97	984	0.07	472.3	0.04
Faraday rotator	210	202	10	0.98	0.98	0.98	994	0.14	487	0.07
Polarizer	218	202	10	0.97	10^{-2}	0.97	1014	0.08	496	0.04
Spatial filter lens (EFL = 2.22 m)	212	202	17	0.99	0.99	0.99	1045	0.17	512	
Pin hole	0.3/0.5									0.08
Spatial filter lens (EFL = 1.59 m)	156	145	12	0.99	0.99	0.99	1074	0.24	517.5	0.11
4 γ disks	150	145	30	0.95	0.2	2.6	1085	1.35	523	0.72
Spatial filter lens (EFL = 1.59 m)	156	145	12	0.99	0.99	0.99	431	0.10	244	0.06
Pinholes	0.3/0.5									
Spatial filter lens (EFL = 1.0 m)	106	91	8	0.99	0.99	0.99	531	0.25	248.5	0.1
6 β disks	94	91	24	0.95	0.1	3.8	536	2.2	249	1.02
Spatial filter lens (EFL = 1.0 m)	106	91	8	0.99	0.99	0.99	152	0.07	89.9	0.04
Pinhole	0.3/0.5									
Spatial filter lens (EFL = 1.0 m)	106	91	8	0.99	0.99	0.99	155	0.08	90.8	0.04
2 transmission polarizers	100	91	10	0.96	10^{-4}	0.96	156	0.15	91.7	0.08
Faraday rotators	95	91	14.5	0.98	0.98	0.98	162	0.22	95.5	0.11
2 transmission polarizers	100	91	10	0.96	10^{-4}	0.96	166	0.16	97.5	0.09
12 β disks	94	91	24 ^d	0.9	0.01	14.4	173	0.91	102	0.4
Spatial filter lens (EFL = 1.0 m)	106	91	8	0.99	0.99	0.99	124	0.01	8.4	
Pinhole	0.3									0.00
Spatial filter lens (EFL = 0.48 m)	44	44	5	0.99	0.99	0.99	12.5	0.02	8.5	
2 transmission polarizers	50	44	10	0.96	10^{-4}	0.96	12.6	0.03	8.6	0.01
Pockels cell	48	44	65	0.94	0.94	0.94	13	0.25	9	0.16
2 transmission polarizers	50	44	5	0.96	10^{-4}	0.96	14	0.03	9.5	0.02
β rod	48	44	400	0.9	0.9	11.5	14.6	0.64	10	0.44
Relay lens (EFL = 2.3 m)	55	44	5	0.99	0.99	0.99	1.3	0.00	1.0	0.00
Pinhole	1.5									
Relay lens (EFL = 3.1 m)	28	21	5	0.99	0.99	0.99	1.3	0.01	1.0	0.01
2 transmission polarizers	30	21	6	0.96	10^{-4}	0.96	1.3	0.01	1.0	0.01
Pockels cell	25	21	50	0.98	0.98	0.98	1.4	0.09	1.0	0.07
2 transmission polarizers	30	21	6	0.96	10^{-4}	0.96	1.4	0.01	1.1	0.01
γ rod	23	21	400	0.9	0.88	100	1.5	0.17	1.1	0.13
Apodizing aperture	35	21	9.5	0.1	0.1	0.1	0.015		0.01	
							Total	9.1	Total	4.7

^a T_p = transmission for parallel polarization

^b T_s = Transmission for perpendicular polarization.

^cSmall-signal gain: net gain (includes loss).

^dReflectivity of the 1st turning mirror is 0.98. Reflectivity of the 2nd turning mirror is $0.95 < 0.98$. Pinhole sizes a/b: short pulse (a), long pulse (b).

Initial FWH factor = 0.5

and β disk stages, substitution of transmitting polarizers for reflecting polarizers in the δ isolation stage, and addition of rotatable half-wave plates between the α and β rod amplifiers in each chain for polarizers selection. The spatial filter modification resulted from recent experimental and theoretical results on image relays (discussed below). The reflecting polarizers were eliminated because of cost and potential beam-alignment difficulties.

Figure 2-42 also shows the major alignment systems. The prototype of the oscillator alignment system (OAS) has been completed at LLL and is now being adapted for Shiva. Pointing and centering accuracies are $\pm 2 \mu\text{rad}$ and $\pm 500 \mu\text{m}$, respectively, at the input to the apodizing aperture. The chain input pointing system (CHIP) consists of an Aerotech angle gimbal positioned in front of the apodizing aperture and an Aerojet position sensor following this aperture. The controls were designed and built at LLL. A full prototype of the system has achieved a pointing accuracy of $\pm 15 \mu\text{rad}$. Pointing and focusing of the beams on target and centering

of the beams on the final focusing lenses are done with two angle gimbals, an imaging sensor, and a three-axis drive on the focusing lens. The sensor and final pointing gimbals were developed under contract to LLL by Aerojet. The mount for the first turning mirror and the lens system drive have been designed and built at LLL. A prototype of the entire alignment system has been evaluated on the Cyclops laser. Pointing, focusing, and centering has been demonstrated to accuracies of $\pm 1 \mu\text{rad}$, $\pm 25 \mu\text{m}$, and $\pm 0.2 \text{ mm}$, respectively. This performance meets or exceeds all projected Shiva requirements.

Table 2-14 lists pertinent parameters for optical components in a Shiva amplifier chain. Small-signal gains and losses for all of the Shiva amplifiers have been determined experimentally. Losses assigned to other components have, in many cases, been measured, but a few have been calculated based upon specifications submitted to optical fabrication vendors. Nominal performance figures result from calculations discussed below. Figure 2-43 shows an optical profile of the chain as well as input

Fig. 2-43. Optical profile of a single Shiva laser chain. Representative values of laser power are given for 0.1- and 1-ns pulses at each stage. Also shown is the clear aperture of each amplifier and the electrical energy supplied to the flashlamps. All spatial filters are f/10 with the exception of the f/30 relay/filter located between the α and β rod amplifiers. Pinhole diameters for these filters range from 300 to 500 μm .

Table 2-15. Components and parameters for the master beam line portion of the pulse generation and preamplifier stage for Shiva

Element	Clear aperture (mm)	Nominal beam diam (mm)	T_p (%)	T_s (%)	Small-signal gain	Nominal output power (MW)
Pulse oscillator S/O		4.6		100	1.0	1
Mirror	31.4	4.6			0.90	
Lens	21	4.8	99.5	99.5	0.995	
Mirror	31.4	4.8			0.98	
Master beam expander	14.3	4.8/9.5	98	98	0.98	
Mirrors (4)	31.4	9.5	95		0.95	
R/ α polarizer	30	9.5	97	0.12	0.998	
$\lambda/2$ plate	33	9.5	99.5	99.5	0.99	
Spatial filter						
a) Input lens	1.4	9.5	99.5	99.5	0.995	
b) Pinhole	0.03				0.95	
c) Output lens	31	21	99.5	99.5	0.995	
α rod amplifier	23	21	97	97	100	
R/ α polarizers (2)	30	21	94	0.015	0.94	
Pockels cell	25	21	96	96	0.94	
R/ α polarizers (2)	30	21	94	0.015	0.94	
α rod amplifier	23	21	97	97	100	100
R/ α polarizers (2)	30	21	94	0.015	0.94	
Pockels cell	25	21	96	96	0.96	
R/ α polarizers (2)	30	21	94	0.015	0.94	
Dye cell						30
Mirrors (3)	31.4	21			0.97	
R/ α polarizer	30	21	97	0.12	0.998	
$\lambda/2$ plate	33	21	99.5	99.5	0.995	
OAS splitter	55	21	99	91	0.91	
90° rotator	34	21	99.5	99.5	0.995	
α rod/ β rod Galilean telescope	26/55	21/44	99	99	0.99	
β rod amplifier	46	44	97	97	20	300
Spatial filter						
a) Input lens	55	44	99.5	99.5	0.995	
b) Pinhole	0.100				0.95	
c) Output lens	55	44	99.5	99.5	0.995	
6-in. folding mirror	102	44	90		0.90

Fig. 2-44. Pulse generator and preamplifier staging. The pulse from a mode-locked YAG oscillator is first injected into a pulse shaper and then into preamplifier stages. The cw laser, shown is used with the automated alignment system. A second mode-locked YAG oscillator is used with the pulse synchronization system. The three oscillators are collinearly aligned with automated pointing gimbals and the alignment sensor.

flashlamp energy and output laser power at each stage.

The pulse generator and preamplifier staging is shown in Figure 2-44. A pulse from a mode-locked YAG oscillator is first injected into a pulse shaper and then into preamplifier stages. The preamplifier stage consists of two α rod amplifiers, a β rod amplifier, a spatial filter and concomitant beam expansion telescopes, Pockels cell isolation stages, and turning mirrors. A dye cell between the α and β rod amplifiers provides 20 dB of attenuation for both amplified spontaneous emission from the laser rods and prepulses from the oscillator. (See § 2-5.4 for a thorough discussion of the pulse shaper.)

The beam of the cw laser shown in Fig. 2-44 is positioned on pointing and centering detectors located in the alignment sensor by means of automatic pointing gimbals. Pointing and centering of the mode-locked pulses from the master oscillator and the pulse synchronization system are also performed with the alignment sensor. A portion of the pulse from the master oscillator is injected into a separate amplifier chain, which will be dedicated to plasma diagnostics. Table 2-15 lists pertinent optical parameters for the pulse generator

and preamplifier assembly. (A detailed discussion of the master oscillator and pulse synchronization system is given in § 2-2.4).

Realistic performance models of the Shiva laser chain have evolved as a result of extensive experimentation with the Cyclops and Argus systems. The Argus system in particular has provided a wealth of data on beam propagation, spatial filter transmission, and power performance for pulses ranging from 30 ps to 1 ns. To obtain the calculations below, we used both linear and nonlinear models of beam propagation, spatial filter transmission and gain saturation. Specifically, we used the Frantz and Nodvik single-parameter saturation equation to model gain.³⁹ The saturation parameter has been chosen to be $h\nu/2\sigma = 3.24 \text{ J/cm}^2$, which gives a reasonable fit to experimental data. Spatial filter transmission was modeled with a function dependent upon the incremental phase retardation, B , accumulated between spatial filters and having two adjustable parameters. The parameters were determined by fitting the function to experimental data taken with the Argus laser. Beam propagation was modeled using the ARTEMIS code discussed in § 2-6.2

The pertinent performance equations are listed below:

$$W(L) = s \ln [1 + e^{\alpha_0 L} (e^{W_i/s} - 1)] ,$$

$$G = W(L)/W_i ,$$

$$B = \frac{2\pi\gamma}{\lambda\tau} \int_L W(\ell) d\ell ,$$

$$T = \exp (-B/2.5)^8 ,$$

where W_i and $W(L)$ are input and output fluxes in the amplifier, s the saturation parameter, $e^{\alpha_0 L}$ the small-signal gain, τ the pulse width, G the saturated

gain, and B the incremental nonlinear phase retardation.

In application, the spatial profile of the beam is reduced to a number of radial zones and the above equations calculated for each zone. The temporal profile is assumed to be a Gaussian, which does not change appreciably due to saturation. The output power is then obtained by summing up the energy contained in each zone and dividing by the Gaussian pulse width. The validity of fixing the pulse width throughout the calculations has been substantiated with the ARTEMIS code for pulses as long as 1 ns. See § 2-1.4, 2-6.3, and 2-3.10 for a thorough discussion of chain analysis methodology.

Figure 2-45 shows calculated performance curves for Shiva chains with and without the δ amplifier booster stage. As observed, the output power is approximately constant for pulses shorter than 200 ps.

Fig. 2-45. Calculated focusable output power and energy from the Shiva amplifier chain for pulses up to 1 ns. The upper and lower curves correspond to chains with and without the 20-cm diam δ amplifier booster stage. For short pulses, performance is limited by small scale self-focusing. For longer pulses, gain saturation and coating damage limit performance. These calculations were performed with an initial fill factor of 50% of the clear aperture of the optical train.

Fig. 2-46. Energy density on the input lenses of the β - γ and γ - δ spatial filter vs pulse duration. The performance of a Shiva chain is constrained so that the energy density on these two elements does not exceed 50% of their coating-damage threshold. Other elements are well below this 50% limit.

In this range, gain saturation is relatively unimportant, and the power is limited primarily by small scale self-focusing. For longer pulses, the effects of saturation are clearly evident. Here, the obtainable output power is limited by the damage threshold for optical coatings. In performing the calculations shown in Fig. 2-45, the input power to the apodizing aperture for each pulse duration was constrained so that the peak flux at any chain location did not exceed 50% of the coating damage threshold. This limit, while somewhat arbitrary, has been imposed to ensure safe operation even in the presence of moderate beam degradation caused by self-focusing and diffraction.

Figure 2-46 shows the fluence on the two most vulnerable chain components, the input lenses to the β - γ and γ - δ spatial filters, as a function of pulse duration. In general the peak fluence loading shifts backward toward the rod amplifiers as the pulse duration increases. This of course is also true of the incremental nonlinear wavefront retardation. Coating damage thresholds shown in the figure result from measurements taken at LLL⁴⁰ and from the apparent dependence of damage threshold with the square root of the pulse duration.⁴¹ Although

this scaling certainly hasn't been fully tested for large aperture production coatings, experience with the Argus system indicates that these thresholds are not very sensitive to aperture size.

Figure 2-47 shows the focusable output power for chains with γ and δ output stages as a function of the power at the output of the apodizing aperture, that is, at the input of the amplifier chain. The dashed extension of these curves show the power attainable if the factor-of-two safety margin for flux loading of coated optics is relaxed. These curves show that peak power performance is achieved for the shorter pulses. Here, as mentioned earlier, the performance is limited by energy loss at spatial filters arising from small scale self-focusing and not by coating damage. Also, long pulse performance could be increased by about 30% if damage thresholds were not limiting. Further increase in power is limited by self-focusing.

Perhaps the greatest leverage for increasing the performance of laser chains such as Argus and Shiva is the adaption of an optical design that allows the beam to fill the largest possible fraction of the clear apertures. Recently, theoretical considerations followed by experimental confirmation

Fig. 2-47. Focusable output power as a function of pulse width for chains with (a) γ and (b) δ output stages as a function of chain input power. The dashed extension of the curves indicate performance that could be achieved if the constraint on the flux loading of β - γ and γ - δ spatial filter lenses was relaxed. With this constraint, however, it is noted that peak B-limited performance is only achieved for shorter pulses.

using Argus have shown that significant improvement in fill factor can be realized with the use of imaging relays.⁴² Briefly, the idea is to project the image of the apodizing aperture through the laser chain by relaying this image from stage to stage, from the apodizer to the final focusing lens aperture. This of course will retard the growth of spatial modulation caused by near-field diffraction. To this end, an $f/30$ relay has been placed between the α and β rod amplifiers in each chain. Since the existing spatial filters are also relay elements, projection through the chain is nearly complete with this one addition. Computations using the ARTEMIS propagation code show that acceptable beam quality for the Shiva and Argus chains can be maintained with beams as large as 85% of the clear aper-

ture. (Previous fill factors for these chains were typically 40%.)

Figure 2-48 shows ARTEMIS calculations of the Shiva beam profile with and without the relay. The calculations begin with a profile, whose fill factor is 0.83, that has been obtained by illuminating a hard aperture with a Gaussian beam. The evolution of this profile is then traced through the amplifier chain and to the final focusing lens, some 20 m from the output of the last amplifier stage. Comparison of the profiles at the input to the β amplifier dramatically demonstrates the benefits derived from the image relay. Although the difference in peak intensity for the two profiles at this point is only 15%, the beam without imaging shows marked spatial modulation resulting from diffraction. This beam,

Intensity profile without relay

Intensity profile with relay

Apodizing aperture

Input to β rod amplifier

Output of δ disk amplifier

Input to final focusing lens

Fig. 2-48. Near-field beam profiles for a Shiva chain as calculated with the ARTEMIS code. Profiles are compared for chains with and without an imaging relay between the α and β rod amplifiers. Without the relay the peak to average intensity ratio increases due to diffraction and self-focusing.

when propagated through following stages of amplification, deteriorates further because of self-focusing. When it encounters a spatial filter, modulation exacerbated by self-focusing and having frequencies greater than the filter bandpass is stripped off. This stripping results in net power loss. At the output of the chain, following the δ amplifier, the beam without the relay has intensity peaks 35% larger than with the relay. This beam further degrades on its way to the target, and at the final focusing lens has developed intensity variations that are almost twice that of the image-relayed beam. It is clear from Fig. 2-48 that without the relay, beams having a large fill factor could not be used without endangering optical coatings nor without reduced focusable power due to added modulation. To prevent these effects and to improve performance, we have implemented imaging relays on Shiva.

The successes of the Argus system and the good agreement obtained between Argus experiments and theory strongly suggest that Shiva will perform as described above. These predictions will be experimentally tested when Shiva becomes operational in early FY 1978.

References

39. L. M. Frantz and J. S. Nodvik, *J. Appl. Phys.* **34**, 2346 (1963).
40. D. Milam, "Laser-Induced Damage at 1064 nm, 125 psec," accepted for publication in *J. Appl. Optics*, **16** (1977).
41. D. Milam, Lawrence Livermore Laboratory, private communication (March 1, 1977).
42. J. T. Hunt, P. A. Renard, and W. W. Simmons, "Improved Performance of Fusion Lasers Using the Imaging Properties of Multiple Spatial Filters", accepted for publication in *J. Appl. Optics*, April 1977.

Authors

J. A. Glaze
W. F. Hagen

2-2.3 Shiva Laser Components

The Shiva laser components have been designed and prototypes have been tested at LLL to meet the stringent requirements of the 20-arm Shiva laser system. There are five major classes of electro-optical components employed on each arm.

- Laser amplifiers (α and β rod and β , γ , and δ disk) which, when aligned in optical series, are designed to increase the optical power in each chain by a factor of approximately 10^5 .

- Specially designed evacuated spatial filters for smoothing the intensity fluctuations that arise along each laser beam.

- Electro-optical isolators consisting of Faraday rotators mounted in conjunction with dielectric polarizers to protect each amplifier chain from retroreflected laser light.

- Gimballed turning mirrors to direct the individual laser beams through each chain to the target chamber.

- "Fast" electro-optical shutters employing dielectric polarizers and Pockels cells to protect the DT targets from amplified fluorescence.

Rod Amplifiers

The design rationale for the Shiva rod amplifiers embodies eight criteria:

- Minimize the optical path of laser glass in the amplifiers.
- Minimize the number of coated and figured optical surfaces.
- Maximize gain coefficients while achieving $\pm 5\%$ spatial uniformity.
- Minimize contamination of amplifiers.
- Design for moderate ($\sim 1 \text{ J/cm}^2$) optical fluxes.
- Achieve long amplifier life (> 1000 shots).
- Meet Shiva electrical safety requirements.
- Meet birefringence and optical phase-distortion requirements.

To satisfy these difficult design goals, we have completely reconfigured the earlier rod amplifier designs using two-dimensional ray-tracing computer programs together with extensive experimental measurements made on prototype amplifiers. The new design features of the Shiva rod amplifiers include physically larger pumping cavities to satisfy gain homogeneity and electrical insulation requirements as well as double-doped immersion fluids for refractive index-matching and fluorescence absorption. In addition, the electrode assemblies of the standard flashlamps are encapsulated for increased reliability. The cretulated flashlamp-reflector assemblies are insulated and grounded separately. More stringent optical isolation has been designed around the rod amplifiers to prevent spurious

Fig. 2-49. Shiva α and β rod amplifier prototypes. The α rod amplifier (right) has a small-signal gain of 200 and a 2.5-cm aperture. The β rod amplifier (left) has a small-signal gain of 20 and a 5.0-cm aperture.

regeneration, and we have adopted tighter specifications on laser-rod optical properties.

In general, the prototype α and β Shiva rod amplifiers (Fig. 2-49) have successfully met these design criteria. Both amplifiers display adequate small signal optical gain ($G_\alpha = 180$, $G_\beta = 18$), gain uniformity ($\pm 10\%$ or better), longevity, reflector insulation, and optical quality.

Suppression of Parasitic Modes Within Laser Rod Amplifiers. The suppression of parasitic modes inside laser rod amplifiers is complicated by the facts that the optically finished rod ends must be unobstructed to permit the passage of the amplified laser beam and that the cylindrical pumping surface of the rod must admit broad-band optical pumping radiation from the flashlamps. As a consequence, the suppression of parasitic modes must be accomplished in the vicinity of the rod pumping surface with fluorescence-absorbing ions (at 1.06 and 1.33 μm) that have little or no absorption in the 0.4- to 0.8- μm Nd⁺⁺⁺ pumping bands of the $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{11/2}$ transition.⁴³⁻⁴⁵

There are two major types of parasitic modes that represent potential depumping mechanisms for the Shiva rod-amplifier geometries: (1) azimuthal "whisper" modes that totally internally reflect (TIR) from the shield glass/nitrogen gas interfaces and (2) axial-radial "bulk" modes that totally reflect from the shield glass/nitrogen gas interfaces. In practice, vector combinations of both "whisper" and "bulk" modes are possible, and could give rise to "helical" parasitic modes.

The use of an index-matched fluid jacket with a diameter n times that of the laser rod excludes the

TIR "whisper" modes from the rod volume.⁴⁴ With an intrinsic absorber of sufficient optical attenuation in the double-doped immersion fluid, it is possible to push the "bulk" parasitic modes below oscillation threshold. This criterion is met in a uniformly pumped rod laser amplifier if the inequality

$$\xi > \frac{\alpha}{n - 1} \quad (9)$$

is satisfied (where α is the average amplifier gain coefficient and ξ is the intrinsic attenuation coefficient). This condition is easily met with a saturated mixture of 95% ZnCl_2 and 5% SmCl_3 solutions.

A saturated aqueous solution of ZnCl_2 requires the addition of a small quantity of HCl ($\sim 1\%$) to prevent the formation of insoluble $\text{Zn}(\text{OH})_2$ in the presence of ultraviolet light from the flashlamps. This solution has a refractive index of approximately 1.53, which is close enough to the refractive index of silicate glass (1.556) to serve as an index-matching solution.

Shiva Rod Amplifier Reflector Geometries. The α and β rod amplifiers use reflector designs that have been optimized to achieve homogeneous optical gain profiles with moderate efficiencies while meeting the insulated reflector requirements. Because the rod assemblies are grounded to the spaceframe through the external immersion fluid pumps and conducting fluids, it was necessary to increase the lamp-circle radii over those used in earlier designs. The six-lobed, silver plated, crenulated flashlamp reflectors form sectors of ellipses with their axes lying along the axes of the flashlamps and along the common axis of the laser rod (see Figs. 2-50 through 2-53). Table 2-16 summarizes the geometrical properties of the Shiva rod-amplifier pumping cavities.

Laser Rod Design Rationale. To minimize system alignment problems near the front end of each Shiva laser chain, the ends of both the α and β rods are ground and polished so that they are mutually parallel to within 12 arc-seconds and each perpendicular to the rod axis. Consequently, the Shiva rod amplifiers rely on durable "V" antireflection coating to prevent spurious optical feedback from the rod ends.

The product of neodymium-doping (wt%) and rod diameter for both the α and β rods was selected to be 3%-cm so that the optical densities of the two

Fig. 2-50. Cross section of Shiva α rod amplifier.

Fig. 2-51. Small-signal gain vs input energy for Shiva α rod amplifier.

Fig. 2-52. Gain profile of Shiva α rod amplifier at an input energy of 17.5 kJ.

α ROD AMPLIFIER SPECIFICATIONS

Design Details

Clear aperture: 2.3 cm
Small signal gain: 200 @ 20 kJ
Gain homogeneity: $\pm 10\%$ over 80% of
clear aperture
Optical phase distortion: 0.1 μm
Passive insertion loss: 3%
Rod dimensions: 2.5 by 40 cm
Rod doping: $1.2 \pm 0.1\%$ Nd
AR coating: V, 0.15% reflectivity
Shield glass: fused silica
Shield glass diameter: 4.0 cm

Lamps: 6
Lamp dimensions: 1.3-cm bore
37-cm arc length
Lamp circle radius: 5 cm
Reflector lobes: 11-cm major axis
9.798-cm minor axis
Reflector eccentricity: 0.4545
Immersion fluid: 90% ZnCl_2 + 10% SmCl_3
Fluid refractive index: 1.51
Path length: 40 cm
 B/P_{in} : 7.7×10^{-9} Np/W

Capacitor Bank Requirements

Circuits: 1
Capacitors/circuit: 6
Lamps/circuit: 6
Capacitance/circuit: 90 μF
Inductance/circuit: 450 μH
Resistance/circuit: 0.3 Ω

$3\sqrt{LC}$: 600 μs
Reflector ground: separate
Lamp electrodes: encapsulated
Maximum operating energy: 21 kJ @ 22 kV
Mean number of lamp firings
between failures: 4×10^4

Laser Glass Properties

Type: ED-2 silicate
Manufacturer: Owens/Illinois
Stimulated emission cross
section: 2.7×10^{-20} cm^2
Birefringence: 0.5 nm/cm

Fluorescent correction factor: 1.07
Absorption coefficient: 0.003 cm^{-1}
Index of refraction: 1.556 @ 1.061 μm
Nonlinear index of refraction:
 4.3×10^{-16} cm^2/W (1.4×10^{-13} esu)

Fig. 2-63. Cross section of Shiva β rod amplifier.

Fig. 2-64. Small-signal gain vs input energy for Shiva β rod amplifier.

Fig. 2-65. Gain profile of the Shiva β rod amplifier at an input energy of 27 kJ.

β ROD AMPLIFIER SPECIFICATIONS

Design Details

Clear aperture: 4.6 cm
Small signal gain: 18 @ 40 kJ
Gain homogeneity: $\pm 10\%$ over 80% of
clear aperture
Optical phase distortion: 0.1 μm
Passive insertion loss: 3%
Rod dimensions: 5 by 40 cm
Rod doping: $0.6 \pm 0.1\%$ Nd
AR coating: V, 0.15% reflectivity
Shield glass: fused silica
Shield glass diameter: 7.8 cm

Capacitor Bank Requirements

Circuits: 1
Capacitors/circuit: 10
Lamps/circuit: 6
Capacitance/circuit: 145 μF
Inductance/circuit: 450 μH
Resistance/circuit: 0.3 Ω

Laser Glass Properties

Type: ED-2 silicate
Manufacturer: Owens/Illinois
Stimulated emission cross
section: $2.7 \times 10^{-20} \text{ cm}^2$
Birefringence: 1.0 nm/cm

Lamps: 6
Lamp dimensions: 1.5-cm bore
37-cm arc length
Lamp circle radius: 10 cm
Reflector lobes: 17.5-cm major axis
14.4-cm minor axis
Reflector eccentricity: 0.57
Immersion fluid: 90% ZnCl_2 + 10% SmCl_3
Fluid refractive index: 1.51
Path length: 40 cm
 B/P_{in} : $0.8 \times 10^{-12} \text{ Np/W}$

$3\sqrt{\text{VLC}}$: 750 μs
Reflector ground: separate
Lamp electrodes: encapsulated
Maximum operating energy: 40 kJ @ 22 kV
Mean number of lamp firings
between failures: 9.1×10^4

Fluorescent correction factor: 1.07
Absorption coefficient: 0.003 cm^{-1}
Index of refraction: 1.556 @ 1.061 μm
Nonlinear index of refraction:
 $4.3 \times 10^{-16} \text{ cm}^2/\text{W}$ ($1.4 \times 10^{-13} \text{ esu}$)

Shiva rods would be similar. Table 2-17 summarizes the specifications of the α and β rods.

α Rod Amplifiers. The 2.5-cm aperture α rod amplifier was designed to have a small-signal gain of 100 and a gain profile that is flat to within $\pm 10\%$. As shown in Fig. 2-50, the 2.5-by-40-cm α laser rod is placed inside a cylindrical shield glass filled with fluorescence-absorbing immersion fluid. (The immersion fluid is circulated to cool the laser rod and to scavenge bubbles.) Six 1.3-cm bore, 300-Torr xenon flashlamps are imaged onto the rod axis with a silver-plated, six-lobed, elliptically-crenulated cylindrical reflector. Because the diameter of the shield glass is n times the laser rod diameter (where n is the refractive index of the laser glass), the TIR "whisper" modes are excluded from the volume of the laser rod.⁴⁴ This enables us to determine the gain profile of the laser amplifier by the convolution of rod absorption and pumping radiation deposition from the pumping cavity.

α Rod Amplifier Performance. The variation with input energy of the optical gain of the α rod amplifier is shown in Fig. 2-51. As indicated, when index-matching fluid is used in the immersion cylinder, a small signal optical gain of 140X is achieved at an input energy of 17.4 kJ to the flashlamps. The spatial gain profile of the index-matched α rod amplifier is shown in Fig. 2-52. In general, use of dif-

Table 2-17. Specifications and performance evaluations of Shiva rod amplifiers

Property	Amplifier	
	α	β
Rod dimensions, cm	2.5 by 40	5 by 40
Pumped length, cm	37	37
Neodymium doping, wt%	1.2	0.6
Small signal gain	200 (100) ^a	18 (14) ^a
Flashlamp bore, cm	1.3	1.5
Wavefront distortion, μm	<0.1	<0.1
Wavefront distortion gradient, $\mu\text{m}/\text{cm}$	<0.05	<0.05
Homogeneity,	1.3×10^{-7}	1.3×10^{-7}
Clear aperture, cm	2.3	4.6
Birefringence, nm/cm	<0.5	<1.0

^aReduced gain obtained when nonindex-matched immersion fluid is used in the laser rod amplifier.

Table 2-16. Geometrical properties of the Shiva rod-amplifier pumping cavities

Property	Amplifier	
	α	β
Displacement of lamps from reflector, cm	3.00	3.75
Radius of lamp circle, cm	5.0	10.0
Major axis of ellipse, cm	11.0	17.5
Minor axis of ellipse, cm	9.798	14.361
Diameter of shield glass, cm	4.0	7.8
Reflector eccentricity	0.4545	0.5714

ferent bore flashlamps (1.0, 1.3, and 1.5 cm), nonindex-matching immersion fluids, and inaccurate flashlamp reflectors markedly affect the homogeneity of the amplifier gain profile. We must emphasize that although well-designed, accurate flashlamp reflectors are essential to achieve homogenous gain profiles for all Shiva rod and disk amplifiers, the α rod amplifier pumping geometry is the most intolerant of mechanical inaccuracy (tolerance ± 0.10 cm) in the construction and alignment of elliptical/cylindrical flashlamp reflectors.

β Rod Amplifiers. The optical design of the Shiva β rod amplifiers represents an extrapolation of the α rod amplifier design (Fig. 2-53). Namely, the β rod amplifiers incorporate:

- Laser-rod immersion cylinder with a diameter $D = nd$.
- Index-matching inorganic immersion fluid ($\text{ZnCl}_2 + \text{SmCl}_3$).
- Precision silver-plated, elliptically crenulated, cylindrical flashlamp reflectors with foci coinciding with lamp and rod axes.
- Nitrogen gas purge to eliminate oxygen from the pumping cavity.
- Six 1.5-cm bore, 37-cm arc length, 300-Torr xenon flashlamps.

- Fluid circulation system for rod cooling and bubble scavenging.

With a relatively long (40 cm) laser rod, the 5-cm β rod amplifier is able to achieve a more homogeneous and higher optical gain (19 $\times$) than was possible with previous laser amplifiers of this aperture.

β Rod Amplifier Performance. A small signal optical gain of 19 can be achieved with the β rod amplifier at an input energy of 40 kJ and with 1.5-cm bore lamps (see Fig. 2-54). A spatial gain profile that is homogeneous to within $\pm 10\%$ can be obtained using these 1.5-cm lamps together with a mixture of ZnCl_2 and SmCl_3 as an index-matched fluorescence-absorbing immersion fluid (Fig. 2-55). Somewhat higher optical gains can be reached with 1.9-cm bore flashlamps at input energies up to 70 kJ.

In general, it is possible to change the β rod amplifier gain profile, maximum input energy, and overall amplifier efficiency within these limits by varying the flashlamp bore from 1.0 to 1.9 cm. The mechanical design of the β rod amplifier permits the installation of different bore flashlamps without major modifications. The general trend of β rod amplifier gain profiles ranges from axial gains that are higher than edge gains for the small bore lamps (1.0 cm) to axial gains lower than edge gains for large bore lamps (1.9 cm). Significant changes in amplifier gain profiles⁴⁶ can also be effected by varying the properties of the immersion fluid (e.g., refractive index and intrinsic absorption coefficient). These features permit the gain profile of the β (or α) rod amplifier to be easily altered if the Shiva laser system requires a change in the intensity apodization of the laser beams.

Authors

G. J. Linford
S. M. Yarema
W. T. Crothers

Disk Amplifiers

To achieve the desired high optical performance at the lowest possible cost, we have designed the Shiva disk amplifiers with the following criteria in mind.⁴⁷

- Minimize the optical path length through the laser glass.

- Maximize the optical gain.
- Obtain spatially homogeneous gain profiles.
- Maintain a high degree of cleanliness and freedom from contamination.

- Perform adequately for at least 1000 shots.

In general, the prototype Shiva disk amplifiers have met these demanding requirements. In the following subsections, we describe the performances and characteristics of each amplifier (see Table 2-18).

The commonality of components in these disk amplifiers also is strongly emphasized. As a result, the internal structural elements of the amplifiers are similar. Welded-hydroformed and welded-stamped stainless steel structural elements are used in all three sizes of the Shiva disk amplifiers. This provides significant improvements in strength, cleanliness, durability, and cost effectiveness. In addition, all three disk amplifier sizes use identical electrical bank components and standard 1.5-cm bore, 112-cm arc length cerium-doped xenon flashlamps.

As a consequence of the flashlamp design, the physical lengths of these disk amplifiers are also the same. Thus, a β disk amplifier mounts six 10.8 by 20.0-cm disks, the γ disk amplifier has four 16.4 by 30.9-cm disks, and the δ disk amplifier uses three 22.3 by 41.8-cm laser disks.

As an additional safety feature, a separate ground return for the flashlamp reflector is provided. Thus, if a lamp failure occurs with an arc to the reflector (the component nearest the ground plane), the fault will not raise the potential of the spaceframe ground, thereby eliminating the concomitant hazard to personnel and equipment.

Disk Amplifier Pumping Cavities. Each Shiva disk amplifier uses linear flashlamps featuring encapsulated lead ends. The 112-cm arc length, 300-Torr xenon flashlamps have cerium-doped, fused silica walls (0.25 to 0.3 cm thick). Each lamp is mounted with its axis displaced 1.3 cm from the surface of a mating multicylindrical, crenulated, silver-plated reflector. Each pair of lamps is wired in series and fired by a pulse-forming network circuit (PFN). Each PFN circuit has a capacitance of 90 μF and an inductance of 450 μH . The properties of the flashlamp reflector designs for the β , γ , and δ disk amplifiers are summarized in Table 2-19.

A single-piece, fused silica, cylindrical shield glass separates the pumping cavity from the optical cavity containing the laser disks. Tight gaskets permit separate purging with nitrogen gas of both the

Table 2-18. Specifications and performance evaluations of Shiva disk amplifiers

Property	Amplifier		
	β	γ	δ
Laser disk dimensions, cm	10.8 by 20.2	16.4 by 30.9	22.3 by 41.8
Disk thickness, cm	$2.4^{+0}_{-0.04}$	$3.0^{+0}_{-0.04}$	$3.2^{+0}_{-0.04}$
Neodymium doping, wt%	2.9 ± 0.1	2.2 ± 0.1	1.9 ± 0.1
Small signal gain	4.3	2.9	2.1
Wavefront distortion (per disk) μm	0.05	0.06	0.08
Wavefront distortion gradient, $\mu\text{m}/\text{cm}$	0.02	0.02	0.03
Homogeneity	9×10^{-7}	9×10^{-7}	10^{-6}
Clear aperture, cm	9.4	15.0	20.8
Birefringence, nm/cm	2.5	5.0	5.0

Table 2-19. Pumping cavity parameters for the Shiva laser disk amplifiers

Parameter	Amplifier		
	β	γ	δ
Lamp reflector lobes	16	24	32
Reflector lobe radius of curvature, cm	1.9	2.2	2.5
Lamp circuits	8	12	16
Lamp circle radius, cm	17.2	23.8	29.9

flashlamp and the laser disk volumes. Nitrogen gas purging is essential because air must be excluded from the laser disk cavity. Otherwise, absorption of flashlamp-generated ultraviolet light by oxygen would produce serious optical distortions within the gas filling the interdisk volume.⁴⁸

The laser disks are chevron-mounted at Brewster's angle to cancel beam offset and to eliminate reflection losses (see Fig. 2-56). Each elliptical laser disk is edge-coated with a durable, fluorescence-absorbing glass to suppress oscillation of spurious parasitic modes (at 1.06 and 1.33 μm) within the laser disk. The hydroformed stainless steel disk holder prevents direct illumination of the

thin, highly absorbing, disk edge-coating by the flashlamp radiation.

Parasitic Mode Control With Index-Matched Edge Coatings. The physical geometry of a thin laser disk oriented at Brewster's angle provides very large optical gains for rays totally internally reflected from the laser disk faces. For a "bulk" parasitic mode with rays reflected at the critical angle along the major axis L of a laser disk, the optical gain for a single pass is

$$G_b = \exp(\alpha L_n), \quad (10)$$

Fig. 2-56. Completely assembled Shiva β disk amplifier (a) and detail of the disk-rail structure (b) showing the hydroformed disk holders welded into the stamped, rolled, and welded rail truss.

where α is the average gain coefficient of the laser disk and n is the index of refraction. For a γ disk, $G_b \approx 30$, compared with the optical gain (per disk) for a transmitted laser beam of only 1.3.

The optical gain within a laser disk is greatest just beneath each face. For the disk thicknesses and dopings used in the Shiva disk amplifiers, it is likely that the gain coefficient associated with these "face modes" is simply

$$G_f = \exp(2\alpha L), \quad (11)$$

for a "face" mode directed parallel to the major axis. For example, in the case of the γ disk amplifier, $G_f \approx 43$.

The laser disk faces must be highly polished and unobscured to permit the high-power laser beam and the pumping radiation from the flashlamps to enter the laser disks. As a result, the only surface available to suppress the oscillation of these internal parasitic modes is the laser disk perimeter. Therefore, we use an index-matched, fluorescence-absorbing glass edge-coating on the disk perimeter. These parasitic modes are interdicted after only one pass through the amplifier, provided that the disk bevels are minimized (<0.1 cm). Once these measures are taken, the only major remaining depumping mechanism within the laser disk is single-pass superfluorescence.

In a study⁴⁹ conducted at the Battelle Memorial Institute and sponsored by LLL in 1975-1976, index-matched edge-coating glasses able to meet

our stringent requirements were successfully developed. Although the edge-coating glass was optimized initially for ED-2 silicate laser glass, another coating⁵⁰ better suited for LSG-91H silicate laser glass has been developed recently and successfully applied to 20-cm aperture C disks.

Laboratory measurements indicate that a 5 to 10% increase in small signal gain is obtained for the prototype γ disk amplifier using this new index-matched edge coating in place of the EI-4 coating used on the β disks.⁵¹ An increase in small-signal gain of 16% over previous C disk amplifiers is predicted for the index-matched coating in the δ disk amplifier.⁵² Because the major axis of the β disk is only 65% that of the γ disk, the nonindex-matched EI-4 edge coating is able to suppress the bulk and face modes arising in the smaller β disks.

β Disk Amplifier. A diagram of the β disk amplifier in cross section is given in Fig. 2-57. When pumped with an input energy to the flashlamps of 203 kJ delivered in a $3\sqrt{LC}$ time of 600 μ s, a small-signal gain of 4.3 is obtained (see Fig. 2-58). The gain profile of the β disk amplifier (Fig. 2-59) is spatially uniform to within $\pm 7\%$ across the full 9.3-cm clear aperture of the amplifier. Passive insertion losses have been measured to be $5 \pm 1\%$. A photograph of a partially disassembled β disk amplifier (Fig. 2-60) illustrates the scale of the shield glass and the laser disk-rail structures.

β Disk Amplifier Performance. Extensive longevity tests of several β disk amplifier prototypes have demonstrated the effectiveness of the single-piece shield glass design. With this design, sources

Fig. 2-57. Cross section of Shiva β disk amplifier.

Fig. 2-58. Small-signal gain vs input energy for Shiva β disk amplifier.

Fig. 2-59. Gain profile of Shiva β disk amplifier at an input energy of 140 kJ.

β DISK AMPLIFIER SPECIFICATIONS

Design Details

Clear aperture: 9.4 cm
Small signal gain: 3.67 @ 20 kV
4.26 @ 24 kV
Gain homogeneity: $\pm 2\%$ over 80% of
clear aperture
Optical phase distortion: 0.12 μm
Passive insertion loss: 5%
Disks: 6
Disk dimensions 10.8 by 20.2 cm
Disk thickness: 2.4 cm

Disk doping: ED-2 $2.2 \pm 0.1\%$ Nd
Edge coating: EI-4 nonindex match
Lamps: 16
Lamp dimensions: 1.5-cm bore
112-cm arc length
Lamp envelope: cerium-doped silica
Reflector cusp radius: 1.9 cm
Shield glass: monolithic fused silica
Path length: 17.12 cm
 B/P_{in} : 9.24×10^{-12} Np/W

Capacitor Bank Requirements

Circuits: 8
Capacitors/circuit: 6
Lamps circuit: 2
Capacitance/circuit: 90 μF
Inductance/circuit: 450 μH
Resistance/circuit: 3 Ω
3VLC: 600 μs

Reflector ground: separate
Lamp electrodes: encapsulated
Capacitor voltage rating: 30 kV
Maximum operating energy: 204 kJ
Maximum operating voltage: 24 kV
Mean number of lamp firings
between failures: 6×10^6

Laser Glass Properties

Type: ED-2 silicate
Manufacturer: Owens/Illinois
Stimulated emission cross
section: 2.7×10^{-20} cm^2
Absorption efficiency: 73%

Absorption coefficient: 0.003 cm^{-1}
Fluorescent correction factor: 1.07
Index of refraction: 1.556 @ 1.051 μm
Nonlinear index of refraction:
 4.3×10^{-16} cm^2/W (1.4×10^{-13} esu)

Fig. 2-60. The Shiva β disk amplifier on its assembly fixture showing the disk-rail structure, the solid quartz shield, and the end plates (the flashlamp and reflector shells have been removed).

of contamination within the laser amplifier are eliminated or substantially reduced. During one longevity test of 2000 shots, the measured optical gain of a prototype β disk amplifier remained constant within $\pm 5\%$ for the entire experiment.⁵³ The measured performance characteristics of the prototype β disk amplifier compared with the measured and predicted performances of the Shiva γ and δ disk amplifiers are presented in Table 2-18.

γ Disk Amplifier. Since the development of the advanced, index-matched solid edge-coating, 75% of the Shiva γ laser disks were obtained with the new edge-coating. The remaining γ disks are edge-coated with a nonindex-matched, fluorescence-absorbing glass, similar to that used on the β disks (E1-4). The γ disk amplifier in cross section is illustrated in Fig. 2-61.

γ Disk Amplifier Performance. A plot of the small-signal gain vs input energy for the prototype γ disk amplifier is given in Fig. 2-62. In Fig. 2-63, the small-signal gain of the γ disk amplifier with a crenulated, 24-lobed, silver-plated reflector is plotted for an input energy of 305 kJ (corresponding to a bank voltage of 24 kV with the standard $3\sqrt{LC} = 600\text{-}\mu\text{s}$ bank). Each reflector lobe has an individual radius of curvature of 2.2 cm and is located 1.3 cm from the axes of each 1.5-cm bore, 300-Torr, cerium-doped xenon flashlamp.

δ Disk Amplifier. Unlike the β and γ laser amplifiers, the δ disk amplifier mounts an odd number of laser disks (three) at Brewster's angle; thus, the beam offset is not cancelled. Because of this, the exit aperture of the δ disk amplifier must be decentered by a displacement, Δ , given by

$$\Delta = \frac{(n^2 - 1)t}{n\sqrt{n^2 + 1}} \approx 1.58 \text{ cm}, \quad (12)$$

where t is the thickness of the laser disk mounted at Brewster's angle.

The δ disk amplifier uses 32 cerium-doped xenon flashlamps, each mounted 1.3 cm from the silver-plated, 32-lobed, crenulated reflector (see Fig. 2-64). Each lobe of the flashlamp reflector is a cylindrical segment with a radius of curvature equal to 2.5 cm. Three-dimensional computer simulations and experimental measurement made on C-75 disk amplifiers with a similar reflector geometry indicate that this pumping geometry will yield a spatially uniform gain profile. Experimental evaluations of the δ disk amplifier prototype were made in early 1977.

Predicted δ Disk Amplifier Performance. Measurements taken on slightly smaller and thinner laser disks, edge-coated with the newly developed index-matched, fluorescence-absorbing glass indicate that small-signal-gain performance of the δ disk amplifier is limited only by superfluorescence and lamp opacity. The measured optical gain vs input energy performance of a Shiva δ disk amplifier fitted with experimental C-75 disks is plotted in Fig. 2-65. For an input energy of approximately 400 kJ (corresponding to a bank voltage of 24 kV) and corrected for a 4% passive insertion loss, the small-signal gain is 2.07. The gain profile of the Shiva δ disk amplifier is plotted in Fig. 2-66. As shown, the δ disk amplifier gain profile is homogeneous to within $\pm 3\%$ across 90% of the amplifier aperture.

Authors

G. J. Linford
W. S. Neef
W. D. Fountain
W. F. Hagen
C. A. Hurley
D. B. Bubp

Amplifier Design Summary

The designs of the five types of Shiva rod and disk laser amplifiers have been optimized to take advantage of the most cost-effective fabrication techniques while achieving the highest optical performance and acceptably long operational lifetimes. We have given particular emphasis to:

- Control of internal spurious parasitic oscillation modes.
- Cleanliness to avoid beam obscurations and component damage.
- Homogeneous gain profiles to prevent undesirable beam reappodization.
- High optical gain.
- Common use of durable, readily machined, stainless-steel internal elements.
- Well-engineered flashlamp and power conditioning design.

We have built prototypes of the Shiva laser amplifiers and have tested and evaluated their performances. A summary of the measured characteristics of these five amplifiers is given in Table 2-20.

Authors

G. J. Linford

C. A. Hurley

Spatial Filters

The small-scale self-focusing that occurs when a high-power laser beam propagates through optical glass poses a major limitation to high-power laser performance. This deleterious phenomenon is produced by an approximately exponential growth of laser-beam intensity ripples or fluctuations according to the Bspalov-Talenov theory.⁵⁴ In general, the nonlinear intensification of laser beam fluctuations is a complicated function of the laser system geometry. Because the unrestricted propagation of spatially inhomogeneous laser beams through dioptric elements can damage optical components as well as reduce the radiance of the laser system, the maximum tolerable nonlinear phase shift accumulated between successive amplifier stages must be less than 3 Np. This 3-Np quantity corresponds to a twentyfold increase in laser beam modulation for ripples with spatial frequencies near gain maximum.

Principal Function of Spatial Filters. An experimentally acceptable solution to the small-scale self-focusing problem is to use evacuated spatial filters, together with rigorous efforts to eliminate the sources of intensity modulations of laser beams (e.g., contaminated amplifiers, Faraday rotators, polarizers). Typically, Shiva spatial filters are spaced in ΔB increments of 2 to 2.5 Np. Because the apertures of the Shiva rod and disk amplifiers are increased at intervals corresponding to these ΔB increments, the spatial filters also serve as recollimators and image relays within each laser chain. The specifications of the individual spatial filters are summarized in Table 2-21; the significant features of these Shiva filters are illustrated in Fig. 2-67.

The Shiva spatial filters are designed to maintain a vacuum of 10^{-5} Torr with two 28-liter/s vac-ion pumps. Care must be exercised during the cleaning and assembly of these filters to minimize the leakage and out-gassing rates. The vac-ion pumps require only one high-voltage lead connected to each unit; additional supporting vacuum and interconnecting lines required by alternative pumping systems are eliminated.

Spatial-filter field stops are fitted with high-vacuum manipulators to position the field stop in three orthogonal directions. Each axis is driven by a stepping motor to position the field stop remotely in the waist of the laser beam with a least-count resolution of 3.2 μm .

The input lens for each spatial filter is fixed. However, the output lens has a focusing adjustment along the optical axis as well as positioning adjustments in the plane perpendicular to the optical axis. In addition, the output lens is provided with a small amount of angular tilt adjustment, to aid primarily in beam alignment.

The output lens of each spatial filter is mounted in a piston. This piston is fitted in a cylinder with a sliding O-ring seal to hold a rough vacuum during focusing. After focusing is complete, the distance to the proper focus is measured. A shim cut to the exact length is then installed with compression-type O-rings to form the final high-vacuum seal.

Each laser chain is staged with five spatial filters of increasing aperture (see Fig. 2-67). Two additional spatial filters are located on the oscillator table before the beamsplitters. Thus, the Shiva laser system uses a total of 102 spatial filters.

Fig. 2-61. Cross section of Shiva γ disk amplifier.

Fig. 2-62. Small-signal gain vs input energy for Shiva γ disk amplifier.

Fig. 2-63. Gain profile of Shiva γ disk amplifier at an input energy of 210 kJ.

γ DISK AMPLIFIER SPECIFICATIONS

Design Details

Clear aperture: 15.0 cm
Small signal gain: 2.61 @ 20 kV
2.86 @ 24 kV
Gain homogeneity: $\pm 4\%$ over 80% of
clear aperture
Optical phase distortion: 0.12 μm
Passive insertion loss: 5%
Disks: 4
Disk dimensions: 14.4 by 30.9 cm
Disk thickness: 3.0 cm

Disk doping: ED-2 $2.2 \pm 0.1\%$ Nd
Edge coating: EI-6 index-match, 75%
EI-4 nonindex-match, 25%
Lamps: 24
Lamp dimensions: 1.5-cm bore
112-cm arc length
Reflector cusp radius: 2.2 cm
Shield glass: monolithic fused silica
Path length: 14.26 cm
 B/P_{in} : 2.3×10^{-2} Np/W

Capacitor Bank Requirements

Circuits: 12
Capacitors/circuit: 6
Lamps/circuit: 2
Capacitance/circuit: 90 μF
Inductance/circuit: 450 μH
Resistance/circuit: 0.3 Ω
 $3\sqrt{LC}$: 600 μs

Reflector ground: separate
Lamp electrodes: encapsulated
Capacitor voltage rating: 30 kV
Maximum operating energy: 300 kJ
Maximum operating voltage: 24 kV
Mean number of lamp firings
between failures: 6×10^6

Laser Glass Properties

Type: ED-2 silicate
Manufacturer: Owens/Illinois
Stimulated emission cross
section: 2.7×10^{-20} cm^2 (peak)
Absorption efficiency: 73%

Absorption coefficient: 0.003 cm^{-1}
Fluorescent correction factor: 1.07
Index of refraction: 1.556 @ 1.061 μm
Nonlinear index of refraction:
 4.3×10^{-16} cm^2/W (1.4×10^{-13} esu)

Fig. 2-64. Cross section of Shiva δ disk amplifier.

Fig. 2-65. Small-signal gain vs input energy for Shiva δ disk amplifier.

Fig. 2-66. Gain profile of Shiva δ disk amplifier at an input energy of 280 kJ (experimental LSG-91H C-75 disks with index-matched edge coatings).

8 DISK AMPLIFIER SPECIFICATIONS

Design Details

Clear aperture: 20.8 cm
Small signal gain: 1.95 @ 20 kV
2.10 @ 24 kV
Gain homogeneity: $\pm 5\%$ over 80% of
clear aperture
Optical phase distortion: 0.13 μm
Passive insertion loss: 4%
Disks: 3
Disk dimensions: 22.3 by 41.8 cm
Disk thickness: 3.2

Capacitor Bank Requirements

Circuits: 15
Capacitors/circuit: 6
Lamps/circuit: 2
Capacitance/circuit: 90 μF
Inductance/circuit: 450 μH
Resistance/circuit: 0.3 Ω
 $3\sqrt{LC}$: 600 μs

Laser Glass Properties

Type: LSG-91H silicate
Manufacturer: Hoya
Stimulated emission cross
section: $2.46 \times 10^{-20} \text{ cm}^2$ (peak)
Absorption efficiency: 68%

Disk doping: LSG-91H $1.9 \pm 0.1\%$ Nd
Edge coating: HBL-306 index-match
Lamps: 32
Lamp dimensions: 1.5-cm bore
112-cm arc length
Lamp envelope: cerium-doped silica
Reflector cusp reflector: 2.5 cm
Shield glass: monolithic fused silica
Path length: 11.42 cm
 B/P_{in} : $1.8 \times 10^{-12} \text{ Np/W}$

Reflector ground: separate
Lamp electrodes: encapsulated
Capacitor voltage rating: 30 kV
Maximum operating energy: 400 kJ
Maximum operating voltage: 24 kV
Mean number of lamp firings
between failures: 6×10^6

Absorption coefficient: 0.003 cm^{-1}
Fluorescent correction factor: 1.053
Index of refraction: 1.549 @ 1.061 μm
Nonlinear index of refraction:
 $4.19 \times 10^{-16} \text{ cm}^2/\text{W}$ ($1.4 \times 10^{-13} \text{ esu}$)

Table 2-20. Characteristics of the Shiva rod and disk laser amplifiers

Property	Amplifier				
	Rod		Disk		
	α	β	β	γ	δ
Laser glass type	ED-2	ED-2	ED-2	ED-2	LSG-91H
Small signal gain	200	18	4.3 ^b	2.9 ^b	2.1 ^b
Peak design output flux, J/cm ²	0.17	0.59	$\left\{ \begin{array}{c} 0.38^c \\ 1.29 \\ 3.51 \end{array} \right\}$	2.63	2.56
Saturated gain	193	16.0	$\left\{ \begin{array}{c} 4.1^c \\ 3.7 \\ 3.1 \end{array} \right\}$	2.3	1.8
$(\Delta B/\Delta P)_{IN}, 10^{-12} \text{ Np/W}$	7743	303	9.1	2.3	0.8
$(\Delta B/\Delta P)_{OUT}, 10^{-12} \text{ Np/W}$	38.7	16.8	2.1	0.8	0.4
Clear aperture, cm	2.3	4.6	9.4	15.0	20.8

^a1-ns pulsed operation; output energy per arm = 1 kJ.

^bBank voltage = 24 kV.

^cThere are three β disk amplifiers in each chain: β_1 , β_2 , and β_3 listed top to bottom.

Table 2-21. Physical characteristics of the Shiva spatial filters

Unit	Number required	Inlet lens, mm		Outlet lens, mm		Distance between lenses, cm	Unit weight kg (lb)
		f_1 , focal length	d_1 , diameter	f_2 , focal length	d_2 , diameter		
Main front end	1	269.7	14	597.0	31	0.866	
β rod/ β rod	1	480.5	55	480.5	55	0.961	
α rod/ β rod	20	1083.3	30	2273.9	55	3.357	382.1 (173.7)
β rod/ β disk	20	480.5	55	995.2	106	1.476	305.8 (139.0)
β disk/ β disk	20	995.2	106	995.2	102	1.990	330.0 (150.0)
β disk/ γ disk	20	995.2	106	1586.2	156	2.581	479.6 (218.0)
γ disk/ δ disk	20	1586.2	156	2209.6	212	3.796	1168.2 (531.0)

Fig. 2-67. Shiva spatial filters.

Authors

C. B. McFann
W. D. Fountain
C. A. Hurley
G. J. Linford

Electro-optical Isolators

The Shiva chain design requires 44 Faraday rotators: 4 with a 5-cm clear aperture (β -rod), 20 with a 10-cm clear aperture (β), and 20 with a 20-cm clear aperture (δ). Centerline design parameters for these three isolation units are presented in Table 2-22. The requirements for the β -rod and β rotator magnets are nominal. These units are essentially identical to those used on the Argus, Cyclops, and Janus laser systems. However, the δ -rotator magnet design departs from its predecessor — the C-rotator — in several significant ways.

Isolator Design Details. The Shiva polarizers and rotators are designed as a combined package to be installed on the spaceframe as a single unit. Figure 2-68 illustrates the β isolator. All components in the vicinity of the coil are made either of plastic or glass, avoiding distortion of the magnetic field. However, plastic is difficult to machine accurately

and causes outgassing problems. For these reasons, the polarizer plates are mounted in metal supports located some distance from the coil, thereby increasing the length of the total package. The entire unit is surrounded by and supported in a large cylindrical aluminum shield. Induced currents in this shield effectively contain most of the magnetic field so that linkage with the adjacent spaceframe and nearby electronics is considerably reduced.

The rotators are constructed so that the support for the glass is mechanically separated from the coil. This reduces the amount of mechanical shock transmitted to the glass when the coil is energized. Conveniently, it also permits the flow of nitrogen gas between the coil and the glass mounting to remove the heat generated in the coil.

The rotator components are attached through rubber dampening supports to the magnetic shield which, in turn, is supported on cradles identical to those used for the amplifiers. As a result, the polarizer-rotator package can be aligned as a single unit.

Faraday Rotator Design. The Shiva δ rotators are designed to satisfy two unique requirements. The peak axial field must reach 4.0 T instead of the 2.75 T required by the Argus and Cyclops C rotators. Also, fringing fields that are exterior to the magnet

Fig. 2-68. β isolator assembly. There are two polarizers on both the input and output apertures of the coil; an alignment sensor is attached to the last output polarizer. The δ isolator has single input and output polarizers but is otherwise identical to this β assembly.

must be as small as practical. We met this second requirement by surrounding the magnet with a cylindrically symmetric aluminum conducting shield with a barrel approximately twice as long as its diameter. The induced current flow in this shield creates a magnetic field that opposes the driving field (Lenz's law). The net field far from the magnet is reduced by this cancellation effect (see Fig. 2-69).

However, the shield carries an energy penalty for

its implementation.⁵⁵ For our chosen shield diameter (slightly less than twice the mean coil diameter, $1.18\times$ the stored energy required for an unshielded coil is needed for this shielded coil. Combining this factor with the 4-T peak field requirement, we must obtain 200 kJ of stored capacitive energy per magnet (see Table 2-22).

To maintain field homogeneity across the clear aperture while reducing magnet length and stored

Fig. 2-69. Axial field of δ rotator magnet with shield (solid curve) and without shield (dotted curve).

energy, we are implementing an end-corrected solenoid design. Calculations confirmed by experimental measurements⁵⁵⁻⁵⁷ indicate that homogeneity 30 dB or better is possible for a corrected solenoid with a length/mean-diameter aspect ratio of 0.9.

Finally, a high-current, high-voltage diode string across the magnet effectively clamps the current at its peak. This modification serves a threefold purpose. The capacitors are protected from reverse voltage swings, resulting in longer component lifetimes. The ignitron switches are protected from

Table 2-22. Shiva isolator design parameters

Parameter	Isolator		
	β -rod	β	δ
Forward transmission	0.90	0.90	0.92
Minimum rejection, dB	-20	-20	-18
Length of rotator-polarizer assembly, m	1.55	1.55	2.55
Polarizer plates, No.	4	4	2
Polarizer plate thickness, cm	0.5	1.0	1.0
Beam offset	no	no	yes
Beam diameter, cm	4.4	9.1	20.2
Clear aperture, cm	4.8	9.5	21.0
Glass diameter, cm	5.2	10.0	22.0
Glass thickness, cm	2.5	1.45	1.0
Coil diameter, cm			
inner layer	13.6	13.6	27.5
outer layer	15.2	15.2	29.5
Coil length, cm	20.6	20.6	26.5
Turns for 2 layers, No.	124	124	100
Wire gage	No. 10	No. 10	No. 6
Shield inside diameter, cm	28.6	28.6	50.8
Shield length, cm	139.5	139.5	122.0
Inductance, μ H	940	940	1540
Resistance, m	184	184	119
Magnetic energy stored at 45° rotation, kJ	4.0	11.8	170
Peak coil current, kA	2.90	5.00	14.9
Peak center field, T	1.6	2.7	4.0
Time to peak rotation, ms	0.26	0.46	1.89
Rotation homogeneity, dB	-34	-26	-26
Capacitance, μ F	30	90	1000
Volts to change, kV	17	17	20
Capacitor energy storage, kJ	4.3	12.9	200

reverse current; in fact, because the ignitrons only conduct during the first quarter cycle, total coulomb transfer is well within the specifications for the switches. Finally, the heat generated in the coil itself is reduced. Thus, the diode ahead of the 15-kA current limit fixes the magnet-turns requirement at >100 turns.

Authors:

W. W. Simmons

J. O. Myall

Turning Mirror Gimbals

The turning mirrors direct the parallel laser beams emerging from the spaceframe into the clustered array needed to successfully illuminate the target. This is accomplished in two stages to minimize path length differences and to allow the beams to pass through the target structure without vignetting. The first turning mirrors center the beams emerging from the laser bay onto the final turning mirrors which, in turn, point the beams onto the target. The first mirror behaves in a static mode. However, the final mirror operates in a closed loop in conjunction with the pointing, focusing, and centering (PFC) sensor package, correcting the beam-pointing angle that may have become perturbed by small thermal effects, component sag, creep, or the accuracy of target placement.

For the two mirrors, we explored several conventional mounting systems — concentric gimbal rings, bolted plates with differential screws, spring-suspended bezels, flexure-supported frames, and extendable six-legged structures. Designs were evaluated for reliability, function, complexity, and cost. The six-legged structure was selected for the first mirror because of its adaptability and good performance for minimal cost. The gimbal-ring design was selected for the final turning mirror because the PFC sensor package requires access to the entire back of the mirror. In addition, the concentric gimbals allow very precise orthogonal position corrections.

First Turning Mirror. A unique six-legged expandable truss configuration (Fig. 2-70) allows for six modes of alignment freedom at an economical price. The rectangular glass mirror is edge-supported in an aluminum bezel. The glass rests on a 12-durometer silicone rubber strip, attached to a

flat ledge machined on the inside of the bezel. The mirror is held in place axially by a series of rubber faced clips that are bolted to the top of the bezel. With these clips, the mount constraint can be tuned, eliminating the need for very fine tolerances on the bezel seat. Adjustable steel-backed rubber pads are also provided for radial support of the mirror. In addition, the silicone rubber acts as a thermal barrier, isolating the glass from the aluminum bezel.

The bezel is supported and adjusted by a series of three trusses, linking the mirror to a baseplate through spherical bearings. When the length of any leg is changed, the entire mount rolls within the bounds of the spherical joints, changing position and orientation. This design is stable because gravity loads the spherical joints and turnbuckles. The mount provides freedom of adjustment in six modes — pitch, roll, yaw, focus, and (x,y) centration. (The latter three modes are nonessential for most of our requirements.)

Because of the relative inaccessibility of the mounts on the target structure, it is advantageous to drive certain axes with a motorized system that is remotely operated. For this purpose, we have developed a drive package consisting of a stepping motor, worm-gear assembly, ball screw, and a flexure that can be substituted for any of the three trusses. By preselecting the number of lead threads on the worm gear, resolutions from 1.3 to 0.3 $\mu\text{rad}/\text{step}$ are possible. The mount has a total range in excess of 100 mrad. The worm gear also provides sufficient mechanical stability to enable the stepping motor's normally low detent torque to hold the bezel in the desired position without backdriving.

Final Turning Mirror Gimbal. The Aerojet ElectroSystems Company developed the pointing gimbals (Fig. 2-71) that we use to direct the laser beam onto the target. The open-faced gimbal permits the PFC sensors to be positioned directly behind the mirror. The two orthogonal axes are supported at opposite ends by high-spring-rate torsion bars. The mirror bezel is aligned by applying a force at the edge of each gimbal with a low-spring-rate coil extension spring.

The inner gimbal holding the mirror is designed carefully so that the force deflecting the gimbal does not distort the mirror. The assembly has a 20-Hz natural frequency and is statically balanced to eliminate externally induced oscillation. To dampen the gimbal vibrations, tachometer generators between the gimbal axes are coupled to torque

motors at the torsion-bar supports, blocking natural resonances. The ends of the extension springs are positioned by a miniature ball screw driven by a dc stepping motor. When electrical power is removed, the detent torque is insufficient

to prevent backdriving; therefore, an integral brake is attached to the lower end of the motor shaft.

The mirror is sandwiched between circular rings fastened to the front and rear of the inner gimbal. Thin silicone rubber pads are located between the

Fig. 2-70. The first turning mirror directs the beam onto the final turning mirror. The heavy bezel (aluminum alloy weldment) is supported by three adjustable trusses.

rings and the mirror to minimize surface deflections resulting from the weight of the mirror. The silicone rubber has a tendency to creep. However, because the gimbal system operates in a closed-loop mode, the mirror drive automatically compensates for long-term creep. Short-term creep is inconsequential.

The prototype assembly has proven its ability to point within a resolution of $0.0625 \mu\text{rad/step}$. It is also well matched to the $1\text{-}\mu\text{rad}$ sensitivity of the PFC sensor. Presently, we are scaling down the design to accommodate the 20-cm beam diameter configuration. However, even in its present form, we expect that this gimbal system will have a negligible effect on laser performance.

Authors

B. J. Kowalskie

E. S. Bliss

Pockels Cells

The electro-optic crystal employed in the Shiva Pockels cells is a solution-grown KD_2PO_4 (KD*P) crystal of uniaxial (42m) symmetry. The crystal is formed as a right circular cylinder with its rotation axis coincident with the optical (Z) axis of the crystal (see Fig. 2-72). Electrode bands of variable width and spacing are placed on the circumference of the cylinder (see Fig. 2-73).

When a voltage is applied across the electrodes at the same time a polarized laser beam is passing through the crystal along the optical axis, the electro-optic effect in the KD*P causes the light polarization to shift. The voltage required to shift the polarization by 90° is called the halfwave voltage, V_π . In KD*P for $1.06\text{-}\mu\text{m}$ light, V_π is approximately 7 kV. As soon as the voltage is removed from the electrodes, the crystal no longer affects the

Fig. 2-71. The gimbal assembly of the final turning mirror points the beam onto the target. The open-framed gimbal has two orthogonal axes supported by high-spring-rate torsion bars. The mirror bezel is aligned by applying force at the edge of each gimbal with a low-spring-rate coil spring.

polarization of the transmitted light. Therefore, by placing a KD*P Pockels cell between crossed polarizers, the transmission T becomes a function of the applied voltage V , according to the expression

$$T(V) = T_0 \sin^2 (\pi V / 2V_\pi), \quad (13)$$

where T_0 ($0 \leq T_0 \leq 1$) accounts for the losses due to reflection, absorption, and scattering in the Pockels cell and polarizers.

Design Considerations. The basic design problem for the large-aperture Pockels cell isolators involves optimizing certain important performance parameters by varying the crystal geometry and electrode dimensions. In addition, the surrounding optical and electrical packaging of the crystal must be carefully designed. Transmission uniformity across the aperture and the contrast (on/off) ratio are the most important parameters for large-aperture isolators; switching speed is a secondary consideration.

To satisfy the requirements for the Shiva laser, a 50-mm clear aperture Pockels cell with a transmission uniformity better than 2% across the full aperture was needed. We also desired a reasonable driving voltage (≥ 10 ns) and the fastest possible risetime (≥ 10 ns). In addition, the primary design objective was to reduce the length of the KD*P crystal. This would minimize the contribution of the Pockels cell to nonlinear phase distortion and would improve the contrast ratio by reducing the

Fig. 2-73. The KD*P crystal used to verify the voltage-distribution calculations for the large-aperture β Pockels cell isolators. (Scale is graduated in millimeters.)

strain-induced birefringence intrinsic to large crystals. In addition to decreasing the cost, reducing the amount of crystal material would tend not only to improve the device contrast ratio; it would also considerably shorten the delivery time of the 42 large-aperture devices needed for Shiva. In fact, the volume of high-optical-quality crystal material required for the twenty 50-mm devices and the twenty-two 25-mm devices would severely strain the KD*P crystal-growing capacity of this country for the next year.

Initial Pockels Cell Design. The cylindrical ring-electrode (CRE) Pockels cell designed at LLL and used in the Argus laser system satisfied most of our objectives for the 25-mm α cell. Therefore, this was taken as our starting point for the design of the 50-mm β cell. It was clear that by scaling the α geometry ($L/R = 2$; see Fig. 2-74) to meet the clear-aperture requirements, a usable 50-mm-diam Pockels cell could be constructed if large, high-quality KD*P crystals were available in sufficient quantities. These crystals grow along the optical axis at rates varying from 0.1 to 1.0 mm per day, depending on the deuteration level and the growing technique. If the CRE geometry were scaled at $L/R = 2,3700$ mm of KD*P Z-length would be needed for Shiva. Because of the time required to grow this quantity of crystal, we sought to reduce the crystal length, i.e., develop a design with $L/R < 2$.

Our calculations indicated that a reduction in the crystal length would result in an unacceptable loss

Fig. 2-72. CRE Pockels cells. The Z axis of the KD*P crystal is both the optical axis of the crystal and the axis of the cylinder. The variables R , L_1 , and L_2 are selected to produce the desired operating characteristics.

in transmission uniformity. However, it seemed possible that a slight modification in the electrode geometry might allow the loss in transmission uniformity to be recovered at the expense of an increase in driving voltage. We made an analysis of the electrode geometry based on the fundamental relationship given in Eq. (13). In general, V (the radius-dependent voltage between crystal faces) is some fraction of the voltage applied to the electrode. This radial dependence is caused by the electric-field fringing effects of the CRE geometry. We were able to minimize spatial nonuniformities in transmission through the polarizer-crystal combination resulting from the radial variations in voltage at the expense of voltage coupling (i.e., the ratio of voltage between crystal faces to the electrode voltage).

Radial voltage distributions were calculated from a numerical solution to the Laplace equation for several electrode geometries in which electrode position, electrode width, and crystal size (L/R) were varied systematically. Results from computer simulations were summarized graphically; from these data, we were able to select an optimum electrode geometry and crystal size. We found that acceptable transmission uniformity and voltage coupling

Fig. 2-74. The voltages obtained with prototype, large-aperture β Pockels cell correspond closely with our predicted values.

Fig. 2-75. Complete Pockels cells enclosed in aluminum housings: 25-mm α cell (left) and 50-mm β cell (right).

ing could be achieved with a cylindrical crystal with $L/R \approx 1.3$. This ratio reduced the crystal length by 35% (volume reduction), shortened the delivery time, and improved the contrast ratio. We built and tested a prototype to verify the voltage calculations (see Fig. 2-73). The prototype crystal performed as predicted; see Fig. 2-74 for a comparison between the measured and calculated values of $V(r)$, normalized to the electrode voltage.

The complete α and β Pockels cells are shown in Fig. 2-75. The crystal is enclosed in an aluminum housing with protective glass windows. This device yields an even closer match to the calculated values of $V(r)$ than was expected. The transmission uniformity of the Pockels cell between crossed polarizers is better than 2% peak-to-valley for an applied electrode voltage of 1.2 V, or less than 10 kV pulsed at $\lambda = 1.06 \mu\text{m}$. The Pockels cell mounted with the polarizer assembly is illustrated in Fig. 2-76 and Table 2-23 presents a summary of the Pockels cells' performance.

Using a driver with a 50- Ω source impedance, we obtained switching times of 2 and 5 ns for the α and β cells, respectively. Faster risetimes could be achieved by reducing the driver impedance. The intrinsic contrast ratio of the complete α and β assemblies (Fig. 2-75) were measured at $\lambda = 0.6328 \mu\text{m}$ to be 1000:1 and 400:1, respectively. This means that contrast ratios of approximately 3000:1 and 1000:1 can be expected at $\lambda = 1.06 \mu\text{m}$. Strain effects would probably have prevented the achievement of the high contrast ratio in the β cell if the crystal were

Fig. 2-76. Diagram of Pockels cell with polarizer assembly.

longer (i.e., $L/R > 1.3$). However, the reduction in crystal length from 10 cm at $L/R = 2$ to 6.5 cm at $L/R = 1.3$ has made the 50-mm clear aperture

Pockels cell practical in the unprecedented quantities required for the Shiva laser system.

Authors

M. A. Summers

B. C. Johnson

J. Uroff

G. S. Bradley

Table 2-23. Performance of the Shiva Pockels cells

Parameters	Pockels cell	
	α	β
Clear aperture, mm	23	48
Wavefront distortion, ^a μm	0.1	0.1
Intrinsic contrast ratio at $\lambda = 1.06 \mu\text{m}$	3000:1	1000:1
Halfwave voltage, kV	8	10
Risetime, ns	2	5
Transmission uniformity, ^b %	<0.1	<2.0

^aSingle pass, $\lambda = 1.06 \mu\text{m}$.

^bBetween crossed polarizers.

References

43. G. Dube and N. L. Boling, *Appl. Optics* 13 (1974).
44. G. J. Linford and L. W. Hill, *Appl. Optics* 13, 1387 (1974).
45. J. McMahon, R. Burns, and T. DeRieux, *NBS Special Publication* 414, 17 (1974).
46. G. J. Linford and S. M. Yarema, "Design Techniques and Measured Performance for a Uniformly Pumped 4-cm Diameter Rod Amplifier," presented at *IEEE/OSA Conf. Laser and Electro-Optical Systems* (San Diego, CA, 1976); see also Lawrence Livermore Laboratory, Rept. UCRL-78579 (1976).
47. W. D. Fountain, W. F. Hagen, and G. J. Linford, "Design of Disk Laser Amplifiers for Laser Fusion Applications," presented at *IEEE/OSA Conf. Laser and Electro-Optical Systems* (San Diego, CA, 1976).

48. G. J. Linford, H. H. Chau, J. A. Glaze, C. B. Layne, and F. Rainer, *Appl. Optics* **14**, 3057 (1975).
49. R. B. Bennett, SANL 358/011, Battelle Columbus Laboratories, Columbus, OH (1977).
50. K. R. Shillito and R. B. Bennett, SANL 456/021, Battelle Columbus Laboratories, Columbus, OH (1977).
51. G. J. Linford, S. C. Roberts, and S. M. Yarema, UC/LLL Internal Memorandum AD 76-06 (December 2, 1976).
52. G. J. Linford, UC/LLL Internal Memorandum SSD 76-225 (August 27, 1976).
53. G. L. Linford, UC/LLL Internal Memorandum AD 76-15 (December 16, 1976).
54. V. I. Bespalov and V. I. Talanov, *JETP Lett.* **3**, 307 (1966).
55. W. W. Simmons, Lawrence Livermore Laboratory, Internal Memorandum CDG-74-10 (1974).
56. Shielding originally conceived by W. Gagnon.
57. K. Halback, Lawrence Berkeley Laboratory, private communication (1976).

2-2.4 Optical-Pulse Generation and Synchronization

The primary Shiva optical-pulse generator will be an actively mode-locked, quasi-CW, Nd:YAG laser oscillator (see Fig. 2-77). This technology was developed at Stanford University and at Stanford Research Institute by D. J. Kuizenga^{58,59} (see § 2-5 for a more detailed discussion).

In this oscillator, the modulator and lamps are pulsed so that much greater peak powers are available for the allowable average-power dissipations. The Q switch constrains the oscillator to

operate at a low level during the initial optical buildup and stabilization (a few milliseconds). After this buildup period, the Q-switch drive power is turned off to allow subsequent amplification. The energy available in a single pulse is approximately 0.5 mJ and the pulse duration can be varied from less than 100 ps to greater than 2 ns. An intracavity etalon is required for pulse durations greater than about 450 ps. An intracavity aperture restricts oscillator operation to the fundamental transverse-resonator mode. In addition, the resonator is Invar-stabilized. The temperatures of the etalon, laser rod, and acousto-optic devices are held constant by temperature-controlled water cooling. The lamps are also water-cooled. The voltage on the selector Pockels cells is switched on and off rapidly to extract a single pulse from the pulse train. The Pockels cells in the switchout are driven by avalanche-transistor chains.

The mode-locked oscillator emits temporally (and spatially) Gaussian pulses. Different temporal shapes can be obtained by pulse-stacking the output of this oscillator or by "chopping" the output of a single-axial-mode, Q-switched laser oscillator, as are discussed in section T-105. (Neither of these alternatives will be implemented on Shiva in 1977.)

The laser pulses from all amplifier arms must arrive at the laser-fusion target within approximately 10 ps of one another. In other words, the optical path lengths of the laser arms must be equal to within about ± 1.5 mm. The Hughes Aircraft Company (HAC) is currently developing a pulse synchronization system (PSS) under subcontract to LLL.⁶⁰

Fig. 2-77. Diagram of Shiva's actively mode-locked oscillator with the dump-section, single-pulse selector ("switch-out").

Fig. 2-78. The path-length equalization/pulse synchronization system. The operator changes the length of a delay line in the amplifier chain, adjusting it until the pulses from the LO and signal arms exactly overlap in time. This produces a null signal (see Fig. 2-79) and the process is repeated for each amplifier chain.

(a) Laser output

(b) Detector input

(c) Signal-processor output

polarization. This shifted portion is directed to the local-oscillator (LO) arm by the polarizing beamsplitter and passes to the detectors on its return. The unshifted portion of the beam passes through the beamsplitter to the arm of the amplifier chain selected by the operator and retroreflects from the surrogate target. Half of the return signal, directed by the polarizing beamsplitter to the detectors, heterodynes with the LO signal. The Wollaston prism (depicted in Fig. 2-78 as rotated 45° about the beam line from its actual orientation) combines the signal and LO beams; rotation of this prism enables balancing of the two detector inputs. A sinusoidal current is applied to the field windings of the magnetic linear-translation stage that holds the cat's eye retroreflector in the LO arm. This dithers the length of the LO arm to obtain a delta path length null when the amplifier and LO arms are synchronized (Fig. 2-79). Repeating the procedure for each arm in the system assures simultaneity of pulse arrival at the target.

References

58. D. J. Kuizenga, *Generation of Short Optical Pulses for Laser Fusion*, Final Report under P. O. #5241805 (UCLLL), Report #2451 (Microwave Laboratory, Stanford University); Lawrence Livermore Laboratory, Rept. #UCRL-13651 (1976).
59. D. J. Kuizenga, *IEEEOSA Conference on Laser Engineering and Applications*, June 1-3, 1977, (to be presented).
60. Subcontract 9660315 between the Regents of the University of California and Hughes Aircraft Company (1976).
61. C. F. Buhner et al., *Appl. Phys. Lett.* 1, 46 (1962).

Author

W. D. Fountain

2-2.5 Optics Procurement

The requirement for Shiva optics procurement is to obtain high-quality optics at reasonable prices and within schedule. A key factor is that the optical components purchased for Shiva are generally similar to those produced by industry for Cyclops and Argus lasers (lasers comparable to Shiva). At present, all major components for Shiva have been ordered; some have been delivered, either as prototypes or as part of the production run. The

procurement program has been highly successful to date, largely because of the commitment of qualified optical vendors and LLL's close interaction with them.

The Shiva laser system includes about 2000 optical components (of which 20% are spares), as well as several hundred components for laser and laser-target diagnostics. The cost of purchasing the optics (including booster stage, spares, and diagnostics) is about \$5 million, which breaks down as follows:

Unfinished glass	
Laser glass	42%
Rotator glass	8%
BK-7 substrate glass	4%
Optical finishing	26%
Optical coating	16%
Pockels cells	4%

Ongoing Development

Even though most of the basic components and manufacturing technologies for Shiva were closely related to those previously developed, additional improvements in optical components achieved during the manufacturing phase.

Edge-Cladding Improvement. A requirement for laser performance is the cladding of the edges of laser disks with an absorptive material for the suppression of parasitic modes. The larger the disks, the more effective the cladding must be. The formulation and application of solid edge-cladding has been difficult, as it must behave physically as if it were the glass to which it is applied—except that it must be highly absorptive at the 1.06 and 1.34- μm laser wavelengths instead of highly transparent. That is, it must have matching index of refraction and coefficient of thermal expansion over a considerable temperature range, have the correct transformation temperature region, and be resistant to damage from high-intensity flashlamp radiation. Previous claddings have been developed that achieved satisfactory mechanical characteristics but which evidenced enough index mismatch to allow internal reflection and parasitics in gamma (15 $\times$ 30 cm) and larger disks. With the efforts of LLL, Battelle Memorial Institute, Hoya, and Owens-Illinois, new index-matched cladding has been developed and reduced to a reliable production technology during the Shiva procurement. Versions of this edge-cladding are now being applied to Shiva

Fig. 2-80. Hoya FR-5 Faraday rotator glass, with quality indicated by oil-on-plate interferogram: of unfinished 22-cm blank (top). The reduced glass thickness reduces the beam break-up integral in a high-power laser chain. Photograph (bottom) shows a typical 22-cm blank, which has a Verdet constant of 0.070 min/g-cm at 1.064 μ m.

gamma and delta (20×40 cm) disks. With the new cladding, the index match is within 4×10^{-2} , for which the Fresnel reflection is less than 0.02%. Owens-Illinois' version of this cladding is known as EI-6, while Hoya's is called HBL-306.

Large FR-5 Faraday Rotator Disks. Previously, large-diameter Faraday rotator components had been manufactured from EY-2 and FR-4, with Verdet constants of 0.037 and 0.032 min/Oe-cm, respectively. Subsequently, FR-5 was developed and procured in small pieces. This material has a Verdet constant at 1.06 μ m of 0.07 min/Oe-cm. Because of the high Verdet constant, the FR-5 rotator disk can be about half the thickness of the previous components, with no increase in the magnetic field. The result is that the nonlinear beam propagation disturbance due to the rotator can be approximately halved, while the cost of an equivalent rotator remains about the same. We have specified this material for Shiva, and Hoya has now melted over twenty-five 22-cm-diam pieces. The pieces contain about 70% terbium oxide by weight. These parts are now being optically finished in the United States. In Fig. 2-80, an oil-on-plate interferogram of a prefinished 22-cm FR-5 part indicates the material quality being achieved.

Very Thin 20×40 -cm Polarizer Substrates. To reduce nonlinear beam propagation effects, we need to minimize the thickness of the BK-7 glass substrates for the delta size polarizers. These have a 22-cm-diam aperture projected at Brewster's angle, so the clear aperture on the part is 22×40 cm. To test the feasibility and economics of making the substrates thinner, we had two sets of prototypes manufactured (two 5 mm thick and two 10 mm thick). Perkin Elmer finished them to a wavefront transmission accuracy of 0.06 μ m peak to valley; then they were coated by the Optical Coating Laboratory with a dielectric polarizing stack (about 30 layers) on one side. After coating, the wavefront transmission at Brewster's angle for both thicknesses was essentially unchanged. We did observe, however, that the 5-mm-thick polarizer was significantly more difficult to handle and mount without introducing wavefront perturbations, so the 10-mm version was adapted for production. Previous 20-cm aperture polarizers had been 22 mm thick, so the new configuration, with two parts per beam at Brewster's angle, resulted in a glass path reduction of nearly 3 cm. In Fig. 2-81, an interferogram of one of the 10-mm polarizers is shown,

along with a photograph showing comparative thicknesses.

Thin Film Coating Development. As indicated elsewhere in this report (§ 2-4.10), we are beginning to investigate the correlation between laser damage and a variety of thin film variables. We are primarily interested in the long-range improvement of the damage threshold of new lasers (current damage thresholds allow a reasonable margin of safety for most locations as staged in the Shiva system). It is expected, however, that for high energy, 1- μ s pulses some of the input spatial filter lenses on Shiva may see uncomfortably high fluxes in relation to experienced antireflection (AR) coating damage thresholds. Because of this, we have tried to improve AR damage levels, with results just now being evaluated. Should improvements be demonstrated by these current experiments, they will be in time to be implemented for Shiva spatial filter lens coatings.

Glass Storage and Inventory Control

Within the last year, the Laser Program has set up an entire building for the storage, inventory, and control of all laser components for the various programs. The building will provide space for:

- Glass storage
- Inventory control
- Record keeping of test data
- Repairing and recycling damaged optics
- Miscellaneous services (marking, packaging, transporting and expediting)

With the handling of about 2000 optical components for Shiva, as well as those for Janus and Argus, the facility has become an essential part of the program.

Glass Storage. The facility includes a temperature- and humidity-controlled modular trailer with a floor space of 167 m² (1850 ft²). The area contains space for raw glass storage arriving from glass manufacturers as well as shelving to store finished components from all vendors for Shiva, Argus, Janus, and various development programs.

The facility has, in addition, packaging capability for components being sent to vendors, a small laminar air flow booth with inspection equipment, and a sand blasting station for serializing components.

Fig. 2-81. A 0.633- μ m double pass interferogram (top) of a transmitting Brewster's-angle polarizer with a 22-cm aperture. Because the polarizer is only 10 mm thick, it reduces the beam breakup integral. The bottom figure shows components of various thicknesses. Each has a coating on one surface that allows 98% transmission of P-polarized light while rejecting all but 0.3% of S-polarized light. Optical finishing was done by Perkin Elmer and coating was done by Optical Coating Laboratories.

Early in the Program, the requirement for special clean storage and transportation cases for all components was established. These cases are reusable, with modifiable interior configuration, and can accommodate from one to several components, depending upon size, with both safety and ease of handling.

Inventory Control. Probably the most critical and vital aspect of the storage facility is the inventory control system. The system has a cardex file system with an individual card for each component. The card system provides the following data:

- Each component is identified by title (i.e., rod, disk, spatial filter lens, etc.), condition, and next operation

- Each type of component is color coded and the corresponding storage containers have similar coding

- Part number, serial number
- Vendor and purchase order number
- Melt data
- Location in shelving (row, bin, and shelf)
- Disbursement information as to when the item was removed, why it was removed (e.g., inspection, installation, rework), and where it is presently located. For components installed in assemblies, the serial number of the assembly and the location is fed back to the record data.

Record Keeping. A second vital aspect of the facility is the processing and filing of all optical and mechanical test data either received from our manufacturers, processed in the LLL inspection facility, or both. All optical component shipments for Shiva include inspection reports generated by our vendors. Two sets of test data are filed, one in a permanent book kept in the facility and a second set in a file available to accompany the component. The data may include interferograms, melt data, birefringence, and coating performance.

Quality Control

With the advent of Shiva we decided to test and inspect as many of the laser optics and components as possible at the various vendor facilities. These source inspections are performed by qualified LLL employees who periodically visit the vendor facilities. This program was initiated for the following reasons:

- In general, 100% inspection and documenta-

tion of all important characteristics is required from the seller. Complete retesting would be duplication of effort. The documentation contains substantial information, including, for instance, interferograms of all completed optical components.

- The place to catch errors is at the vendors.

- The logistics of testing all the components for all important characteristics at LLL would require enormous duplication of equipment. Furthermore, the number of inspectors would have to be increased to handle peak loads. There are approximately 2000 Shiva optical components, and many of these would have to be passed through the system on more than one occasion (e.g., wavefront testing on final turn mirrors before and after coating).

- The less handling and cleaning cycles the components undergo, the better. Present procedures require the vendors to provide clean, specially wrapped parts. In general, these parts are not unwrapped at LLL until it is time for their use.

There are two areas where tests are not based on source inspection.

- The Shiva coating vendors currently cannot do after-coating wavefront tests on parts larger than about 10 cm; therefore, all after-coating wavefront tests on gamma or larger sizes will be conducted at LLL or separately subcontracted.

- Reliable laser damage tests are currently available only at LLL. All coating runs include witness pieces specifically designated for damage tests. Alternatively, the parts themselves may be tested at the periphery of the aperture.

The plan for source inspection of Shiva optical components has been implemented in the following ways:

- All drawings contain explicit test and documentation procedures and requirements.

- In general, the vendors' test equipment and procedures are reviewed by LLL personnel and upgraded as necessary.

- We are notified by the vendors at each major inspection stage so that we can be present. At such times, we may also selectively review the records.

- The LLL Optical Shop provides three full-time inspectors (to cover both source and in-house inspection), additional personnel for peak loads, and engineering and management backup. The Laser Program's Optical Material Management Group has been assigned specific responsibility for the coordination and management of the Shiva optical component quality control program.

- Inspection documentation is designed to provide all the information required by the user; for each component, one set of documentation remains on file in the laser optics depot and one copy accompanies the component.

In addition to verifying the wavefront quality and other important characteristics of each optical element after manufacture, it is necessary to ensure that the components, after mounting, retain satisfactory optical quality. It is particularly important, in the case of Shiva, to do this testing on each subassembly before it is placed on the space frame, because of the obvious impracticality of finding sources of wavefront errors after the entire system has been assembled without prior knowledge and documentation of the subassemblies.

The components most sensitive to mounting stress are, of course, reflecting optics, in which case the wavefront deformation caused is roughly twice the mechanical deformation, depending on the angle of incidence. The surfaces of transmitting optics compensate to first order for bending; however, higher order effects enter quickly when wavefront requirements are high. In addition to minimizing wavefront deformation, it is important to control the stress birefringence of transmitting optics, as the laser is staged in a manner highly sensitive to polarization. In the case of spatial filter assemblies, collimation as well as wave front testing is performed prior to assembly on the space frame.

To facilitate these subassembly tests, two 30-cm aperture interferometers have been placed in a Shiva assembly area. One is a dual mode 0.633- μm Zygo Fizeau instrument on a special, large bed, and the other is a 1.06- μm Twyman Green interferometer designed, and currently being assembled, by the LLL Materials Fabrication Optics Group. The base of this interferometer is an air-mounted granite slab 7.6 $\times$ 1.5 $\times$ 0.6 m weighing approximately 19 300 kg.

Technology Transfer

Among the areas of technology improvement and transfer, one which has been of particular significance to the Shiva program (as it will be also for future programs such as Nova), is in the advancement of continuous polishing flat lapping equipment for large, high-precision flat laser components. The basic technology has been known for some time; however, certain recent developments by

the LLL Materials Fabrication Department have resulted in increased productivity in industry:

- Temperature control of slurry to about $\pm 0.05^\circ\text{C}$ through recirculating mechanisms
- Control of lap and station speed through tachometer monitoring
- Improved pitch formulation
- Increased rigidity in machine base design

Through the interaction of our shop with industry in the last 2 years, the productivity of this type of machinery for very high precision work has been significantly improved, and industry has substantially increased its capacity in this area.

Authors

E. P. Wallerstein
F. T. Marchi
N. J. Brown
W. Allerton

2-2.6 Disk Amplifier Contamination and Damage

Ideally a disk amplifier, once set in operation, should function indefinitely with constant optical parameters and gains. In practice, however, we find two kinds of damage—glass damage and optically absorbing films—that degrade performance by scattering the beam or modulating the wavefront intensity. Glass damage results from contamination accidentally left in the amplifier during assembly or carried in by the nitrogen atmosphere, or from loose particles generated when a damage site is created (see Figs. 2-82 and 2-83). The net effect often is non-recoverable energy loss from the beam; the only remedy is to resurface the disk. Optically absorbing films, while not permanent, require rebuilding of the amplifier to remove them. The cost of rebuilding an amplifier and resurfacing the disks is several thousand dollars—ample financial incentive to solve these contamination-caused surface damage problems.

Contaminants

Potential Sources. Many potential contamination sources must be controlled during assembly, installation, and eventual use of a disk amplifier.

Fig. 2-82. Heavily damaged neodymium disk removed from Argus laser system (left) with typical damage site (right). Green-brown color of contamination is accurate whereas red disk color is from red background.

Table 2-24 lists common sources, together with a measure of their potential significance. For reference, the present cleaning methods are designed to clean all structural components to less than two particles with diameters greater than $5 \mu\text{m}/\text{cm}^2$ of surface area. This is an extremely stringent cleanliness requirement; therefore, all

potential contamination sources must be carefully scrutinized.

Contaminant Composition and Quantity. We have found that a typical amplifier cleaning process removes 200 to 500 particles ($>5\text{-}\mu\text{m}$ in diam) per square centimeter of surface area. An amplifier has approximately 10 m^2 of surface area; thus, there are potentially more than 10^7 particles that must be removed, examined, and analyzed. Obviously not all of these particles are unique; we have therefore attempted to catalog many of the known contaminants for later comparison with the unknown particles. Each of the known contaminants is also photographed to identify structural characteristics.

Table 2-25 gives typical chemical analysis of the contaminant particles. Most of them have a composition expected of material naturally occurring in the earth's crust. Typically, the particles contain aluminum, silica, iron, and calcium in the form of clays and minerals such as albeite, asbestos, and bauxite. After contaminant particles are flushed from the amplifiers, they are examined, microprobed, and photographed with a scanning electron microscope (SEM).

Table 2-26 lists 10 randomly selected particles flushed from a single amplifier frame. Their identification is complicated by the fact that no two particles are alike in composition. We have observed, however, that the majority of particles are composed of the most abundant natural minerals, implying that they are simply naturally occurring dirt and clays.

Fig. 2-83. Typical large damage site on neodymium disk showing fractured glass surface and cracked glass fragments adhering to edge of damage site.

Methods to Remove Contaminants. We performed a quantitative survey to determine the efficiency of various methods for removing loose particulate from glass and metal surfaces. Removal efficiency is defined as the initial particle concentration minus the final particle concentration, divided by the initial concentration.

Table 2-27 presents the results of this analysis. From these results, we have decided to use only high-pressure liquid spraying to clean the metallic surfaces of laser-disk amplifiers.

Figure 2-84 graphically illustrates the remarkably high particulate-removal efficiency of liquid sprays. In this analysis, a glass surface was artificially contaminated with aluminum oxide particles. The sur-

face was then cleaned in an ultrasonic cleaner, vapor-degreased, and finally spray-cleaned at 340 kPa. Even with this relatively low-pressure spray, the removal efficiency was substantially greater than the combined effect of ultrasonic cleaning and vapor degreasing.

SEM photomicrographs of metal surfaces before and after cleaning by high-pressure solvent spraying are shown in Fig. 2-85. This high-pressure spraying technique, using Freon TF and Freon TE solvents, is currently being applied to our laser components. After contacting the contaminated amplifier part, all spray effluent is passed through a membrane filter where the particles are collected. During the cleanliness validation stage, the membrane filter is

Table 2-24. Potential sources of contaminating particles (>5- μ m-diam) in disk amplifiers

Contaminating potential	Sources
<u>Cleaning and Assembly</u>	
0.5 particle/cm ² /24 hr	Airborne particles settling on clean surfaces in a Class-100 clean room.
5 particles/cm ²	Clean-room uniforms cleaned to ASTM F-51, Class A.
40 particles/cm ²	Clean-room uniforms after 1 wk of normal use.
25 particles/cm ²	Clean-room gloves.
1 mg/m ² dissolved residue	Lens cleaning tissue.
0.2 particle/cm ² /100-s exposure	Undissolved residue in cleaning solvents.
2 particles/cm ³ (>5-μm diameter)	
1 μg/cm ³	Dissolved residue in cleaning solvents.
2 particles/cm ²	Contaminants not removed during cleaning.
<u>Transportation and Installation</u>	
0.2 particle/cm ²	Nylon bagging material cleaned to KSC C-123E level 50A. ^a
1 μg/cm ²	
<u>Normal Operation</u>	
180 particles/cm ² /yr (Class 100 N ₂)	Airborne particles settling from the nitrogen atmosphere.
18 particles/cm ² (Class 10 N ₂)	

^aSpecification for surface cleanliness of fluid systems. John F. Kennedy Space Center, NASA, September 28, 1975.

examined under a microscope, the particles are counted, and that number is normalized to the area that was flushed.

Damage Sites. Generally, we have found that the quantity of damage sites per unit area increases linearly with use of the amplifier. The average value from the Argus laser system is 0.0010 damage sites (with diameters greater than 100 μm) per square

centimeter of disk surface per shot. After a typical 6-mo amplifier lifetime (corresponding to approximately 250 shots), the beam is obscured about 0.045% per surface or 0.54% per amplifier. This loss is definitely below the detectable level of our present calorimeters. However, if amplifier lifetimes on the Shiva system are to be extended to a minimum of 1 yr, even cleaner amplifiers must be built.

Table 2-25. Composition of typical contaminant dust particles ($>5\text{-}\mu\text{m}$ -diam) collected by air settling

Particle	Major ($>10\%$)	Minor (1-10%)	Trace ($<1\%$)
1	Si, Al	Ca, Na, S	Cr, Zn, Fe
2	Si, Al, P	S, Cl, Zn	—
3	Si, Al	Fe, Ca, Na, K, Ti, S	—
4	S	—	—
5	Al	Fe, Ca, K, S, Cl	—
6	—	—	Undetectable with x-ray microprobe
7	Si	Fe, K, Cl	—

Table 2-26. Composition of randomly selected contaminant particles ($>5\text{-}\mu\text{m}$ -diam) flushed from amplifier surface

Particle	Major ($>10\%$)	Minor (1-10%)	Trace ($<1\%$)
1	S, Zn, Cu	—	Al, Fe
2	Si, Al, Mg	—	Fe, K, S
3	Al	—	Si, Fe
4	Si, Al	Fe, Ca, K, Mg, Ti, S	Zn
5	Al, Cr	Si, Ni	—
6	Si, Al, Na	—	Fe
7	Al	Ca, Na, K, Cl	Si, Cu
8	Si, Al	Fe, Ca, K, S	Na, Cl
9	Al	Ca, K, S, Cl	Si, Na
10	Al	Si, Fe, K	—

Table 2-27. Experimentally observed efficiencies of various methods to remove contaminant particles ($\geq 5\text{-}\mu\text{m}$ -diam) from optically polished glass and rough metal surfaces

Method	Removal efficiency, %	
	Glass surface	Metal surface
Vapor degreaser and Freon TF solvent	11 to 28	—
Photon irradiation (flashing): 10 flashings each 20 J/cm ² for 800 μs	32 to 34	33
Compressed gas jet: 10 s at 690 kPa (100 psi)	—	52 to 61
Ultrasonic cleaning in Freon TF solvent for 1 to 2 min	69 to 92	85 to 90.0
Liquid spray of freon solvent: 5 to 10 s at 6.9 MPa (1000 psi)	99.8 to 99.95	99.5 to 99.7 (81 for $\geq 1\text{-}\mu\text{m}$ -diam particles)

Fig. 2-84. From this graph, it is obvious that the 6.9-MPa (1000-psi) high-pressure spray is very efficient in removing and carrying away particulate contamination from laser components. However, ultrasonic cleaning and vapor degreasing, two other commonly used cleaning methods, allow suspended particles to recontaminate the components.

Clean Assembly Rooms

Flashlamp energies of 20 J/cm² and laser-beam energies of 4 J/cm² cause serious damage to contaminated metal and glass surfaces. Therefore, laser amplifiers and components with high light energies incident on their surfaces must be assembled and operated in clean rooms.

The laser rooms must be operated as clean rooms. The degree of cleanliness of these rooms depends, to a great extent, on the room design and operating procedure of the particular laser system. Because all laser components are eventually opened to the laser-room environment, it is essential that this environment not compromise the cleanliness of the component.

The Building 381 clean room—3000 ft² in area—is used to maintain Argus, Janus, and Cyclops lasers as well as other special research lasers. The Building 174 clean room (Fig. 2-86) covers 1650 ft² and is used to assemble the Shiva beta-disk amplifiers. This horizontal-flow room has High Efficiency Particulate Air (HEPA) filters on one wall and return-air filters in the opposite ceiling. The room functions as a Class-100 room without activity and at less than Class 200 during working hours. The horizontal-flow rate is maintained at 100 ft/min. Working procedures, access,

(a)

(b)

Fig. 2-85. Scanning electron micrographs of a rough aluminum surface artificially contaminated with aluminum oxide particles (a) and then cleaned (b) with a 6.9-MPa (1000-psi) liquid solvent (Freon TF) spray.

and personnel are more tightly controlled in this room than in the Building 381 clean room.

The Shiva clean room in Building 391 is LLL's first clean room to have been specifically designed for this function. This 3150-ft², Class-100 room is located adjacent to the laser bay (see Fig. 2-87). It is a vertical-flow room with an air velocity of about 100 ft/min. Two amplifier assembly fixtures are

currently installed in the room; a third will be moved from Building 174 in the near future.

Special features of the Shiva clean room include a tube-washing machine to clean the amplifier quartz-shield tubes. A large polypropylene sink with distilled and domestic water taps is available for cleaning many components. A high-pressure (up to 10.3 MPa), Freon solvent-spray system, and a glove box have been installed. A cleaning-solvent recovery

Fig. 2-86. Shiva disk amplifiers presently are cleaned and assembled in this clean room. The high-pressure spray box is located to the right and two assembly fixtures are shown in the background. The assembly fixtures have been designed to handle all three sizes of Shiva amplifiers.

Fig. 2-87. The Shiva laser, Class-100 clean room in Building 391 is not yet complete. When finished, this room will maintain all Shiva components that are sensitive to contamination.

and distillation system is also designed into the room. Freon is recovered from the high-pressure unit, distilled, and filtered before reuse. Water for the sink and quartz-shield tube washer is distilled and filtered before use. In addition, a Zygo Interferometer is available to inspect assembled disk amplifiers. Finally, the room is equipped with the necessary instruments to count and identify the removed contaminants.

Amplifier Cleaning and Assembly

The Shiva laser employs three sizes of disk amplifiers—beta, gamma, and delta. All amplifiers

have the same configuration, the same overall length, and the same mounting bearing that mates them to the Shiva space frame. Figure 2-88 shows the diagram of the assembly of the Shiva disk amplifiers. The amplifier assembly fixture (Fig. 2-89) was designed to employ readily interchangeable plates and V-blocks so that all sizes of disk amplifiers could be assembled.

Before assembly, all components of the amplifier are cleaned and subjected to rigorous cleanliness validation tests. For the initial cleaning, the amplifier core is electropolished and chemically polished; both steps remove 0.0005 in. of core material. This ensures smooth surfaces, devoid of

Fig. 2-88. In the assembly of Shiva disk amplifiers, all metal parts are subjected to an acid bath and electropolishing to remove surface oils and other contaminants from the machining processes. A high-pressure spray (6.9 MPa) of Freon is then used to remove loose surface particulate. Disks are cleaned and inspected with alcohol and acetone on lens tissue. All flashlamps are pretested to ensure reliability and are cleaned with the high-pressure spray after assembly. Quartz tubes are automatically cleaned in a low-pressure spray booth with distilled water and Freon. All components are then assembled and the optical quality of the total laser assembly is checked and recorded with a Zygo interferometer. The assembly is then installed on the space frame.

asperities and crevices in which contaminants are trapped. This process also removes any traces of manufacturing oils and oxides.

For the final cleaning, each part is placed inside a glove box equipped with a high-pressure spray gun. The parts are sprayed manually with Freon TE at 6.9 MPa (1000 psi). Figure 2-90 shows the high-pressure spray system in Building 174.

For cleanliness validation, the spray-solvent effluent is passed through a 2- μ m filter and the collected particulate is counted. Amplifier pieces are cleaned until there remain fewer than two particles/cm² with diameters greater than 5 μ m of cleaned surface area.

The Nd:glass laser disks are cleaned with ethanol and acetone. They are first scrubbed with lens tissue and cotton balls. For the final cleaning, a lens tissue saturated with solvent is drawn across the surface. Final inspection and cleaning is accomplished with a high-intensity light and a vacuum probe.

The quartz blast shield, which surrounds the laser disks and rail weldment, is cleaned with detergent and distilled water and then blown dry with nitrogen. Then it is sprayed with Freon TE (in the high-pressure spray box) until there are fewer than two particles (>5- μ m-diam) remaining per square centimeter of cleaned surface area. An automated system for cleaning the quartz blast shield is being installed. For this system, the blast shield will be enclosed in a chamber for a cleaning cycle including a

Fig. 2-90. This high-pressure spray cleaning system, operating at 6.9 MPa (1000 psi), can clean Shiva amplifier components in about one-fourth the time required by other cleaning techniques.

detergent wash, distilled-water rinse, nitrogen dry, and Freon TE spray.

The last major subassembly of the amplifier involves the flashlamp covers. For initial cleaning of the individual parts, the high-pressure spray system is used. The lamps are then assembled into their covers, and the entire assembly is again high-pressure sprayed and validated.

Authors

H. G. Patton

I. F. Stowers

W. A. Jones

D. E. Wentworth

Fig. 2-89. This type of assembly fixture is able to handle all three sizes of Shiva amplifiers. An amplifier can be assembled in less than 4 hr with this fixture. The cart is used to transport the assembled amplifiers directly from the assembly fixture to the Shiva space frame.

2-2.7 Spaceframe

The skeleton that supports the mirrors, amplifiers, and other components of the Shiva laser system is a three-dimensional optical bench made of square steel tubing (see Fig. 2-41). This framework must remain relatively immobile regardless of static loading, thermal changes, stress relieving, or vibration. Since the entire building will act as a Class-10,000 clean room, the support for the system must be an open structure that will allow a rapid air flow around the components to remove dust. A pervious mounting region is also needed to facilitate heat

removal by convection, and the components must be accessible for maintenance. Because staging of laser amplifiers for maximum power may be modified, component mounting systems must be adaptable to a variety of configurations.

The Shiva support structure was designed as an open spaceframe to facilitate air flow, component access, piping and cable connection, and cost-effectiveness. Square steel tubing was chosen for the structural members because it provides flat surfaces for mounting hardware, eases fabrication of welded joints, and has good stiffness characteristics. The spaceframe is many times stronger than necessary to keep the stresses below the allowable limit because the design criterion was structural stiffness, not strength.

Construction

The Shiva amplifier and target frames were shop-

fabricated in large modules. Prefabrication allowed the work to proceed concurrently with the building construction. The modules were ready for installation on July 26, 1976.

Fabrication and installation were trouble-free and very successful. A model of the more complex target frame structure was made to one-twelfth scale to check dimensions, interferences, and other engineering data. This model helped ensure an error-free assembly.

Shop fabrication techniques were well controlled to assure good fit when the modules were assembled. Flat panels of the frame were welded using fixtures on large flat tables; these fixtures ensured accuracy and good dimensional control. Modules were prefitted before shipment to ensure proper matching at installation. Excellent rigging practices also expedited installation. Strict attention was paid to machining the joints for good fit. Each cut piece

Fig. 2-91. Installation of the higher target frame required approximately 62 modules to be welded together. Three hundred tons of square steel tubing were used in both frames, requiring over 13,000 welds.

of square steel tubing was laid into the fixture, clamped rigidly in place, and welded.

The laser frame (Fig. 2-91) was installed first, followed by the target frame, Fig. 2-92, which was completed in September 1976, except for painting which was delayed because of minor additions to both frames. Distortion due to field welding was held to a minimum by proper balancing of weld deposits and by mechanically vibrating the frame during welding.

When installation was completed, tolerances were inspected and showed full compliance with specified dimensions. This inspection was done in November 1976. Work remaining on the laser frame involves installation of the honeycomb table top for the oscillator and front-end hardware and installation of component cradle shim plates. Work remaining on

the target frame involves construction of final turning mirror platform supports and personnel platforms.

Two major structural mirror supports for the final turning mirrors also support the pointing, focusing, and centering sensors (see Fig. 2-93). Five other personnel platforms are located at convenient locations. The target chamber is supported top and bottom by five brackets. These brackets and all other platforms extend from and are anchored to the nose of each of the five target frame towers.

Figure 2-93 shows the beam tubes, through which the beam travels from the first mirror to the second mirror and then to the target chamber caps which house the lens positioners. Transparent plenums allow for easy maintenance and accessibility.

Fig. 2-92. Installation of prefabricated modules of the laser frame. Approximately 34 modules were welded together for this frame.

Fig. 2-93. Target space frame. Twenty laser beams converge on the target, ten from above and ten from below. The final turning mirrors are supported by very rigid platforms shown just above and below the final beam turns.

Stability

The spaceframe design for Shiva has shown through a variety of analyses and measurements that it is an ideal structure for supporting large laser systems. A finite-element computer program, SAP IV, was used to determine the static and dynamic characteristics of the system. Vibration measurements were made after construction was completed. Air conditioning fans were operating, but no construction activity was taking place.

Natural frequencies, mode shapes, and ambient vibration were measured using velocity meters in conjunction with the TDAC system (computer-based Transportable Data Acquisition and Control). Velocity meters were placed at critical locations, and the frame was struck at other locations

with a hammer that contained a force transducer. The natural frequencies associated with motion of the frame are derived from the transfer function as shown in Fig. 2-94. The velocity data were processed and integrated to provide displacement information. The target frame rotation was less than ± 0.3 mrad and was predominantly due to the 3.8-Hz mode with a contribution from the 11.8-Hz mode. Relative motion between the amplifier frame and the target frame was less than ± 3.0 μm in the north-south axis (perpendicular to laser beams), ± 2.5 μm in the east-west axis, and ± 1.4 μm in the vertical axis, due basically to the 3.8-Hz mode of the target frame. Relative motion between the two ends of the amplifier frame was less than ± 1.2 μm in the north-south axis, ± 0.16 μm in the east-west axis,

Fig. 2-94. Lateral natural frequencies of the target frame. The principal oscillation frequencies are around 4 and 12 Hz.

and $\pm 0.7 \mu\text{m}$ in the vertical axis. The dominant frequencies were between 10 and 20 Hz.

Thermal motions of the spaceframe will be limited by the strict specification of the building environment. The temperature cannot drift more than $\pm 0.5^\circ\text{C}$ in a period of 15 min or less, the floor-to-ceiling differential will be less than 1°C , and the vertical air flow will provide a complete air change every 20 s. Measurements of the building with the spaceframe installed show that these requirements have been met and exceeded.

Supports for the spaceframe are designed to accommodate thermal expansion when the air temperature changes. Roller-bearing supports allow the frame to expand accurately. Actual measurements have confirmed that the frame expands and returns to its original position without excessive strain.

Beam Splitters and Folding Mirrors

The laser beam from the oscillator is divided by beam splitters clamped to rails located in a vertical array on the side of the space frame. They are in mounts which have angular adjustments in two directions and can be positioned anywhere along the rails.

The beams leave the splitters and are directed toward two mirrors positioned at 45° angles that fold the beam 180° to point down the laser chain. One of the 45° mirrors is positioned in both angular directions by stepping motors. The assembly is mounted on a plate positioned on rails over a distance of 30 cm to provide a coarse adjustment for

equalizing the beam-path lengths. Fine adjustment is accomplished by driving the mounting plate through a range of 6 cm along the same rails with stepping motors. This fine adjustment has a least-count resolution of $3.2 \mu\text{m}$.

Cradles

Staging of laser chains for maximum power may be modified; thus, component mounting systems must be adaptable to a variety of configurations. The cradles supporting all components are basically V-blocks at each end of each component, which are adjustable in the x and y axis. Once adjusted they are fixed and cannot be moved until a portable adjusting fixture is used. They can also be repositioned along the axis of the frame by sliding the shim plate to a new location and locking it. The cradle hardware is made of hard, black, anodized cast aluminum. Figure 2-2 shows an example of a typical component support. The component can be rotated in its cradle for polarization setting. Arms that clamp the components in place can be swung out to allow the component to roll clear for crane handling. Cradles are designed with the same stability criteria as the frame and have damping features at the frame interface for shock loads from flashlamp firing and magnetic pulses.

Gas System

Gas cooling is required to allow Shiva to be fired every two hours. The laser is heated when the lamps

are fired, and the glass disks become optically distorted. Clean, filtered cooling gas is passed separately over the disks and lamps. Nitrogen is delivered in liquid form to a large storage tank and vaporized when required by a heat exchanger in the main supply line. The gas passes through a coarse filter and then to two control consoles for each side of the amplifier frame. Control consoles contain remotely operated valves which permit the choice of high, low, or zero flow. They also contain pressure regulators that effectively control the actual flow rate, since the fine filters adjacent to the laser components have an approximate linear relation between pressure and flow. Downstream of the controls, individual manifolds are provided in parallel with each laser chain, supplying all components in the chain including the beam pipes to the target. Laser chains can be selectively supplied by means of a manually operated valve on each manifold. The gas passes through fine filters adjacent to the laser components. Separate circuits and filters are provided for the lamp and disk cavities on the amplifiers.

In several instances, the disk cavities are directly connected to corresponding cavities in other components. In these cases the gas is allowed to pass through several components before flowing to an exhaust; thus the supply goes to sections of each chain rather than to individual components, permitting better control of the flow and avoiding dead spots in the system. Additional manual valves control these individual sections of each chain. Coarser filters are provided at the exit points of the component to prevent dirt from entering during possible backflow and also to provide further pressure control. The gas finally passes through larger ducts and is exhausted outside the building. Pressure switches and gauges, and relief and check valves are provided at appropriate locations. Temperature sensors will be provided at various points in the system. All flow velocities are designed low to avoid vibration problems and to allow for possible later increases in flow rate.

The largest amplifier in a Shiva chain, the δ amplifier, has an energy input to its lamps of 260 kJ per shot. Almost all of this energy must be removed by the cooling gas. Flow rates of 5.2 standard (SCFM) ft³/min for the lamp cavity and 2.6 SCFM for the disk cavity have been chosen as adequate for the maximum cooling rate required immediately after a shot. After most of the heat has been removed, the

second control circuit reduces this to between 10 and 20% during maintenance. Prior to the next shot, the flow is turned off and the gas is allowed to become stagnant. Flow to the other amplifiers and the rotators on Shiva is proportional to the amount of energy dissipated in each component. The maximum flow velocity through a typical amplifier is only about 0.1 ft/s. Total flow to all components in Shiva is 44 SCFM/chain and 880 SCFM for 20 chains.

Author
C. A. Hurley

2-2.8 Power Conditioning

The final design and construction of the Shiva power conditioning system^{62,63} has evolved through the extensive experience gained from the Janus, Cyclops, and Argus lasers as well as from the numerous systems developed for specific experimental applications. Several new features have been incorporated into the Shiva design—a digital-based control and diagnostic system, high-energy-density capacitors, and cost-effective modular production and installation techniques. Figure 2-95 shows the chronological development of power conditioning systems for the solid state laser program over the past four years.

Significant technical and manufacturing ingenuity exists in outside industry and this expertise has been applied profitably to a range of problems relevant to our power conditioning systems. For example, several energy-discharge-capacitor firms in this country have developed a high-energy-density capacitor⁶⁴ for roughly half the cost of the 14.5- μ F unit selected for our first lasers. These new capacitors are used in the Delta rotator banks and have resulted in a substantial cost savings. Also, many components within the capacitor bank system either have been improved in quality or reduced in cost because outside industry was able to identify similar components that already were developed and would fulfill our requirements.⁶⁵ In addition, continued developmental efforts by flashlamp vendors have yielded lamps of vastly increased reliability for lowered cost. This close coordination

with industry has enabled us to construct a high-quality, low-cost power conditioning system for the Shiva laser.

A notable innovation in this system design is the implementation of a computer-based control and diagnostic system (see Fig. 2-96). The first-level

Fig. 2-95. Chronological development of the power conditioning systems for the solid state laser program.

functional elements are LSI-11 microprocessors plus a digital data bus that addresses all control and diagnostic elements in the power conditioning system.

There are obvious hazards associated with the use of low-level digital circuitry in close contact with pulse power equipment. If high-voltage transients are allowed to couple to low level digital components, there is little doubt about the result. With this in mind, we employed two levels of optical isolation. A 60-kV level is maintained between the data bus and any control or diagnostic element in the system. The data bus is routed through the bank and laser areas in a steel cable tray to minimize stray-field coupling. This control system has been successfully tested on the 600-kJ Shiva prototype bank (see Fig. 2-97).

The preionization lamp check (PILC) was implemented successfully for the first time in the Argus laser. This check enables us to detect faulty flashlamps before catastrophic failure occurs in an amplifier. This is particularly important for Shiva because this laser uses large numbers of lamps (about 2500). The collection, organization, and display of PILC data is accomplished with the digital-based control and diagnostic system.

Because instantaneous power levels during the discharge of the Shiva banks approach 60 000 MW, it is essential to design a grounding and fault protection scheme to minimize coupling of the pulse power system to the numerous low-level control and diagnostic elements within the laser. The important features of this design include a single-point, pulse

Fig. 2-96. Diagram of the Shiva power conditioning control system. A digital-based control system will be implemented for Shiva power conditioning. Two levels of optical isolation are used to ensure that low-level circuitry is protected against possible destructive coupling from the pulse power equipment.

Fig. 2-97. The 600-kJ Shiva capacitor bank (a) and the control system prototype (b). A 600-kJ segment of the Shiva bank and control system has been successfully tested at full energy levels for many thousands of pulses.

power ground located at the amplifiers, fused individual bank modules at levels below 30 kJ that prevent rupturing of the capacitor cases in the event of a major bank fault, and carefully routed pulse power cables that minimize displacement-current coupling to the building and the laser spaceframe.

In addition, we also discuss the significant features of the Shiva staging and layout, the assembly of prototype capacitor banks, the Pockels cell drivers, and the flashlamps. The many unique characteristics of the Shiva laser are the result of much experience gained on smaller LLL laser systems and as the system activation is completed, we will finally have an indication of the extent of Shiva's capabilities.

Authors:

W. L. Gagnon
P. R. Rupert
R. W. Holloway

Staging and Layout

The selection of the final distribution of capacitor bank modules, charging power supplies, and switches for the Shiva power conditioning system was heavily influenced by the following design constraints.

- Limit maximum bank-charge time to less than 1.5 min.
- Charge and switch as much energy as possible with a given power supply and switch, consistent with the requirement of beam-to-beam energy balance and component limitations.
- Develop a physical layout to fit within the given space, minimizing load cable lengths and maintaining a common length for all cables associated with a given amplifier.
- Maintain a spatial and operational symmetry consistent with the operational or energy-balance needs of individual beam bunches.

Capacitor bank charge time must be limited to less than 1.5 min to ensure that only a minimum of capacitor failures occur during a system life of 10^5 shots. Total capacitor life is determined by the total integrated time at dc voltage, the number of faults, and the number of normal discharge pulses. Because a large number of faults causing high-voltage reversal is not anticipated, this factor carries little weight in the life consideration. The time at dc voltage and the number of discharge pulses are the dominant factors that determine the end-of-life characteristics for the capacitor.

A large capital investment in power supplies would be necessary if we desired to reduce the bank-charge time substantially below 60 s. Consequently, the total supply capability of the Shiva system is a compromise that allows a nominal capacitor life to at least 10^5 operations for a reasonable monetary investment in power supplies. (All supplies in the system are identical and are rated at a nominal 25 kV, 100 kVA.)

This approach ensures component commonality, flexibility, and ease of maintenance. A small cost penalty is associated with this approach when it is

compared with a solution that exactly tailors each supply capability to its load. The number and distribution of power supplies is shown in Fig. 2-98. Our arrangement enables the maximum utilization of space and volume and is consistent with the need to minimize total cable lengths and keep cables connecting a given amplifier a constant minimum length. This avoids the possibility of differential gain pumping with an amplifier as a result of unequal cable losses.

The specific requirements for spatial and operational symmetry are best seen in Fig. 2-99. The 20 output beams from the laser are divided into two clusters; 10 beams enter the top of the target chamber and 10 beams enter the bottom. Each 10-beam cluster consists of five inner and five outer beams. It is desirable to be able to balance the energy as a unit, top and bottom clusters and inner and outer beams. These requirements are met by distributing charging power supplies as shown in Fig. 2-98.

The 20 α rod amplifiers have four power supplies arranged, so that each inner and outer beam group (both top and bottom) can be independently adjusted for energy balancing. The remaining power

Fig. 2-99. Spatial symmetry of the 20 Shiva output beams. In (a) the arrangement of beam clusters as they enter the target chamber. Here, odd-numbered beams are on the inside and even-numbered beams are on the outside of the cluster; factors of 10 oppose (i.e., 3 $\leftrightarrow$ 13, 8 $\leftrightarrow$ 18). In (b), the laser arms are numbered as they appear on the laser spaceframe. The power conditioning system is staged so that the top and bottom as well as inner and outer beam clusters can be energy-balanced.

Table 2-28. Power conditioning system characteristics of the Shiva optical elements. All elements in the system operate at a nominal 20 kV. Switching is accomplished with dual size-"D" ignitrons. All charging power supplies are identical with a voltage rating of 25 kV; 100-kVA high-density capacitors are used in the delta Faraday rotator stages

Component	No. heads	Lamps per head	Circuits per head	No. of circuits	No. of switches	Circuits per switch	No. of capacitors	Size of capacitors (μ F)	Capacitors per circuit	No. of power supplies	Maximum voltage (kV)	Maximum energy (kJ)
α rod oscillator	2	6	1	2	2	1	14	14.5	7	2	22.2	25
α rod diagnostic	1	6	1	1	1	1	7	14.5	7	1	22.2	25
β rod oscillator	1	6	1	1	1	1	10	14.5	10	1	23.5	40
β rod splitter	4	6	1	4	1	4	40	14.5	10	1	23.5	40
β rotator splitter	4	0	1	4	1	4	28	14.5	7	1	20.0	21
α rod	20	6	1	20	4	5	140	14.5	7	4	22.2	25
β rod	20	6	1	20	2	10	200	14.5	10	2	23.5	40
β rotator	20	0	1	20	1	20	168	14.5	7	0	20.0	21
β amplifier	60	16	8	480	24	24/16	2880	14.5	6	6	20.8	150
γ amplifier	20	24	12	240	12	24/12	1440	14.5	6	4	19.6	200
δ rotator	20	0	5	100	8	15/10	800	23.0	8	4	20.0	200
δ amplifier	20	32	16	320	12	32/16	1920	14.5	6	4	19.3	260
Total	192			1212	69		7647			30		
					+ 6 (PILC)					+2 (1 spare, 1 PILC)		
					75					32		

supplies are distributed to allow for top and bottom adjustment only. The four β rod amplifiers in the splitter array share a common power supply. Each of the rod amplifiers on the oscillator table has a separate power supply. The RG-217 coax cable used in the pulse power system has an impedance of approximately 1.5 m Ω /ft at 1 kHz. The maximum cable length from bank to load is 150 ft. Under these conditions, the cable resistance absorbs about 5% of the load energy.

Because the capacitor bank area is not placed symmetrically under the laser space frame, cables to the south laser arms are longer than those to the north arms. However, this difference can be easily compensated by setting voltages on the south arm power supplies slightly higher. Cables within the bank area, as well as from the banks to the amplifiers and rotators, are routed to minimize the displacement current coupling. Table 2-28 shows the power conditioning system characteristics as associated with the Shiva optical components.

Authors

K. Whitham

P. R. Rupert

R. W. Holloway

N. L. Gagnon

Pulse Power Grounding

Very high peak power levels are generated during the energy transfer from the capacitor banks to the flashlamps and to the Faraday rotator coils.⁶⁶ Clearly, it is essential that this energy transfer occur with minimal effects on the many low-level control and diagnostic systems.

Many potentially destructive coupling paths exist between the pulse power system and the control and diagnostic circuitry. We have examined each of these coupling modes and the final design and location of the pulse power circuitry and laser system grounding reflects attempts to eliminate the damaging coupling to low-level system components and to ensure personnel safety.

Personnel Safety. Safety is a foremost consideration in the pulse power system design. Although the hazards of similar high-voltage capacitor banks developed for the MFE and accelerator communities are well known, the laser system energy storage banks present new and unique problems.

The banks are required to deliver energy to a large number of relatively small elements distributed throughout the laser bay. Thus, the potentially hazardous voltage and energy levels are extended from the bank room to almost every point in the laser room. A further problem arises in routing and terminating the large number of high-voltage coax cables that distribute the bank energy to the numerous flashlamp and Faraday rotator loads.

In addition, low-level control and diagnostic elements are located in proximity to pulse power loads at many locations in the laser system. This requires that special attention be given to the degrees of fault isolation implemented within the pulse power circuitry.

The pulse power circuitry and low-level equipment are isolated. A coaxial configuration for the pulse power system is maintained wherever possible. In addition, the laser amplifiers and the total system grounding concept are designed so that the possibility of a capacitor bank fault extending outside the power conditioning system is minimized.

Personnel safety from high-voltage bank hazards is ensured by excluding entry to either the bank room or the laser bay during system operation. This is achieved with a redundant, hardwired door-interlocking system and a carefully structured operating procedure including a careful search and audible warning of both areas before beginning operation.

Authors

N. L. Gagnon

P. R. Rupert

Grounding. During the pump pulse, a voltage drop is generated along the coax cables running from the capacitor banks to the flashlamps. This voltage drop is several hundred volts during a normal pulse but can be as high as several kilovolts under high-current fault conditions. The voltage drop occurs as the result of the resistive component associated with the impedance of the coaxial center conductors and shields and places two important constraints upon the design.

The system can have only one hard ground point. If hard grounds were located at the laser amplifiers and the capacitor banks, the potential developed along the cable shields would force a large, undesirable circulating current to flow through the

Fig. 2-100. Pulse power grounding. A low-impedance, single-point ground is established at the laser amplifiers. Flashlamp reflectors are insulated from the amplifier outer cases to act as electrostatic shields between the pulse power circuitry and the laser spaceframe. Displacement currents from the pulse power system are contained in a ground-return buss that is separated from the building ground grid.

Fig. 2-101. Photograph of a Shiva amplifier illustrating the insulator between the flashlamp reflector and the outer case.

ground return conductors. Also, because this potential drop exists along the coaxial shields, care must be taken to prevent displacement currents from coupling from the shields to the laser spaceframe at points where the two are in proximity.

Given these constraints, the design shown in Fig 2-100 has evolved. Here, the pulse power ground is located at the laser amplifiers to ensure minimum effects from cable voltage drops. Furthermore, the amplifiers are designed so that the flashlamps and flashlamp reflectors are insulated from the outer cases (see Fig. 2-101). The shield-reflector combination is routed to a separate ground bus that is insulated from the spaceframe and is tied directly to a system of earth rods at the substation.

Thus, displacement currents generated by the pulse power system are, for the most part, contained within the power conditioning system. In addition, should an arc occur from lamp to reflector, the fault resulting current returns along the cable shields and does not couple to other components on the spaceframe. In effect, the reflectors act as electrostatic shields between the high-voltage circuitry and the spaceframe.

Authors

N. L. Gagnon

B. M. Carder

Fault Protection

Ignitron Switches. Dual size-"D" ignitron switches are used throughout the system. Each

Fig. 2-102. Dual size-"D" ignitron switch. This switch unit is used throughout the system. Two size-"D" ignitrons are employed in a coaxial arrangement. Each switch unit passes a peak current of 150 kA and is able to handle a total charge transfer of 70 C.

Fig. 2-103. Ignitron switch trigger system. To ensure triggering reliability, two independent ignitors are triggered in each tube. Each trigger chassis receives an input signal from the data bus through the bus interface unit (BIU).

switch consists of two ignitrons in series to ensure a reliable voltage holdoff at 25 kV. These switches operate at 25 kV, 150-kA peak current, and 70-C total charge transfer (see Fig. 2-102).

In previous systems,⁶⁴ high-level trigger pulses were distributed from a common trigger chassis to a number of switches. However, this resulted in high-frequency noise coupling back along the trigger cables. This noise can then be coupled to other elements in the system, causing them to trigger prematurely.

For the Shiva switches, the high-level ignitor triggers are generated locally within each switch rack (Fig. 2-103). Two independent trigger circuits are used for each tube to ensure reliable triggering; each trigger circuit drives a separate ignitor within the tube.

Each trigger chassis receives an input signal from the computer through the interface chassis. This permits the adjustment of trigger times with the computer program to suit the various components online. A single SCR switches a 2- μ F capacitor charged to 1.5 kV through a 1- to 1.7-pulse transformer, creating a 2.5-kV, 400-A pulse to the ignitrons. The pulse transformer is isolated primary to secondary to 60 kV and has an electrostatic shield to reduce the coupling of ignitor noise to the trigger circuitry. The SCR is operated at less than 70% of its rated voltage; over one million test shots have

Fig. 2-104. Ignitron trigger circuit. A single SCR switches a 2- μ F capacitor charged to 1.5 kV through a 1- to 1.7-pulse transformer. This provides a 2.5-kV, 400-A pulse to the ignitor. The pulse transformer is insulated primary-to-secondary for 60 kV and includes an electrostatic shield to reduce noise coupling to the primary circuit.

been made in various test configurations to ensure a reliable operation (see Figs. 2-104 and 2-105).

Authors

N. L. Gagnon

K. Whitham

M. M. Howland

Power Supply. The controls for the 100-kVA power supply shown in Fig. 2-106 have been modified for Shiva. One of the changes involves the isolation of the control circuitry. Because the system has a single-point ground at the amplifier, the power supply secondary circuitry sees a voltage rise

Fig. 2-105. Ignitron trigger package. High-level ignitor triggers are generated locally within each switch rack.

equal to the cable drop during the pulse. All circuits tied to the secondary circuit therefore have been isolated with transformer-coupled, highly linear isolation amplifiers with 5-kV isolation voltage. A 2.5-kV spark gap is placed between the secondary common and ground in the event of a fault. The common-to-ground voltage during normal pulse conditions is a few hundred volts.

Isolation diodes and fuses (Fig. 2-107) were also added to the power supply. Because one supply feeds up to four ignitron switches, the switches must be isolated from each other to prevent large fault currents. If, for example, there are four switches each with 32 circuits tied to one power supply and if one switch prefires, the other three sets of circuits (96) try to dump through that switch. The isolation diodes prevent this. If the diodes fail, the fuses open. For another example, if a short occurs in the power supply, the isolation diodes and fuses prevent the circuits tied to the supply from dumping into the short. These diode and fuses are unquestionably essential protection elements.

Tests have revealed that a high resistance must be placed across the diodes to achieve the proper power supply regulation. Without this resistance, when the supply reaches voltage, the diodes stop conducting and the load impedance jumps from a few kilohms to megohms. This nonlinear load changes the pole-zero locations in the regulator and causes an instability. However, 20-k Ω of bypass resistance solves this problem without opening a significant path for a fault current.

Fig. 2-106. The 100-kVA capacitor bank-charging power supply. The three-phase, full-wave voltage doubler developed for the Argus, Janus, and Cyclops lasers will be used for Shiva. The control and diagnostic interfaces have been redesigned to be compatible with the digital-based control system.

Another change in the power supply is the addition of the computer interface. In brief, the layout of the supply was modified so that all low-level electronics are located in one shielded area to prevent noise from coupling to the data bus.

Authors

K. Whitham

M. M. Howland

Capacitor Bank Assembly and Testing

The assembly of the Shiva capacitor bank represents a sizable production run of its various sub-assemblies. The capacitor circuit requires the largest number of subassemblies—1200. These involve the assembly of 7000 capacitors, each weighing about 70 kg into individual modules (Fig. 2-108) in a production line (Fig. 2-109). Incoming materials are prepared and stored in the area adjacent to the assembly. Capacitors are removed from storage cartons, brought in on pallets, and stored on their side to help identify leaky bushings before they are installed.

Fig. 2-107. Power supply isolation scheme. As many as four switch-bank modules are charged from a common power supply. In the event of a fault at the supply or a prefire of one ignitron switch, isolating diodes and fuses prevent all parallel bank modules from discharging into the fault or through the single switch.

Fig. 2-108. Capacitor module. The Shiva capacitor bank consists of over 1200 individual modules. Each module is easily assembled on the production line, tested at full energy, and properly positioned in the racks.

Fig. 2-109. Capacitor module production line. Modules are assembled on sleds as a complete unit.

Fig. 2-110. Test area for capacitor modules. After assembly and before installation, 16 modules are tested at one time at full energy levels to identify infant mortality failures.

The capacitors are then loaded onto sleds with a crane. Because of their bulk and weight, handling of these pieces is always mechanically assisted. The sleds are assembled at one of five work stations using precut, predrilled, or prefabricated subassemblies and air-wrenches. The sleds at this point are on carts equipped with crowbar circuits; thus the circuits can be wheeled into a test area, separated by shrapnel barriers from assembly, and hooked up to a power supply, switch, and dummy load for test. A three-stage inspection of mechanical, electrical, safety features is conducted at this point.

Sixteen circuits are tested at once. They are first brought up to 23 kV and held for 5 min, stressing the capacitors to eliminate infant failures. The circuits are then pulsed 70 times at 23 kV into dummy loads. Charge and fire time is 20 s; delay time is 150 s. At the end of the test cycle, after the circuits are shorted, each circuit is inspected to detect any leaking capacitors or loosened or broken hardware. Faults during the test are detected by pulse current monitors on each circuit. If a circuit fails to fire, a detector circuit drops the system out. The test area is shown in Fig. 2-110.

A traveller keeps statistics on each circuit, recording the capacitor, and inductor serial number, and values in addition to test results. Any component replacements or comments are also recorded to provide a complete history of the circuit. A copy of this record is kept with the circuit and another copy is filed.

Circuits are loaded onto shelves with the CLEM (Capacitor Loading and Equipment Module) shown in Fig. 2-111. CLEM permits convenient and safe handling of the 2860-kg device and permits later servicing of individual circuits by direct replacement. The time required for CLEM to install a bank circuit is about 15 min for the top shelf and 10 min for a bottom shelf.

Authors

K. Whitham
R. W. Holloway
E. A. Ataidee
J. M. Cothey
R. D. Demaret
M. M. Howland
D. L. Johnson
C. J. Nelson
E. H. Padillo
T. A. Pelley

Fig. 2-111. Capacitor loading and equipment module (left). Circuits are loaded onto shelves (right) with this piece of equipment, allowing for safe handling of the 1300-lb modules and permitting easy servicing of individual modules by direct replacement.

Preionization Lamp Check (PILC)

If a cracked or broken flashlamp is fired at full energy, it will probably fail catastrophically, damaging other flashlamps and expensive optical components in the amplifier. Despite extensive preinstallation testing, lamps do break. Most often, lamps fail at the end of a shot. When this happens, the lamp current still appears normal but at the onset of the next shot, failure occurs. For these reasons, PILC was developed. In this check, each lamp in the system is pulsed with about 1% of the normal pulse energy. Lamp current is monitored and compared with a standard. When abnormalities are detected, the circuit is identified for closer inspection and lamp replacement (see Fig. 2-112).

Because of the large number of ignitron switch assemblies required by Shiva, six PILC circuits are charged by one power supply. Each PILC circuit is routed by a coaxial cable to each of several switch-rack assemblies (Fig. 2-112). With Ross switches, PILC can address any of the 8 to 12 ignitron switches reached by this array. Thus, each PILC circuit addresses an average of 10 of the 59 total switches in the system. A PILC sequence requires 15 s; therefore, the entire PILC operation can be completed in only a few minutes.

Each PILC capacitor assembly includes a damping resistor sized to produce an optimally damped or overdamped waveform. This prevents negative overshoot from drawing a high current through the isolation diodes. As the computer steps the PILC

circuits through their assigned switches, it simultaneously removes the adjacent high-voltage power supply from the switch rack. The PILC power supply is sized to charge the PILC capacitor assemblies in 5 to 10 s.

Data from the flashlamp-circuit-current transformers are fed into the computer and compared with standards for the circuits to identify any abnormalities. A typical PILC current waveform is shown in Fig. 2-113. Some variation occurs among the waveforms in the system because the number of lamp circuits per PILC capacitor varies. Therefore, the computer uses standards specific for each PILC capacitor. Variation in waveforms also occurs as a result of the charge state of the lamp; this, too, is accounted for in the comparison test.

Authors

N. L. Gagnon
L. W. Barkbigler
K. Whitham

Controls and Diagnostics

Controls and diagnostics for the Shiva pulse power components are implemented with a digital-based system (see Fig. 2-114). LSI-11 microcomputers address each control or diagnostic element in the system with a digital data bus. Bus interface units (BIUs) provide common-mode isolation. BIUs also transfer the digital information between

Fig. 2-113. Typical PILC current waveform (PILC bank voltage = 15 kV). During the pulse ionization lamp-check sequence, about 1% of normal pulse energy is directed into the flashlamps. The pulse current is monitored and compared with a standard to detect any abnormalities.

the data bus and each element of control or diagnostics. Each system element is identified by a unique digital address. The decode logic circuitry interprets this address and allows each element to pass or transmit information from the data bus in the proper sequence.

Initially, operator-system interaction takes place through control panels with selection switches. In the final operational mode, this interaction is accomplished with a page-selectable, color video display slaved to the intermediate processor. The initial system is also structured to allow for rudimentary, stand-alone operation with manual controls and readouts. In addition, personnel safety interlocks are triply redundant and hard-wired. Computer monitoring of interlock chains ensures a rapid graphic display of the current status through the entire system.

Fig. 2-114. Digital-based control and diagnostic system designed and tested for the Shiva laser. For initial operation, the elements shown in gold and green will be implemented. The green elements are simply parallel and redundant to those in gold. After initial system integration, the elements shown in blue—touch digitizer, video display, PDP-11/39—will be put into operation.

The integration of a low-level, digital control system into a pulse power environment is a difficult task. Much attention has been given to understanding the many possible transient coupling modes that can exist between the pulse power and control circuitry. To minimize destructive coupling, two levels of optical isolation are designed into the system. A 60-kV isolator separates the FEP from the data bus and 3-kV isolators separate each element in the system from the data bus.

Primary control functions include setting the power supply references, the charging and firing sequencing, the trigger-pulse generation, and the PILC initiation. Diagnostic functions include

monitoring the flashlamp waveform during the pump pulse, the status of the capacitor bank at voltage, the interlock status, and the PILC current waveform.

A prototype control system has been constructed and operated for more than 6000 pulses at the 23-kV, 600-kJ level in the Building 611 test facility. Details of system design and hardware implementation are discussed in following subsections.

System Design and Prototype Tests

The 600-kJ Shiva prototype capacitor bank and control system was used to verify the basic design

Fig. 2-115. Major control functions as interfaced to the pulse power system. Control and diagnostic circuitry is designed with sufficient voltage isolation to allow for the transient voltage rise that occurs at the bank end of the system. This voltage rise occurs as a result of the impedance drop in the coax cables that deliver bank energy to the flashlamps.

features and to carefully investigate the transient coupling modes (Fig. 2-115) from the pulse power circuitry to the digital control elements.

The single-point pulse power ground is located at the laser amplifiers where the high-voltage cable shield, flashlamp return, and reflector are common. The outer cases of the amplifiers are at building ground potential. During the pump pulse, the capacitor-bank end of the pulse power system undergoes a momentary voltage increase of several hundred volts above building ground. This increase results from the impedance of the coax load cables from the bank room to the flashlamps. Most control and diagnostic interface points occur in the capacitor bank area. Consequently, all these circuits must be designed to withstand this displacement between pulse power and building ground.

Another factor that we must consider is the high-frequency noise associated with ignitron triggering and high-energy faults. Thus, we need a low-impedance bus with a large voltage swing to increase the noise immunity of the power conditioning system.

With these environmental considerations in mind, we designed a system to provide flexibility and room for expansion when data on shot-initiation-timing requirements are obtained. The environmental considerations (i.e., ground reference displacements) dictate that each control point in the system must float freely from the other control points in the system. If this were not done, severe cross coupling in ground loops would occur.

The isolation thus required manifests itself in the BIUs (Fig. 2-114). There is an independent BIU for every power supply and each group of four ignitron switches as well as for every five disk amplifiers. The secondary, 40-kV isolation of the triggers and the physical proximity of the switches make it possible to address four ignitron switches from a common BIU. The disk amplifier grouping is practical because the amplifiers form the common signal-point ground; in addition, the ground inductance between those amplifiers in physical proximity is negligible.

The noise immunity requirement was met by providing a 50-V signal level operating into a 100- Ω transmission line. The speeds are slow enough on the bus (approximately a 2-MHz change rate) that reasonable waveforms can be maintained with twisted pairs.

System Hardware. Most of this year's effort has

Fig. 2-116. LSI-11 chassis. This package is used as the FEP for the power conditioning control and diagnostic system. Included are a CPU, 20K by 16 bits of core memory, a disk interface, a teletypewriter interface, and a ROM boot terminator board.

involved the development and prototyping of the various hardware elements shown in Fig. 2-114. In addition, we generated the necessary software to provide rudimentary manual control with the front end processors.

Front End Processor (FEP). We chose an LSI-11 as the FEP and developed a chassis for common use throughout the Shiva control system (see Fig. 2-116). This chassis was designed to meet the maximum requirement within the Shiva control system. In this configuration, the LSI-11 is composed of a CPU, 20K by 16 bits of core, a disk interface, a paper tape interface, a teletypewriter interface, and a ROM boot terminator card. Sixteen slots are provided for external interface cards, programmable clocks, and user design interfaces.

The power supply is composed of three diode-isolated 25-A, 5-V supplies and one 3-A, 12-V supply. Capacitance added to the 12-V line and to the third 5-V supply ensures 4 ms of operation under full load after a power supply fault or an ac line failure. Power-up and power-fail routines provide continued operation after a power failure without

requiring reloading. The power-fail routine is designed to place all external devices in a predetermined safe configuration, preserving external data and registers. Plugs for a teletypewriter paper tape and disk as well as run/halt and reset switches are provided under a maintenance panel on the chassis face.

If an FEP collects data during a shot and communication with the second-level processor is lost, the shot data can be retrieved with the above features. Obviously, as the system is brought up, these utility interfaces also provide a stand-alone and maintenance capability.

Other features of this chassis include an external 110-V ac, 3-A connector that is switched by the front panel on/off switch; a relay closure for control of heavier loads is also switched from this source. An 8-by-9.5-in. front panel can be customized for specific requirements. This panel provides the necessary local control for spatial filter pinholes, lens and gimbal motor drives, and beam diagnostic readouts.

Fig. 2-117 Control system manual-switch interface panels. First-level interaction between operator and system occurs through the control panels with these selection switches.

In cases where such a complete system is not required, reduced-capability chassis have been fabricated from the same print package with dash number control.

Power Conditioning Control Panels. The master control panel (Figs. 2-117 and 2-118) provides for either manual one-for-one switching or automatic operation. In the one-for-one manual mode, the operator has direct control over all system functions except the safety interlocks; he may exercise these functions in any manner he chooses. Sufficient summary data and detailed quick-look panels are provided to identify any system element not in compliance with issued commands. For instance, if the system does not come to voltage in the requisite time, the "At Voltage" summary will identify which power supply failed. This supply may then be dialed up on the power supply control panel and the problem identified. However, the operator always has the option to proceed and fire the system, in spite of the failure, if he so chooses.

The power supply control panel provides for one-at-a-time, readout, and voltage-set capabilities for any high-voltage power supply in the entire system. In this manner, it is possible to control the gain of all individual stages. The power supply select panel provides for the disabling of any power supply in the system. Thus, in the event of a high-voltage power supply failure, a backup supply is switched in. Through the use of this panel, only those amplifiers required by system staging need be fired when less than the full system is used.

Figure 2-118 shows the planned layout of the entire power conditioning control console. To support the indicated number of interfaces on a LSI-11, the required design of a transistor-transistor logic interface must be able to drive a larger number of inputs and outputs per bus load than is available with standard commercial interfaces.

To overcome this problem, we have designed and tested a pair of cards with 64 inputs and outputs (300 mA per output) per bus load. These cards use 122-pin Agat PC connectors and a Scanbe 7.5 by 7.5 card cage and are arranged on two-sided PC cards. These cards and a backplane scheme are used in each of the panels identified in Fig. 2-117.

60-kV Optical Isolator and 50-V Bus. A prototype optical isolator is pictured in Fig. 2-119. The air gap between the LEDs and photodiodes (transmitters and receivers) hipots to 60 kV.

The 50-V bus input logic uses a 21- to 24-gage twisted pair terminated in a 100- Ω resistance. Active low logic allows the use of open collector techniques along the bus, resulting in a relatively stiff, noise-

immune bus. Each leg of this bus is designed to be up to 600-ft long and to provide for 200 bus interface units. The bus can issue sequential commands at a 500-kHz rate. The overall bus layout for Shiva

Fig. 2-118. Power conditioning control room console. The control room is a mix of dedicated readouts and a sophisticated computer-driven color CRT display. Rudimentary system control and readout may be accomplished using either LSI-11 and the dedicated displays.

Fig. 2-119. Prototype 60-kV isolator. This Building-611 prototype isolator hipotted to 62 kV prior to extension of the LEDs and photodiodes. This isolator provides for isolation of control room personnel and equipment from potential faults in the 25-MJ capacitor bank, and couples an abbreviated DEC LSI-11 Q bus to a 50-V, 100- Ω bus in the laser bay and capacitor bank.

Fig. 2-120. Overall power conditioning bus for Shiva laser.

power conditioning is shown in Fig. 2-120. The two separate north and south branches combine at the 60-kV optical isolator and run the length of the basement and spaceframe. This isolator provides for input/output at each capacitor rack power supply and laser amplifier. Because the bus effectively blankets the laser bay, it is also used to monitor miscellaneous items such as beam blocks, air flow, and building temperatures.

Bus Interface Units (BIU). The key to providing a distributed bus system that allows each interface to float independently is a cost-effective isolated bus interface unit (see Fig. 2-121). As shown, this unit provides a bridge between a 50-V bus and the local CMOS decoders. The unit hipots to 3.5 kV non-destructively across the isolators and to 4.2 kV destructively; estimated cost is approximately \$400/BIU.

The BIU is designed to minimize problems caused by faulty interfaces in any external device. A reply to the system is only enabled by the BIU when a reply is expected. If, because of a fault, a decode logic board attempts to maintain a reply (thus stalling the bus), a time delay on the 50-V side of the BIU expires and disables that BIU. A light-emitting diode on the BIU is lighted to notify the operator. Failure of a BIU bus drive will also stall the bus.

Fig. 2-121. Prototype bus interface unit and data card. This unit provides local isolation of 3 kV at those points the 50-V, 100- Ω power condition control bus must service (power supplies, PILC, disk and rod amplifiers). The unit successfully hipotted to 4.2 kV before breakdown occurred through the optical isolator. Hence, faults with a smaller excursion than this will be isolated from the main bus.

This failure is detected by a current monitor; the bus that failed is identified at the 60-kV isolator. That branch is then physically checked to determine the specific BIU at fault.

Decode Logic. The decode logic for the system must exist in a relatively noisy environment. For this reason, we chose CMOS (operating at 14 V) as the logic family. Each input or output card is able to handle 64 interfaces. Switches on the board allow address selection. Outputs are latched and provide an open collector, maximum 20-V, 150-mA current sink. Both inputs and outputs are pulled up through 2.2-K Ω resistors. The pull-up may be eliminated in blocks of 15 interfaces by removing a wirewrap jumper. These boards provide the bulk of the system logic and cost approximately \$65 apiece.

Prototype Tests. Prototypes of all of the hardware described have been built and tested in the prototype 600-kJ capacitor bank. Two actual amplifiers were used as loads.

The prototype bank included 32 capacitor circuits, one size-"D" ignitron switch set, one 50-kVA, 20-kV power supply, and a prototype interlock system. The controls used an LSI-11, a master control panel, a power supply select panel, a power supply readout and voltage set panel, a 60-kV isolator, three BIU's, 400 ft of 50-V buss (21 to 24-gage twisted pair), and three sets of decode logic. This test set has successfully fired more than 6000 shots in an automatic repetitive mode.

In addition to repetitive firings, we also introduced some intentional faults to determine system response. In every case, these failures never propagated across the 60-kV isolator into the control room. During one fault at the ignitron switch, sufficient energy was coupled across the ignitron-trigger isolation transformer to destroy the decode logic. The logic faulted and stalled the bus with an active bus reply. As a result, we added the time delay feature discussed above under BIU hardware. In addition, lower interwinding capacitance transformers are now used in place of the older ignitron-trigger isolation transformers.

At the time of this writing the control system has been installed in the Shiva laser and has successfully fired the first arm without any major problems.

Authors

P. R. Rupert
L. W. Berkbigger
D. G. Gritton

Pockels Cell Drivers

Pockels cells are located in each of the 20 laser arms after the α rod amplifiers and β rod amplifiers. In addition, two Pockels cells are located after the first two α rod amplifiers on the oscillator table. The purpose of these Pockels cells (42 in total) is to provide fast shutters or gates for the fast laser-output pulse. The gates are closed while the flashlamps are pumping the amplifiers. This prevents a low-level signal originating near the front end from being amplified and destroying the target. After opening to pass the pulse, the gates close again so that light reflected from the target will not destroy small front-end optics.

Operation of the Pockels cell gates follows this sequence (see Fig. 2-122):

- Each gate is normally open to allow low-level continuous beam alignment of each laser arm.
- Bias voltage closes each gate before the amplifier flashlamps are triggered.
- A signal from the oscillator table, about 260 ns before the output pulse, fires the gate trigger generator. This generator fires a master spark-gap that, in turn, triggers two secondary spark gaps in pulse generators that provide multiple gate-open pulses, one for each Pockels cell.
- After the gate-open pulse, each gate closes until the laser is no longer activated.
- The bias voltage is removed, and the gates return to their normally open position.

Electrical Requirements. The open-close state of each Pockels cell is controlled by an electrical signal of 6 to 9 kV. In the normal open mode of operation, the cell and its polarizers pass light when the voltage across the cell is zero and reject light (from either direction) at full bias voltage.

The Pockels cell can be considered a lumped-element capacitor, after the wave transit time through the cell of about 1 ns. Two sizes of cells are used. The α cells are 1 in. in diam with about 15-pF capacitance; the β cells are 2 in. in diameter with about 40-pF capacitance. Each cell is driven by a terminated 50- Ω cable. The 0 to 99% risetime to a square pulse in the cable is obtained from

$$t_{gg} = (50C/2) \ln [1/(1 - 0.99)] = 115C, \quad (14)$$

so that the shortest possible (0 to 99%) rise in an α cell is

$$t_{gg}(\alpha) = 115 \times 15 \times 10^{-12} = 1.7 \text{ ns}, \quad (15)$$

and in a β cell,

$$t_{gg}(\beta) = 115 \times 40 \times 10^{-12} = 4.6 \text{ ns}. \quad (16)$$

The requirement for a fast-gate pulse occurs at the third event of the Pockels cell sequence. Here,

Fig. 2-122. Sequence of five events for the Pockels cell gates. The gates normally are open to allow the alignment laser beam to propagate. During laser operation, the gates are closed with a bias voltage and then opened momentarily to allow the laser pulse to pass. The fast-gate pulse must cause a small ($\sim 10\%$) undershoot below the "gate-open" position for optimum open/close ratio.

the gate is momentarily opened to pass the 0.1- to 2-ns laser pulse. Adding the 0 to 99% risetime to the 2-ns maximum laser pulsewidth and allowing a system jitter of ± 5 ns, the gate pulsewidth (rounded to 1 ns) becomes, for an α and β cell respectively,

$$2 + 2 + 10 = 14 \text{ ns,}$$

$$5 + 2 + 10 = 17 \text{ ns.}$$

Thus, each Pockels cell provides a bias voltage (6.0 ± 0.5 kV for α cells, 8.5 ± 0.5 kV for β cells) at t minus 1 ms or earlier that lasts at least through t plus 1 μ s and preferably longer.*

Superimposed on this electrical bias is a fast-rise square pulse in a 50- Ω cable that provides voltage to the cell of polarity opposite to the bias with about 10% greater amplitude. The timing of this square pulse is such that the leading edge of the electrical pulse arrives at the cell 7 ns (α cells) to 10 ns (β cells) before the expected laser pulse arrival. The duration of the square-pulse is 14 ns for α cells and 17 ns for β cells.

Arrival Sequence. Counting from $t = 0$ (the time that the laser pulse is switched out of the master oscillator), the arrival times at each of the Pockels cells are as follows:

$$\alpha_1 t = 55 \text{ ns,}$$

$$\alpha_2 t = 60 \text{ ns,}$$

all α and β cells in each chain:

$$\alpha t = 230 \pm 20 \text{ ns,}$$

$$\beta t = 240 \pm 20 \text{ ns.}$$

The variation in arrival times at the cells of each chain results from differences in distance along each chain from the pulsed oscillator to the Pockels cells.

Multiray Pockels Cell Drivers. The 43 Pockels cells are each driven with a 50- Ω RG214 cable. The 42 cables are driven from one of three multiple-way

pulsers. A six-way pulser provides signals for the α_1 and α_2 Pockels cells, as well as impulses to trigger two 20-way pulsers. One of these pulsers drives the 20 cables to the α Pockels cells in the laser chains, and the other drives the cables to the 20 β cells. A block diagram of the pulsers and cable layout is given in Fig. 2-123.

Triggering of the six-way pulser is accomplished with a high-voltage trigger generator. The trigger generator is fired with a 300-V signal from the oscillator table. The delay through this generator TG is about 250 ns and the jitter is less than 2% or < 5 ns.

The two 20-way Pockels cell drivers are identical in every mechanical detail. The voltages supplied to the 20-way β cell driver is about 40% higher than the voltages supplied to both the 20-way α cell driver and the six-way pulser. This six-way pulser is identical in construction to the 20-way drivers except that it only drives six cables and is triggered by the high-voltage trigger generator.

A diagram of one of the 20-way drivers is shown in Fig. 2-124. The 6-way pulser is similar except for the trigger input. In addition to driving two α Pockels cells, the 6-way pulser supplies two cables to each 20-way driver. These cables are stacked at the trigger input to each 20-way driver (Fig. 2-124). The resulting high-voltage pulse ensures positive, low-jitter triggering. Operation of the drivers proceeds in the following sequence.

At about minus 1 s, a high-voltage relay connects the power supplies, with preset voltages, to the drivers. This provides bias to all the Pockels cells through the centers of the coax cables (see Fig. 2-125). Vernier control of bias voltage to provide for variation between the individual cells is accomplished with individual potentiometer settings in the driver housing.

At minus 260 ns, a 300-V pulse is sent from the oscillator table. It arrives at the high-voltage trigger generator about 15 ns later. The generator fires after a 250-ns delay, triggering the spark gap of the 6-way pulser 20 ns later. This starts a series of events that cause electrical pulses to arrive at each α and β Pockels cell 7 and 10 ns before the arrival of the laser pulse. Jitter on this timing is ± 5 ns (see Fig. 2-125). The electrical pulse width is controlled by the pulse-line cables in each Pockels cell driver: 14 ns for the α cells and 17 ns for the β cells.

At about plus 1 s, the high-voltage relay drops out, disconnecting the power supplies and

*The flashlamps are fired about t minus 700 μ s. The reflected pulse of light from the target arrives at the Pockels cells as late as t plus 700 ns.

grounding the cable inputs. The bias voltage capacitors in each Pockels cell housing discharge and the cells return to their normally open position.

Authors

B. M. Carder

E. H. Padillo

Flashlamps

The Building 611 flashlamp processing facility has been operating at full capacity for over a year. During this period, over 1700 lamps for the Shiva system have undergone initial inspection and infant mortality testing. In addition, several hundred

Fig. 2-123. Pockels cell drivers. The 6-way driver receives an input trigger from the oscillator table. This driver then supplies a pulse to the two α Pockels cells on the oscillator table. A high-voltage trigger is also supplied to the two 20-way drivers. The large drivers provide pulses to the 20 α and 20 β Pockels cells that are located within the 20 Shiva laser arms.

mands from the intermediate-level processors and generate the commands in the output format required by the driven hardware. Where required by the laser hardware, the FEPs also generate specific analog waveforms and feedback control functions.

For a number of applications, particularly in the alignment control subsystem, the FEPs play the key role in closed-loop feedback control operations. In these cases, local consoles will provide operator interactions. Communications between the intermediate-level processors and FEPs performing closed-loop operations will be supervisory in nature, handling interlocks with other FEPs and allowing operators in the central control room to interact with the control operations at the FEP level.

The front-end processors (FEPs) are the basic building blocks of the system. These microprocessor-controlled elements collect raw data that are then reduced and compacted and made available to the intermediate-level processors. In addition, these FEPs accept high-level com-

For example, consider a command issued by a central control room operator to override FEP-level closed-loop operations and to move a particular gimbal in the alignment system for experimental purposes. The command is entered into the alignment control intermediate-level processor by switches, touch panel, or keyboard at the operator's option, and then formatted and relayed to the proper FEP. The FEP disables closed-loop operations involving the gimbal; sends the desired distance, direction, and rate of gimbal motion to the stepping motor control unit; and, as motion occurs, reports position and finally completion to the intermediate-level processor, which displays the information for the operator.

To ensure a maintainable system with adequate information available to operators performing the troubleshooting and fault analysis, two additional requirements have been placed on system design. All system commands must have a verifiable reaction built into the hardware. This provides the data needed for quick and accurate fault determination. Additionally, the FEPs must be programmed to interrogate the system hardware periodically to verify the operational status and to monitor for undesired changes. This ensures a time history of events and allows the correlation of failure data to determine cause and effect in the event of multiple failures. We have presently planned to acquire 10 interrogation samples per second in the critical area of power conditioning.

FEP design also will allow the entire laser to be controlled manually through a minimum interface with individual elements. Thus, the initial laser debugging and target shots could be performed in a degraded control mode without relying on the second- and third-level processors. This way, all control is rudimentary with operators providing most closed-loop-function, data-recording, and troubleshooting expertise.

Intermediate-Level Processors

The second-level processors will provide the central capability for effective operator control of the data acquisition and control processes occurring in the FEPs throughout the laser facility. These processors will also handle most interactions and interlocks between the various FEPs, monitoring the desired and actual performance and communicating information on discrepancies to the operators.

Change data from the FEPs will be recalled and maintained for 30 m at this level. If a fault is detected, these data plus the fault indication will be passed to the third-level processor for archival. These same data will be archived after a laser shot to establish the system configuration and shot results. Typically this information contains all parameter changes, switch settings, and resultant data, complete with identity and time information.

In addition to providing for post-test data analysis, diagnostic programs utilizing the system's built-in self-test and calibrations capabilities are also planned. These routines will be capable of automatically verifying proper configuration and control system operation in a few minutes. Verification of individual redundant paths will be incorporated as a part of the system power-up procedure. These routines also will be available on command to the system operators. If errors are detected or if temporary system-configuration changes are required for a given test, a user-oriented language will provide temporary system-configuration patch capability.

Finally, this processor level will provide for shot analysis in a limited sense. Analysis routines will be available to interpret test results to a level that is sufficient to determine the desired system configuration for subsequent shots, to detect system malfunctions, and to provide a "quick look" at performance data.

Supervisory Monitoring, Analysis, and Control (SMAC)

A third-level processor will be incorporated in the Shiva control system to provide common system peripherals and to enable integration into a single-operator-directed system.

Initially, during system development, this machine will provide system software development capabilities. In this capacity, it will be used to develop programs for the FEPs and intermediate-level processors. The resulting programs will be loaded downline through appropriate hardware links. In this time frame, SMAC can provide online storage for several shots of test data from the second-level processors. System configuration and calibration data will also be stored here. Magnetic tapes of shot data will be recorded for transmittal to

the Octopus system after each day's operation. Control system configuration information will be recorded on magnetic tape with the corresponding experimental data and filed for future reference and analysis.

As the system is developed, SMAC will provide the mechanism for system integration. Initially, this will be limited to generating a real-time display of the total Shiva system. By the time the first target shot is attempted, we plan to have upgraded this capability so that this processor can serve as a backup for the power-conditioning intermediate processor. In addition, backup capability for the remaining second-level processors will be added as they are operationally brought online. After this is accomplished, we plan to reduce operator requirements by controlling each second-level processor at a supervisory level. These capabilities are scheduled for early FY 1979. As this processor takes on more of its long-term operational load, another processor probably will be required. Future plans call for a stand-alone duplicate, third-level minicomputer system to enable us to analyze laser and target performance as well as develop software concurrent with every-day laser system operations.

Intersystem Communication

Communications between processors will be provided in three ways. The first is a parallel, very-high-speed communications link (PCL) between the second- and third-level processors. This will be the normal means of communication for most of the processing tasks.

The second communications method will be by serial, low-speed asynchronous links. These will be used in backup configurations between the second- and third-level processors, as well as for normal communications with the FEPs.

The final interprocessor communications method will be by shared memory using quad-ported memory between the power conditioning subsystem FEP's and second-level processor. As an option, for redundancy, the shared memory can be connected to the third-level processor in the event of failure of the power conditioning subsystem second-level processor.

Special-purpose interprocessor communication software will be developed for communication between the FEPs and the second-level computers

over serial lines. The decision to develop this software was made after a study and trial of the proposed software indicated that it was too cumbersome to be supported effectively on an LSI-11. The manufacturer-supplied network software package will provide the communications support between the second- and third-level processors.

Authors

F. W. Holloway

J. R. Greenwood

J. E. Pollock

P. R. Rupert

2-2.10 Beam Alignment

Efficient and accurate alignment of the laser beam from oscillator to target is essential for productive operation of a laser system. Because manual techniques are often too slow for efficient day-to-day operation even on the present one- and two-beam systems, beam alignment on Shiva will be automated to the greatest extent possible. Adjustments requiring physical access to individual components (which may be four or five stories above the laser-bay floor) will be minimized.

Figure 2-127 is a diagram of the basic Shiva alignment system. Table 2-29 lists the alignment requirements as originally specified and as presently estimated, together with the performance obtained to date from the prototype equipment. We expect that this performance will be satisfactory for even the most alignment-sensitive targets and significantly better than is needed for experiments not requiring highly uniform illumination. Figure 2-128 illustrates the hardware arrangement planned for a typical Shiva chain.

Because high repetition rates are not possible with the pulsed preamplifiers that will be used on Shiva, both system and target alignment will be accomplished with an amplitude-modulated cw laser. Therefore, except for the oscillator section, all of the alignment procedures and hardware described below are designed to be used with a 630-Hz, 1.06- μm source. A separate cw mode-locked oscillator will be used for pulse synchronization (see § 2-24).

Oscillator-Preamplifier Alignment

The oscillator-alignment system automatically points and centers both the pulsed and cw oscillators with respect to a pointing and centering sensor. This sensor is mounted on the preamplifier table, which is rigidly attached to the laser space frame. Signal processing is done in such a way that full corrections for angle and position can be calculated and implemented with data obtained from a single pulse. Thus, only a few pulses of the pulsed oscillator or of a few samples of the cw oscillator are required to reach and verify proper oscillator alignment.

The oscillators are mounted on a second table, also attached to the space frame. Figure 2-129 shows the locations of various components on these tables schematically (see § 2-2.2 for a detailed layout). Centering of the pinholes in the two spatial

filters mounted on the preamplifier table is monitored by imaging the pinhole planes through a turning mirror and onto a silicon vidicon. The relative (x,y) positions of the beam and pinholes can be determined by alternately inserting and removing a negative lens or a diffuser ahead of the spatial filter to overfill the pinholes. The preamplifiers do not have to be centered on the beam with great precision and thus movement of the preamplifiers will rarely be required.

Main Chain Input Pointing

To remain centered in the spatial-filter pinholes, the beam must be properly pointed at the input of each amplifier chain. Between the oscillator-alignment sensor and the apodizer, most beams reflect off seven mirrors; thus, some angular drift

Fig. 2-127 Alignment system for a representative Shiva amplifier chain.

Table 2-29. Requirements and performance for the Shiva alignment system. All performance values are the standard deviation measured at the appropriate alignment sensor

System	Requirements		Performance, σ	
	1975 estimate	Present estimate	Demonstrated to date	Expected achievement
<u>Oscillator Coalignment</u>				
Pointing	$\pm 2 \mu\text{rad}$	$\pm 20 \mu\text{rad}$	2.3 μrad (CW) 3.5 μrad (pulsed)	1.0 μrad
Centering	$\pm 0.5 \text{ mm}$	$\pm 0.25 \text{ mm}$	0.1 to 0.25 mm	0.1 mm
<u>Chain Input</u>				
Pointing	$\pm 60 \mu\text{rad}$	$\pm 60 \mu\text{rad}$	15 μrad	15 μrad
<u>Chain Output</u>				
Pointing	$\pm 1 \mu\text{rad}$	$\pm 5 \mu\text{rad}$	1 μrad	1 μrad
Focusing	$\pm 25 \mu\text{m}$	$\pm 60 \mu\text{m}$	23 μm	20 μm
Centering	$\pm 2 \text{ mm}$	$\pm 2 \text{ mm}$	0.2 mm	0.2 mm

may occur. To measure the angular error at the front of each chain and to correct for any drift beyond the tolerances listed in Table 2-29, a pointing sensor located immediately after the apodizer in each chain drives a servoed chain-input-pointing (CHIP) gimbal in the beam-splitter array.

Spatial Filter Pinhole Positioning

The relative transverse positions of the focused beams and the pinholes in the main-chain spatial filters are determined as described above by imaging the pinhole planes onto a vidicon. In this case, the vidicon is located either in the incident-beam-diagnostics package (§ 2-2.12) or in the output-pointing, focusing, and centering (PFC) sensor, directly across the target chamber from the beam in question. Initially, the video signals are displayed on monitors and the pinholes are positioned in a manual/remote mode. Ultimately, however, these video signals will be digitized and processed in the alignment-system, second-level computer to provide error signals for closed-loop alignment of the

pinholes. The spatial-filter pinhole manipulators are stepping-motor driven and are described in § 2-2.3.

Centering on Focusing Lens

The PFC sensor is located behind the final-turning mirror in each chain and has several modes of operation. In the centering mode, the centering screen (located ahead of the focusing lens) is imaged onto a lateral-effect detector in the PFC package. This retroreflecting screen is positioned with its center on a line passing through the target position and the nominal center of the focusing lens. During initial setup, the PFC sensor is carefully oriented so that the center of the centering screen is imaged onto the center of the detector. Then, when the alignment beam is on and is reflected back into the PFC sensor, any difference between the present position of the beam centroid and its position at the time of initial set-up generates an error signal.

In the simplest mode of closed-loop operation, this error signal drives the first of two output-turning mirrors until the beam is centered on the

screen. With full implementation of the alignment-computer system, this error signal will drive both output-turning mirrors to achieve a pure translation, i.e., no repointing of the beam entering the focusing lens.

Pointing at Target

In the pointing mode, the centering screen is removed and a spherical surrogate target is positioned in the target chamber (see Fig. 2-129). The PFC sensor continues to image the plane where the centering screen was located. When the beam, which was previously centered on the lens, points directly at the target (its central ray normal to the target surface), the beam reflected back through the lens is centered in the plane being imaged and no

error signal is generated. If the beam arrives at the target at any other angle, the back reflection is off-center, and the PFC sensor generates error signals. These error signals drive the servos on the final-turning mirror until they are nulled. This pointing procedure is most accurate when the diameter of the back-reflected beam is small, a condition that occurs for a particular focusing configuration as described below.

Focusing on the Target

Moving the focusing lens toward or away from the surrogate target causes the diameter of the reflected beam to vary in the plane being imaged (see Fig. 2-129). The smallest diameter is obtained when the incoming beam is focused toward a point

Fig. 2-128. Major components of the Shiva prototype-alignment system arranged for a typical beam.

Fig. 2-129. Output pointing with the PFC sensor. The sensor has been initially positioned to indicate zero error for beams which are exactly retroreflected from the surrogate. When the focused beam hits the target at other than normal incidence, the back reflection is off-center. This generates an error signal in the PFC sensor.

about halfway between the center and the front surface of the spherical target. The PFC-sensor optics image the centering-screen plane onto a vidicon as well as onto the quadrant detector, and thus, the operator can visually determine when this focusing condition is achieved. For closed-loop operation, the video signals can be digitized and processed on the alignment-system, second-level computer (see § 2-2.9). This provides a measure of either on-axis intensity or spot diameter that can be maximized or minimized, respectively.

On a given shot, the experimenter specifies the desired offset from the half-radius position. The focusing lens is moved along the beam for that specific amount by the remotely actuated lens drive. The correctness of the final-focus position can be verified by viewing the beam with the opposing PFC sensor and return-beam-diagnostics package.

Target Viewing and Exchange

With a different lens-turret position, the PFC sensor can provide a vidicon image of the target or its silhouette depending on whether the target is illuminated from the same or opposite side. To supplement other target-alignment optics and to

provide the capability for viewing the target directly along a beam axis with good image quality, each beam is provided with a diffuse target-illumination source. To accurately replace a surrogate target with the real target, the surrogate's position is referenced on the monitor and the fusion target then is carefully inserted.

Alignment Controls

As described in § 2-2.9, Shiva will be controlled primarily by a three-level, hierarchical-control network of minicomputers. The controls for the alignment system are a part of this network. Each alignment subsystem can be controlled locally in the laser bay or target room, as well as from the central-control room. In addition, the operator can monitor error signals and gimbal positions for all systems to confirm that the closed-loop functions are being performed correctly.

Author
E. S. Bliss

Major Contributors
M. A. Summers
R. L. Cody
R. D. Boyd
J. D. Wintemute

2-2.11 Alignment Control Subsystem

Shiva alignment includes centering, pointing, and focusing as well as certain selection operations involving over 500 control points (both open- and closed-loop) from the oscillators to the target. Alignment is accomplished with an amplitude-chopped continuous wave (cw) laser directed from the oscillator area through all 20 laser chains to a surrogate target (see Fig. 2-130). Sensors located at strategic locations detect errors and provide feedback through the control system to motor-driven gimbals.

At the front of the alignment system, the oscillator alignment system (OAS) keeps the cw alignment laser, the mode-locked laser, and the master pulsed laser linearly coaligned. The mode-locked

laser is used for pathlength equalization whereas the master pulsed laser is used during an actual laser shot.

The alignment control subsystem (Fig. 2-130) employs seven front-end processors (FFPs), consisting of one or more LSI-11 microcomputers, associated interface equipment, and local control panels to control gimbals, translators, and lens positions along the laser. The FEPs are programmed in an extended BASIC language which, by its nature, is extremely easy to develop and modify on small systems.

A PDP-11/34 minicomputer in the control room coordinates the activities of each FEP with the alignment system operators at the central control panel. This PDP-11/34, in turn, is linked to a third-level PDP-11/70 minicomputer that integrates the major control subsystems.

Fig. 2-131. Shiva oscillator alignment system.

Front-End Processors

A common architecture is used for all FEPs. Two levels of LSI-11 microcomputers have been defined. An "A" package is a fully configured unit for

Fig. 2-132. Sensor-signal integrator unit of the oscillator alignment system with digital outputs to an LSI-11 microcomputer.

developing and executing BASIC language programs. A "B" package is a stripped unit, tailored for controlling a large number of stepping motors through commands over a serial link similar to a special terminal device that simply moves motors. The "B" package is programmed in assembly language and burned into read-only memory, so it is a piece of "hardware".

Front-end processors 1 through 5 are described below. FEP 6 (target positioning) and FEP 7 (vacuum control) are in preliminary design and are not described.

Oscillator Alignment System (FEP 1). The oscillator alignment system automatically points and centers both the cw and the pulsed oscillators with respect to a pointing and centering (PC) sensor. The PC sensor is mounted on a preamplifier table that is rigidly attached to the laser space frame. Selection of the oscillator in use is accomplished by a removable mirror and is also under the control of this FEP. Thus, a simple link to the control room can handle all functions related to oscillator alignment. Figure 2-131 is a simplified block diagram of

Fig. 2-133. Signal processing for the oscillator alignment.

Fig. 2-134. Block diagram of the chain-input pointing control system showing the closed-loop control from the pointing-error sensor through the LSI-11 microcomputer and to the stepping-motor-driven gimbals of all 20 laser beams.

the OAS, including PC sensor and the gimbals associated with one of the three oscillators.

The detector, preamplifier, and integrator box (Fig. 2-132) are designed to accommodate the different laser-oscillator characteristics and to convert the detected signals to a digital format (Fig. 2-133) for closed-loop control by the LSI-11. Portions of this FEP are now in final checkout.

Chain-Input Pointing System (FEP 2). The chain-input pointing system (CHIP) measures the angular error near the apodizer of each chain and provides closed-loop of motor-driven angular gimbals on the oscillator table.

The CHIP system (Fig. 2-134) consists of an optical-mechanical sensor package, sensor electronics, analog-to-digital (AID) conversion equipment, a BASIC language programmed LSI-11 ("A" package), and two stepping-motor-driving units ("B" package) to accomplish closed-loop automatic control. The motor-driving units can also be used to manually control the path-length equalization mo-

Fig. 2-135. Chain-input pointing control system (CHIP) display. CHIP will include a computer-generated video display giving the status of all control loops for local operator control.

tions. A control panel with a video-computer-generated display (Fig. 2-135) is used for local operator control.

Because a microcomputer will be used, a beam-selection function (originally planned as a beam block or similar electro-mechanical device to allow selective use of laser beams during output/target alignment) is accomplished by slewing the pointing gimbal out-of-range or back to its pointed position.

To remain centered in the spatial-filter pinholes of each chain to within approximately one focused-beam diameter (or about one-tenth of the pinhole radius), the beam must be pointed with an accuracy of 70 μ rad at the input of each amplifier chain. Between the oscillator PC sensor and the apodizer, most beams reflect off seven mirrors; the CHIP system compensates for the drift of these mirrors.

Spatial-Filter Pinhole Positioning System (FEP 3). The spatial-filter pinhole positioning system controls the transverse positions of the pinholes in the main-chain spatial filters. The positions are determined by imaging the pinhole planes onto a vidicon camera in the incident-beam diagnostic package, or alternatively in the pointing, focusing, and centering (PFC) sensor that is located directly across the target chamber from the beam in question.

The spatial-filter pinhole manipulators are stepping-motor driven and, attached to a B-level control unit, can be manually controlled locally, or remotely controlled from the control room over a serial communication link.

Ten stepping-motor-control units ("B" packages) are used by an operator to control the system's 100 pinhole positions in the X, Y, and Z directions as he views the vidicon-captured image on a TV monitor. Eventually, these video signals are digitized and processed in the alignment system PDP-11/34 minicomputer to provide error signals for closed-loop control of the pinhole positions.

Chain-Output Pointing and Centering (FEP 4). FEP 4 consists of one "A" package LSI-11, fully configured for BASIC language operations, four "B" package LSI-11s for stepping-motor-driven mirror control, and a local control panel. The chain-output pointing and centering system has two major modes of operation—centering on the focusing lens and pointing at the target. In centering mode, the centering screen located ahead of the focusing lens is imaged onto the lateral photovoltaic detector in the PFC package. The reflecting screen is positioned with its center on a line that connects the target position and the nominal center of the

focusing lens. During initial setup, the PFC sensor is carefully oriented so that the center of the centering screen images onto the center of the detector. When the alignment beam is on, it is reflected back into the PFC sensor. Any difference between the position of the beam centroid and the center of the screen generates an error signal.

In the simplest closed-loop mode, this error signal drives the first of two output-turning mirrors until the beam is centered on the screen. When the alignment computer system is fully implemented, this error signal will drive both output-turning mirrors to achieve a pure translation, i.e., no repointing of the beam entering the focusing lens.

In the pointing mode, the centering screen is removed and a spherical surrogate target is positioned in the target chamber. The PFC sensor continues to image the plane where the centering screen was located onto its detector. When the beam, which was previously centered on the lens, focuses onto the target with its central ray normal to the surface, the beam reflected back through the lens is centered in the plane being imaged; no error signal is generated. However, if the beam arrives at the target at any other angle, the back-reflection is off-center and the PFC sensor generates error signals.

These error signals are measured by interface equipment on the LSI-11 and are used to calculate the necessary corrections to the final turning mirror to null the error signal. This pointing procedure is most accurate when the diameter of the back-reflected beam is small, a condition that occurs for particular focusing configurations which are described in detail below.

Focus-Lens Control System (FEP 5). The focus-lens control system receives motion commands from an operator through a local control panel or from the control room. It moves the final focus lens by stepping-motor-driven X, Y, and Z translation stages. Accurate position transducers are read by the system to verify position. The actual interface to the centering screens as described above is also under the control of this FEP.

When the focusing lens is moved toward or away from the surrogate target, the diameter of the reflected beam varies in the plane being imaged. The smallest diameter is obtained when the incoming beam is focused toward a point that is about halfway between the center and the front surface of

the spherical target. Because the PFC-sensor optics image the centering screen plane onto a vidicon as well as onto the quadrant detector, the operator is able to visually determine when the beam is properly focused. Eventually for closed-loop operation, the video signals will be digitized and processed on the alignment-system PDP-11/34 to enable the on-axis intensity or spot diameter to be, respectively, maximized or minimized.

Alignment Control from Control Room

After the FEPs become fully operational and links are established to the PDP-11/34 in the control room, an integrated operation of the entire alignment-control system will begin. Figure 2-136 shows the preliminary design for the alignment-control panel in the control room. A roadmap-like

status display is provided across five panels of the alignment system from oscillator to target. Operationally, there are two nearly identical stations with a touch-panel display, keyboard, special button panel, video displays, and a computer-generated color video display unit. Both stations can interact with any FEP in the alignment system.

Products Designed to Support FEPs

The key to successful and timely implementation of such a large control system is commonality of design throughout each FEP. Several principal components that will be used in many places are described below.

Stepping-Motor Controls. Control of stepping-motor-driven gimbals and translation stages is an important element in the alignment system; over

Fig. 2-136. Central control panel for the alignment control subsystem will provide two operator stations, each with TV displays to monitor beam-alignment performance as well as computer-interfaced displays and switches to perform alignment functions. Nominally, one station controls the laser bay functions and the other handles the target area; however, both can be used for either application.

Notes

① Each LSI-11 requires a DRV-11 and clock source card LEA77. For clock interrupt and distribution on bus finger AE1. Must be used by user on backplane.

② Required for local motor control panel.

500 motors are currently planned. A number of desirable features were identified and incorporated into a special LSI-11 interface that is compatible with all FEPs. A standard cable and connection configuration is used throughout the alignment system to connect all motors. To minimize the overall design effort for both hardware and software, all motor drives are implemented in sets of three motors per location. Three is the most convenient denominator of all FEP requirements and corresponds to a three-axis motion.

Figure 2-137 shows a complete block diagram of the SHIVA stepping-motor controls. These controls consist of the logic boards (Fig. 2-138) that plug into the backplane of an LSI-11 and the power-amplifier boards that are mounted in a separate chassis (Fig. 2-139). Each logic board controls up to six motors and each amplifier board drives up to three motors. For protection of the LSI-11, the amplifier boards are optically isolated from the logic boards.

Two forms of stepping-motor controls are planned; 1) a few logic boards added to a large LSI-11 BASIC language unit ("A" package) with a separate chassis partially loaded with amplifier cards, and 2) a custom LSI-11-based unit ("B" package) with a serial link and ROM code program that controls up to 30 motors. Table 2-30 lists the features of the LSI-11-based stepping-motor controls for Shiva.

Design of these units is complete and production has begun. The software diagnostic package to test these units has also been completed.

Stepping Motor and Gimbal Test Unit. The large number of different gimbals and other stepping-motor-driven devices within the system necessitate some way to test the motors' responses in a production line manner. A number of identical test units for use in various labs and checkout stations were designed and built to subject the motors to controlled commands similar to those of the the LSI-11 stepping-motor controller, and verify their responses. These test units use the same stepping-motor-drive circuitry as the LSI-11 systems; the first two test units are presently in use. These units can test for marginal current requirements, limit switch and shaft position pot errors, as well as detect wiring errors and mechanical problems in the gimbal (see Fig. 2-140). Both single-step and counted-variable-slew rate operations are provided.

Fig. 2-138. Stepping-motor multiplexer controls the operation of up to 30 stepping motors with their associated limit switches and pot-feedback sensors. Commands are received from either the front panel or a serial link from the control room. Motor-control logic boards plug into an LSI-11 backframe in the standard chassis used for all FEPs. This custom control panel handles the stepping-motor controls.

Fig. 2-139. Stepping-motor power amplifier board mounts into the power-drive chassis. The power-drive chassis is optically isolated from the LSI-11 microcomputer for transient protection.

Table 2-30. Features of LSI-11-based stepping-motor controls for the Shiva laser system

- Automatic power control to energize motors only when they are moved, thus reducing heat generation near optical components.
- Programmable distance commands.
- Nonvolatile memory to store present position.
- Selectable rates from 1 to 300 steps per second.
- Direct translator read/write to avoid "jump" problem commonly encountered with motor controllers on power-up.
- Wide range of motor power up to 24 V and 2 A.
- Provision for pot-feedback option with A/D converters.
- BASIC language callable subroutine.
- Complete self-test capability.
- Limit-switch feedback with software override capability.

LSI-11 Chassis With Custom Panels. Together with the other major Shiva control subsystems, a general-purpose LSI-11 chassis with internal power supplies and many features designed especially for Shiva control has been developed and is being

produced in quantity. Figure 2-137 shows this chassis with the internal LSI-11 backframe and the control panels in an actual application. The "normal" computer on/off and start controls, diagnostic points and interfaces, and power supply monitors are located behind the left panel "door." The right panel contains custom switches and displays that are unique to each FEP; these are mounted on the front with hinged access for wiring.

Control Panel Interface. A control-panel-interface logic card that plugs into the LSI-11 backframe has been designed and prototyped. When produced in quantity, it will be used by all FEPs. With its associated software, this card provides a large number of push buttons, LED lights, digital switches, and digital-display interfaces directly from BASIC language calls.

Network Software and Hardware. We have begun to design general-purpose network software and hardware to link the alignment control FEPs to the PDP-11/34 in the control room. However, this design is still in the early stages and substantial effort remains. Figure 2-141 illustrates the overall scheme. Fiber-optic links will be used between the control room, laser, and target areas for noise immunity. The requirements for a logic card to interface the link to the FEP LSI-11s have been defined.

Fig. 2-140. Stepping motor and gimbal test units are used in various laboratories to check motor-driven gimbals for proper electrical connections and mechanical operations. The driving electronics are identical to the LSI-11-based motor drives used in the alignment control system.

Fig. 2-141. Network hardware and software will be developed to connect the various FEPs to the control-room PDP-11/34, including fiberoptic links and control network protocol software.

In addition, a software package embodying a custom control-network protocol has been designed and written but sufficient hardware must still be developed before this software can be tested.

The link between the PDP-11/34 and the PDP-11/70 was purchased from DEC; DECNET software will be used. However, DECNET has been ruled out as a practical means of communication with the LSI-11s because it is extremely flexible and hence, is too large to fit in the limited memory space of an LSI-11.

2-2.12 Beam Diagnostics

Beam diagnostics is the part of the Shiva control and monitoring system concerned with the performance of the 20 Shiva beams. The goals of the beam diagnostics system are:

- Optimizing laser system output.
- Providing laser data related to target performance and fusion diagnostics.
- Isolating failures with a minimum of diagnostic shots.
- Recognizing trends in laser performance.

Optimization of the Shiva laser includes selecting the proper pulse shape and length, balancing the power in each laser arm, and selecting the gain at each stage to prevent component damage and to maximize throughput energy.

To assess the performance of targets, it is essential to know the characteristics of the irradiating laser pulse: the energy focusable on target, energy reflected from the target, temporal pulse shape, spatial profile in the target plane, prepulse energy, and energy of amplified spontaneous emission.

Authors
F. W. Holloway
R. L. Cody
R. G. Gant
J. Parker
G. L. Snyder
M. A. Summers
G. J. Suski
P. J. Van Arsdall
E. S. Bliss

The limited accessibility of components requires a sophisticated mechanism for isolating failures. In addition, the high cost per shot precludes use of a failure isolation scheme that requires firing a great many shots.

Beam diagnostics may be put into two main categories as listed in Table 2-31: diagnostics done on every shot, and diagnostics done periodically. Diagnostics done on every shot include collection of laser performance data that have a high probability of changing on a shot-to-shot basis and whose

Table 2-31. Many diagnostic measurements need to be done on every Shiva shot, while others need to be done only periodically

Diagnostics Done on Every Shot

Oscillator Performance:

- Power level of oscillator cw cavity.
- Temporal profile of output from cw oscillator.
- RF drive frequency of acousto-optic modulator.
- Selected pulse shape from regenerative amplifier.
- Pulse shape after pulse shaper (determined with a streak camera).

Energy growth:

- Output energy of shaped pulse after first preamplifier.
- Energy at output of first two α rod preamplifiers.
- Energy at output of preamplifier table.
- Energy at beam at selected locations along each amplifier chain.

Output and reflected energy:

- Output energy of each chain.
- Energy reflected from the target back along each chain.
- Prepulse energy.

Temporal and spatial characteristics:

- Far-field beam pattern photographs.
- Temporal recording of slice through beam (with a streak camera).

Periodic Diagnostics

- Amplified spontaneous emission energy.
- Phase front of beam.
- Near- and far-field beam patterns at low and high power.
- Far-field beam patterns at low and high power.

monitoring does not interfere with the operation of the laser as a target-irradiating device. Periodic diagnostics include the collection of those laser performance data unlikely to change for a given system configuration.

Data Acquisition and Control

Beam diagnostics are an integral element of the Shiva computer network that handles data acquisition and system control, as shown in Fig. 2-142. To facilitate the acquisition and reduction of the large quantities of data from beam diagnostics, a three-level computer system is used. The first level of this system is a microprocessor to which the various diagnostic sensors are interfaced. At this level the raw measurements are taken from the sensors, digitized, and preprocessed. The preprocessed data can be accessed by an operator at the front-end processor (FEP) whether or not the other elements of the computer system are operational. Access to data stored in the FEPs, as well as their local operation, is provided by a control panel on each FEP (an example is shown in Fig. 2-143), which may be used to obtain data from an individual sensor in either processed or raw form. This data may be viewed on the control panel LED display. Alternatively, a mobile teletypewriter and floppy disk recorder can be plugged into an access panel on the front of each FEP. With the teletypewriter and disk, a more detailed level of communication with the FEP can be established. In this way the data can be transferred to disk for transfer to another machine if desired. In normal operation, however, the data will be transmitted via an optically isolated serial link to the second-level processor in the control room (a PDP-11/34). This processor collects data from the FEPs and does all the calculation and correlation of the beam diagnostics. It is at this level that the operator normally communicates to the diagnostic system. This second-level machine communicates with the other second-level machines in the system to properly configure beam diagnostics in coordination with the system's operational parameters (i.e., filters inserted, appropriate gains of amplifiers set, etc.).

Operator input and control will be done at a console equipped with programmable switches, a plasma display with touch panel screen, and a color-graphics CRT. The programmable switch array will

allow an operator to input control parameters to the diagnostic system. The plasma display terminal will show system status messages and permit the operator to request data to be displayed by touching

the desired parameter or choosing from a "menu list" presented on the plasma display. In this manner, successively greater levels of detail may be requested by an operator.

Fig. 2-142. Relationship of the beam diagnostics controls to the overall Shiva control system. The first-level high speed minicomputer controls and monitors all second- and third-level machines which are dedicated to one or another of the four major functions of power conditioning, alignment, fusion diagnostics, and beam diagnostics. The second-level machines collect data from a number of third-level machines which contain a variety of interfaces to control functions or acquire data from various sensors.

Oscillator and Preamplifier Diagnostics

Figure 2-144 is a schematic representation of the acousto-optic mode-locked oscillator and its diagnostics, which include measurement of prelude cavity power, sampling of the prelude pulse shape,

recording of the output pulse shape, and recording and display of the switchout-rejected pulse train. In addition, the energy of the beam will be recorded at the output of the pulse shaper, at the output of the two α rod preamplifiers, and at the output of the

Fig. 2-143. Typical local control panel for a beam diagnostics FEP. A display is provided for viewing output data or input calibrations. Thumbwheel switches are used for requesting a particular sensor and for inputting calibration data. The remaining switches are for requesting a particular operation of the FEP.

last β rod preamplifier on the oscillator table. The prelate level of the oscillator will be monitored with a slow photodiode coupled into a high gain amplifier whose output is coupled to an FEP where it is digitized. The other pulse energy measurements are

made with pin photodiodes, whose output is amplified by charge amplifiers and then transmitted to an FEP where it is digitized.

The prelate pulse shape provides a very sensitive measurement of the operation of the acoustically

Fig. 2-144. Oscillator switchout and pulse-shape-related diagnostics. A sampling scope monitors the prelate pulse train of the mode-locked oscillator by recording and displaying the Bragg angle reflection from the switch. A transient digitizer views and monitors the performance of the switchout by digitizing and displaying the rejected pulse train. The detailed temporal shape of a slice of the shaped pulse is obtained with an ultra-high-speed streak camera whose output is recorded by a reticon linear diode array. The control of all data is provided by an FEP which in turn sends the data to and is controlled by the second-level processor in the control room.

mode-locked oscillator. Any change in the operating parameters will affect the pulse shape and stability. Consequently the pre-lase pulse shape will be monitored by using a fast photodiode in a sampling mode to reconstruct a typical pulse shape from the pre-lase pulse train. This pulse will be displayed and its amplitude and width monitored by the diagnostic computer network. The shaped and amplified output pulse will be recorded with a streak camera which observes a spatially fixed temporal slice of the beam. The output of the streak tube is imaged into a Reticon photodiode array. The integrated output of the Reticon array provides an analog signal, proportional to the temporal beam intensity, which is sampled, held, digitized, and fed into memory for readout and processing by the oscillator table FEP. To monitor the performance of the switchout module, the rejected pulse train will be monitored with a fast photodiode and transient digitizer. The rejected train will be displayed in the control room by a graphics display and locally by a long-persistence monitor in the laser bay.

Chain Diagnostics

The chain diagnostics consist of pulse energy measurements at selected locations where high gain or potentially high loss mechanisms exist. Figure 2-145 shows the locations selected for the energy-monitoring diodes.

To avoid inserting optical elements into the beam, energy will be collected and focused onto photodiodes from existing component reflections. Two sources of reflections at the desired monitoring points are available: reflections from the polarizers, and reflections from the spatial filter lenses.

Figure 2-145 shows how energy measurements will be made at polarizers. Light of the correct polarization (p) along with light of the undesired polarization (s), enters the polarizer rotator package. Approximately 97% of the s-polarization is rejected at each of three faces, along with approximately 1% of the p-polarization. At the fourth polarizer surface, previous reflections have reduced the remaining s-polarization to less than 0.01%, while approximately 1% of the p-polarization will

Fig. 2-146. Spatial filter energy monitoring. The output energy of the spatial filter is sampled by using two annular reflectors to image the ghost focus of the spatial filter output lens onto photodiodes whose signal is charged-amplified and transmitted to an FEP, where it is processed to give the output energy.

be reflected, so that the ratio of reflected p- to s-polarization is greater than 100. This reflected energy is then focused onto a photodiode whose output signal is integrated, sampled, digitized, and

Fig. 2-147. A typical FEP contains the microprocessor CPU, 8K to 24K of 16-bit memory, multiplexer, analog-to-digital converter, digital-control drive card for controlling gains of the charge amplifiers and calorimeter amplifier functions, front-panel interface card for operation of the local control panel, serial-link card for communication with the control room, floppy disk controller for use with floppy-disk storage media, and a terminator bootstrap card which contains an ROM-coded power-up routine and termination for the FEP bus lines.

transmitted to the second-level processor by the FEP. The data from four locations on ten arms is multiplexed onto a single interface.

The output energy of the spatial filter will be collected by imaging the reflection from the second surface of its output lens. As shown in Fig. 2-146, two annular spherical reflectors are used to sample nearly the entire beam. This is necessary since large spatial variations in beam intensity would be undetected by small-area sampling.

Figure 2-147 shows the major elements of the detectors and data acquisition FEP for the chain diagnostics. Large-area pin photodiodes are used to intercept an aberrated image from the spatial filter reflectors and the polarizer collecting lenses. The low-level diode output is fed to a nearby charge amplifier (Fig. 2-148) which boosts the signal level to several volts for transmission to an FEP. The signals from as many as 40 diodes are serviced by a single FEP. At the FEP the signals are sampled and held when an external signal from the power conditioning and timing systems notifies the FEP that a shot is being fired. The sampled signals are then digitized serially. The raw data is reduced to give the energy and then transmitted upon request to the second-level processor.

Incident Beam Diagnostics

The output of each beam will be monitored by the incident beam diagnostics (IBD) package shown in Fig. 2-149. This package, which is mounted in the

Fig. 2-148. Prototype charge amplifier, used to amplify the nanoampere signals from the sensing diodes to several-volt signals for transmission to the FEP. The amplifier features high gain, excellent noise immunity from electromagnetic radiofrequency interference, and digitally controlled gain selection.

Fig. 2-149. Incident beam diagnostics (IBD) package contains a calorimeter for measuring total beam energy, pinhole calorimeters for measuring focusable energy, TV monitor for viewing alignment of IBD pinhole and spatial filter pinholes, array camera for recording far-field pattern of beam in equivalent target planes, and photodiodes for recording the temporal shape of long pulses. Collection and reduction of data from calorimeters and control of the various stepping motors and solenoids for positioning optical elements in the IBD are performed by the beam diagnostics computer network. These optical elements are: equivalent-plane focus lens, filter for limiting energy density at focus, pinhole and crosshair, TV viewing mirror, and λ -V filter set.

Fig. 2-150. Schematic of relations of IBD and PFC (pointing, focusing, and centering) packages. Both total-beam and pinhole energy calorimeters are included in the IBD package which receives the incident beam energy transmitted through the final turning mirror. A third calorimeter, PFC sensor package, intercepts the energy reflected from the target back along the beam line through the final turning mirror. A set of four portable large-aperture calorimeters are periodically inserted directly into four beams to calibrate the IBD calorimeters. Numerous stepping motors, used to position the IBD elements and pointing mirrors, are controlled in groups of 60 by the motor control FEP.

target bay, will intercept 2-4% of the incident beam transmitted through the final turning mirror. The IBD will measure the total energy in each beam and the energy focusable to a given spot size in the equivalent target plane will make far-field beam photographs in multiple-image arrays, and will contain a TV camera for pinhole alignment. Provisions

are also made for attaching a streak camera externally to obtain the temporal shape of short pulses and a fast photodiode inside the IBD for long-pulse temporal measurements. The mechanical details of the package are described in Section 3.

Measurement of the output energy is made by a sensitive calorimeter with a 50-mm clear aperture

Fig. 2-151. Temperature response of a calorimeter. Before the shot, the calorimeter has an exponential drift toward a final temperature T_{∞} . After the shot heats the calorimeter at time t_0 the calorimeter cools at an exponential rate starting at T_e . By periodically sampling the amplified output of the calorimeter, an exponential is fitted for the region T_a to T_b before the shot and T_0 is calculated. Similarly for the region T_e to T_f after the shot, an exponential is fitted and the corrected temperature peak T'_0 is determined. $T'_0 - T_0$ yields the temperature rise and hence the energy deposited on the calorimeter.

which intercepts the slowly converging beam of the IBD. Measurement of the focusable energy will be provided by a 25.4-mm-clear-aperture calorimeter which intercepts the diverging beam after it passes through an equivalent-target-plane pinhole of the IBD package. A TV camera is provided which views the plane of the pinhole in the IBD and simultaneously images all the pinholes of a single chain's spatial filters. Images of the target plane and planes before and after the equivalent target plane are provided by a multiple-image-array camera. The functions required to operate the IBD are listed below:

1. Measurement of energy incident on calorimeter.
2. Calibration of IBD calorimeter.
3. Pointing control of beam into IBD.
4. Focusing of beam to desired equivalent target plane.

5. Positioning of appropriate shutter, beam splitters, and filters for the range of input energies and for cw alignment operation of the IBD.

The energy incident on the IBD calorimeters will be as low as 10 mJ, which produces a signal level of approximately 10 μ V. The signal from the calorimeter will be amplified by a low-noise amplifier to give several-volt output signals which are transmitted over cables to an FEP where they are multiplexed, sampled, held, and digitized. Figure 2-150 is a schematic of the data acquisition system for the calorimeters.

A typical response of the isoperibol calorimeter is shown in Fig. 2-151. The corrected temperature rise is defined as ⁶⁷

$$\Delta T = T_c - T_b + k \int_{t_b}^{t_c} [T(t) - T_\infty] dt, \quad (17)$$

Fig. 2-152. Pointing, focusing, and centering (PFC) package and return beam diagnostics. The pointing and focusing elements of the PFC are described in the alignment section. An add-on module for monitoring light reflected from the target is operational during a shot when the PFC shutter mirror is in the position shown after the alignment functions are complete. The reflected energy is measured with a calorimeter. A multiple-array camera views the target planes in reflected light.

Fig. 2-153. A prepulse monitor, housed in one of the IBD packages measures energy incident on the target before the main pulse arrives. A fraction of the diagnostic beam is split off into a photodiode to give an energy reference level followed by a second delayed pulse at 1000 times the power, thereby allowing the low-level prepulse energy to be detected on an oscilloscope trace. (A 100- μ J prepulse is sufficient to destroy a target before the main pulse arrives.)

where k is the thermal leakage modulus and the various times (t) are as defined in Fig. 2-151. Under actual shot conditions, the data between t_b and t_c is often buried in noise; therefore, $T(t)$ (the temperature of the calorimeter) is unknown in this region, and the evaluations of the integral cannot be done. However, in the ideal case, the temperature of the calorimeter in the region t_a to t_b and t_c to t_f is given by:

Before irradiation, $T = T_{\infty} - (T_{\infty} - T_b) \exp [k(t_b - t)]$.

After irradiation, $T = T_{\infty} - (T_{\infty} - T_c) \exp [k(t_c - t)]$.

The processor fits the data points taken at equal intervals before and after the shot to this exponential form. The exponentials are then extrapolated to the shot time to give the temperature rise and hence the energy deposited on the calorimeter. The calorimeters have a built-in heating element with a known resistance. A constant current pulse of known energy is put through the heater elements periodically to confirm that no change in the sensitivity of the calorimeter or acquisition electronics has occurred. Since the calorimeters in the IBD are receiving a fraction of the beam after reflection, they are calibrated in sets of four by inserting a large-aperture calorimeter of the same type directly

Fig. 2-154. An amplified spontaneous emission (ASE) monitor will be periodically inserted in the beam to measure the ASE energy in the beam with no pulse switched from the oscillator. A calorimeter behind a pinhole intercepts the energy in an angular cone equivalent to that of the target. A TV vidicon and monitor are used to center the pinhole on the focused beam.

in the beam after the final turning mirror. In this way a calibration factor accounting for all reflections and transmissions is measured.

Pointing of the beam into the IBD will be accomplished by stepper-motor-driven gimbaled mirrors. The stepper motor will be controlled by an FEP through a motor multiplexer and driver module in the same manner as the spatial filter and other gimbal-drive units described in § 2-2.10. Focusing of the beam to the plane of the pinhole will be accomplished by a linear translation stage driven by a stepper motor. Since a range of energy between 1 and 20 J is incident on the package, there is a variable-reflectance splitter wheel which is positioned in the beam by a 1.8° stepping motor. In addition there are filter wheels for the TV camera and shutters for the calorimeter which are driven by four-position stepper motors and/or solenoids. These are all controlled by an FEP which will have control panels in the target bay and in the laser control room. By controlling the FEP, the second-level processor will select the correct filters, shutters, etc. automatically for a given shot according to its energy. Manual override is provided for special applications.

Reflected Energy

The target will reflect part of the incident light

back along the path of each input beam. Approximately 2% of this light will be transmitted through the final turning mirror and will appear at the diagnostic port of the pointing, focusing, and centering (PFC) sensor as indicated in Fig. 2-152. The reflected energy will be measured by a sensitive calorimeter in a configuration similar to that used for measuring output energy. The response of these calorimeters will be monitored and the data processed in the same manner as for the IBD calorimeter. Alternately, the reflected light in some beams will be monitored by a streak camera to determine its temporal properties.

Prepulse Measurement

Prepulse energy can come either from interpulse noise in the mode-locked oscillator output, some of which gets switched out by the pulse selector along with the main pulse, or from leakage of adjacent pulses through the pulse selector. On at least one beam, the prepulse will be monitored by the arrangement shown in Fig. 2-153. The amount of attenuation required in the short path to reduce the main pulse signal to the same level as the prepulse noise in the long path is a direct measure of the contrast ratio between the prepulse and the main pulse. The very high contrast ratio that is required to prevent target damage can be achieved by use of

saturable dye in the preamplifier section of the laser, where some losses are acceptable and beam breakup is not a severe problem.

Amplified Spontaneous Emission Monitor

Very small amounts of energy deposited on the target in advance of the main pulse can degrade the target's performance or even destroy it entirely. One source of such energy, oscillator prepulse, has already been discussed. A second source of harmful energy is amplified spontaneous emission (ASE) from the amplifiers, approximately one-half of which arrives before the main pulse. For a given chain configuration, the amount of ASE is not expected to vary significantly from one chain to another or over rather extended periods of time, provided that all the ASE-suppression devices, such as Pockels cells and rotating shutters, are working properly. However, to measure the ASE level initially and to periodically confirm proper ASE suppression, an ASE monitor will be assembled in a standard diagnostic module so that it can be used at the output of any chain. As seen in Fig. 2-154, the monitor consists primarily of a sensitive calorimeter to measure the energy focused through a small aperture. The aperture size is chosen to subtend an angular cone equivalent to that of the target, and

the vidicon and diffuser are used to make sure the aperture is centered on the beam.

References

67. S. Gunn, *On the Calculation of the Corrected Temperature Rise for Isoperibol Laser Calorimeters*, Lawrence Livermore Laboratory, Rept. UCRL-52019 (1976).

Authors

R. G. Ozarski
E. S. Bliss
L. G. Seppala

2-2.13 Target Chamber

The final design configuration of the Shiva target chamber incorporates a bi-symmetrical illumination scheme with a 10-beam cluster on top and bottom, as shown in Fig. 2-155. Table 2-32 summarizes the chamber characteristics.

The focusing optics are 200-mm diam, $f/6$, BK7 lenses that focus through 15-mm-thick vacuum windows and 3-mm debris shields as shown in Fig. 2-156. The focal spot from each cluster of 10 beams

Table 2-32. Characteristics of Shiva target chamber

Vacuum vessel — 1.6-m-diam 304L vacuum melted stainless steel; weight 550 kg (12,100 lb).

Illumination geometry — 2 opposite conical clusters of 10 beams each cluster.

Focus lenses — $f/6$, 200-mm-beam diam., $\lambda/10$ at 1.06- μ m wavefront quality, 15-mm thick.

Vacuum windows — $\lambda/16$ wavefront quality, 15-mm thick.

Debris shield — BK7, 3 mm thick, $\lambda/10$ wavefront quality.

Lens positioner — translation ± 5 mm, focus ± 10 mm, rms system linearity 0.05%, single stage accuracy $\pm 5 \mu\text{m}/5$ mm, 2- μ m step size.

Target positioner (cryogenic) — 3 translation stages + 1 rotation; Z ± 30 mm, X, Y ± 10 mm with 0.04% rms system linearity; 455-kg capacity; system accuracy $\pm 10 \mu\text{m}/10$ mm 0.2- μ m step size.

Vacuum — 3×10^{-7} Torr bare chamber, 10^{-6} Torr with diagnostics.

Diagnostics ports — 190 O-ring sealed ports in vacuum vessel.

After the beams are pointed and focused with the use of a surrogate target, shown in Fig. 2-157, the fusion pellet is substituted at the target point with the stepper-motor-driven four-axis target positioner with $\pm 5\text{-}\mu$ accuracy, and the foci are repositioned with the three-axis stepper-motor lens positioners to within $\pm 5\text{ }\mu\text{m}$ in x, y, and z directions of the desired point on the real target.

the vacuum load. Optical analysis shows the refractive shift in focus, as a result of removing the air from the chamber, is $-326\text{ }\mu\text{m}$ for the f/6 lenses. The changes in focus because of vacuum load deflections are obviated by pointing and focusing after pumpdown.

Target diagnostics instrumentation will be mounted at the appropriate positions schematically shown in Fig. 2-155. Measurements to be made are neutron energy and spectrum, energy balance, alpha and beta spectroscopy, x-ray fluence and spectrum, optical spectrum, x-ray streak, x-ray microscope, ion spectrum, and proton detector.

The mechanisms contributing to the focal plane intensity distribution of the clustered f/6 focusing system are evaluated below. The primary contributor to enlargement of the spot diameter is unfiltered small-scale self-focusing. Other contributors

2-170

Fig. 2-156. Shiva focus lens, window, and debris shield. The back focal length of the f/6 lens is 1204.0 mm under vacuum. With air in the target chamber, the BFL is 1204.34 mm.

Table 2-33. Summation of spot-size contributors

Source	Model	Diametral increment, μm (high power shot)
Main Beam (contains ~80% of the energy)		
Main beam central lobe	$2.44N\lambda \text{ (f/No.)}$	78
Main beam zoom	$2.44N\lambda \text{ (f/No.)} \left(\left[1 + \left(\frac{4B}{2.44\pi N} \right)^2 \right]^{1/2} - 1 \right)$	29
Pointing error	$\Delta\theta D \text{ (f/No.)}$	12
Focus error	$\Delta f \div \text{(f/No.)}$	7
Lens repositioning error	System analysis	10
Beam tilt	$D_s \left(\frac{1}{\cos \gamma} - 1 \right)$	6
		Total 142
Small Scale Pinhole Image (~15% of the energy)		
Pinhole image	$D_{ph} [(f/\text{No.})_i \div (f/\text{No.})_{sf}]$	300
Pinhole diffraction	$2.44\lambda \text{ (f/No.)}$	16
Pinhole positioning error	System analysis	6
Pointing error	$\Delta\theta D \text{ (f/No.)}$	12
Focus error	$\Delta f \div \text{(f/No.)}$	7
Lens repositioning error	System analysis	10
Beam tilt	$D_i \left(\frac{1}{\cos \gamma} - 1 \right)$	17
		Total 368
Unfiltered Small Scale Beam (~5% of the energy)		
Small-scale focused beam	$2.44\lambda \text{ (f/No.)}_i D_b \div D_{ss}$	1552
Pointing error	$\Delta\theta D \text{ (f/No.)}$	12
Focus error	$\Delta f \div \text{(f/No.)}$	7
Lens repositioning error	System analysis	10
Beam tilt	$D_s \left(\frac{1}{\cos \gamma} - 1 \right)$	79
		Total 1660

Fig. 2-157. The surrogate target is made by lapping a 5-mm ball bearing to $1/20\lambda$ sphericity and gold vapor plating the surface. The stalk is a 1-mm-diam rod. The photo shows a red laser beam focused at the half radius point. The collimated reflected beam is pointed a little to the left of the incident beam.

are diffraction, phase aberrations, focal zoom, and pointing, focusing and lens positioning errors.

The laser beams enter the 200-mm-diam $f/6$ lenses in a 10-beam cluster on top and bottom of the target chamber (Fig. 2-155). The far-field intensity distribution of each cluster of 10 superimposed focal regions is determined by the combination of many phenomena. Table 2-33 summarizes the error contributors. Figure 2-158 shows the expected typical intensity distribution at focus for a high power shot with beams superimposed at a common point.

Effects of Small-Scale Self-Focusing. In the Shiva amplifier chain, $f/10$ spatial filters with about 500- μm diam pinholes limit the amplification of small-scale structure with divergence greater than 250 μrad . The focus lens images the final spatial-filter pinhole at the focal plane as shown in Fig. 2-159.

The image diameter is

$$D_i = D_{ph} \frac{(f/\text{No.})_1}{(f/\text{No.})_{sf}} \quad (18)$$

where D_{ph} equals the diameter of the pinhole, 500 μm .

Although there are four spatial filters in each amplifier chain, the final amplifier stage has no spatial filter. Thus, the small-scale energy developed in the final amplifier (2 to 5% of the beam) will be focused at a wide angle, i.e., greater than a milliradian. Since the individual lumps of small-scale structure can be considered as separate small-diameter beams, an estimate of their focal diameter is⁶⁸

$$D_i^{(ss)} \cong 2.44\lambda (f/\text{No.})_{ss} \quad (19)$$

$$D_1 = \text{first Airy ring diameter} \quad (20)$$

$$(f/\text{No.})_{ss} = \frac{D_b}{D_{ss}} (f/\text{No.})_1 \quad (21)$$

where

D_b = beam diameter, 200 mm,

D_{ss} = small-scale structure diameter, 2 to 4 mm,

λ = 1.06 μm ,

$(f/\text{No.})_1$ = $(f/\text{No.})$ of focus lens, $f/6$.

Diffraction. The diffraction at the edge of the pinhole increases the size of the pinhole image by a small amount given by

$$\Delta D_1 = 2.44\lambda (f/\text{No.})_1 \quad (22)$$

Main Beam Zoom. The whole beam self-focusing zoom shifts the main beam (consisting of *non* small-scale-self-focused energy) focal plane toward the lens, but does not shift the pinhole image. Thus, the central lobe grows in diameter at peak power by approximately⁶⁹

$$\overline{\Delta D} = \overline{D}_0 \left(\sqrt{1 + \left(\frac{4B}{2.44\pi N} \right)^2} - 1 \right) \quad (23)$$

where

Fig. 2-159. The beam focusing lens produces a focal spot with a diameter equal to the pinhole diameter times the ratio of the f-number of the focusing lens to that of the spatial filter lens.

by misalignment and turbulence, the estimated spot diameter is

$$2.44n\lambda (\lambda \text{ No.}) \quad (24)$$

where N = number of times diffraction limited (~ 5). Figure 2-160 shows the focus of an Argus shot. The spot containing 84% of the energy is about $8\times$ diffraction-limited.

Pointing Error. The beam pointing error for Shiva will be about $\pm 5 \mu\text{rad}$. Thus the superimposed shots of both main beam, small-scale beam, and pinhole image will form a superimposed diameter larger than an individual spot by

$$\Delta D = \theta D_b (f/\text{No.}), \quad (25)$$

where

θ = beam pointing error, $\pm 5 \mu\text{rad}$,

D_b = beam diameter ($\approx$ focus lens diameter).

Focus Error. The focus error of the PFC system has been measured to be $\pm 20 \mu\text{m}$, which causes a change in spot diameter of

$$\Delta D_f = \Delta f \div (f/\text{No.}), \quad (26)$$

where

Δf = focus error.

Lens Repositioning Error. After pointing and focusing the beams at the half radius point of the surrogate target (a 5-mm-diam gold plated $\lambda/20$ ball), each focus will be moved to the superimposed position with an accuracy of $\pm 5 \mu\text{m}$ giving a $\Delta D_i = 10 \mu\text{m}$.

Beam Tilt. Since the focus lenses are not superimposed but clustered, the focal spots of the "tilted" beams are elliptical in the focal plane of the cluster. The increase in spot diameter is given by

$$\Delta D_s = D_s \left(\frac{1}{\cos \gamma} - 1 \right), \quad (27)$$

where

D_s = focal spot diameter (excluding pointing and repositioning errors),

γ = half angle of beam axis, 17.5° (for outer beams).

Target Positioner

Mechanical, Vacuum, and Cryogenic Characteristics. The target holder (pylon) and the pellet temperature control system are mounted on the target positioning system, which is comprised of

three orthogonal translation stages and a rotary stage about the two axes as shown in Fig. 2-161.

The interface between the target positioner and the target chamber is a sliding vacuum valve of 12-in. opening. The positioning system is mounted on the valve through a bracket that transmits the vacuum and weight loads to the target chamber through the stainless steel valve body. The vacuum

valve permits the insertion of the pellet (permanently connected to the cryogenic system) without breaking vacuum in the target chamber.

The interface between the target pylon and the fixed body of the vacuum valve consists of a bellows and a slide-through O-ring. The bellows accommodates a 200-mm-diam pylon with an adjustment range of ± 10 mm in x and y . The 200-mm pylon

Fig. 2-160. The Argus north beam focuses to about $9\times$ diffraction-limited spot diameter. The Shiva beams are expected to focus to a $5\times$ diffraction-limited spot.

diameter is the minimum required to allow room for cryogenic conduction lines and insulation required to cool a cryogenic pellet. The pylon incorporates a mechanism to remove the surrogate target and expose the pellet several seconds prior to the laser pulse.

The cryogenic system with pylon is transported as a unit from the target fabrication facility. The transportation rails are supported by the target spaceframe, but the ends at the target chamber are located on the target positioning system such that the entire unit is centered on the z-axis of the target positioner. This minimizes the shock and vibration during the transition from transportation system to positioning system. A smaller diameter target positioner with a retractable target holder is provided for noncryogenic targets. The target positioner in this non-cryo configuration will also permit the insertion of the target under vacuum. Table 2-34 lists the accuracy specifications of the cryogenic target positioner.

Lens Positioner

The lens positioner places and maintains the lens in a stable and known position so that the laser beam is focused and pointed on the proper area of the target.

To achieve this objective, the lens positioner provides three degrees of freedom along three mutually orthogonal axes.

Since the coma of the f/6 lens used in this design is only $\lambda/17$ ($\lambda = 1.06 \mu\text{m}$) for a tilting error of 1 mrad, no automatic correction is provided for rotations about the x and y axes; however, a manual adjustment is provided for the initial parallelism alignment between the lens and beam optical axes.

The lens translation mechanism consists of three semi-standard Aerotech translation stages arranged as shown in Fig. 2-162. These stages provide for a total travel of 50 mm on each axis, but the required and usable range in this design is ± 5 mm in x and y and ± 15 mm in the z axis.

The stages are driven by stepping motors of 200 step/revolution at a variable rate from 1 pps to 500 pps with step size of $2\text{-}\mu\text{m/step}$. The repeatability of any given position along the 20-mm travel is 4 μm .

As shown in Fig. 2-162, the three stages are mounted on a triangular base plate that is assembled to the target chamber by three extendable legs with universal joints on the base plate.

The "X" stage is directly bolted to the base plate; the "Y" stage is mounted on top of the "X" stage, and the "Z," or focusing stage is mounted to the "Y" stage through a simple aluminum angle bracket. The orthogonality among the three stages is ± 0.50 mrad.

The lens is mounted in an aluminum cell with a deep rim and is retained by a circular retaining ring. The lens-cell assembly cantilevers from the "Z" stage, but it is light enough that its overhanging weight produces negligible deflections on the entire system.

The lens-retaining ring provides a reference surface parallel to the lens principal surface within 0.035 mrad so that a mirror located on this surface is used to align for parallelism between the optical axis of the lens and laser beam with reference to the z axis when the laser beam is pointing to the focal point on the target. This parallelism is achieved by manually adjusting the length of the three independent legs connecting the lens positioner base plate with the target chamber.

The position along each axis is monitored by a linear film potentiometer, C.I.C. model "111 special," with a linearity of 0.1% and a theoretically infinite resolution. The potentiometer is mounted between the translation plate and the base plate of each stage, thereby providing an absolute reading of the relative position between the two plates of each stage. Table 2-35 lists the lens drive specifications.

Centering Screen

The basic function of the centering screen is to retroreflect the laser alignment beam toward the pointing focusing and centering (PFC) detector (where an image of the screen is formed and transmitted to the TV monitor) and centering detector.

By adjusting the angular positions of the turning mirrors, the alignment beam is centered on the centering screen. The screen is mechanically centered on the focusing lens during assembly. There are 20 centering screens, one for each lens, and they can be inserted or retracted individually or simultaneously. (See § 2-2.10 for a fuller description of the beam centering procedure.)

One of the basic requirements for the centering screen is that the direction of the reflected beam be insensitive to incidence angle between laser beam

Table 2-34. Accuracy specifications of target positioner

Parameter	Range (mm)	Full range accuracy (μm)	Drive system linearity (%)	Repeatability (μm)	Orthogonality (mrad)	Runout (mrad)	RMS system linearity (%)	Maximum rate (mm/s)	Remarks
X translation	± 10	± 5	0.02	± 2	0.25	0.25	0.04	1	Uses stepping motors and linear potentiometers on translation stages.
Y translation	± 10	± 5	0.02	± 2	0.25	0.25	0.04	1	
Z translation	± 30	± 15	0.02	± 2	0.25	0.25	0.05	1	
α_z	$\pm 10^\circ$	± 1 mrad	—	± 0.5 mrad	—	0.25 m	—	1 deg/s	

Table 2-35. Shiva f/6 lens positioner specifications

Parameter	Range (mm)	Stage accuracy (μm)	Readout linearity (μm)	Stage repeatability (μm)	Readout repeatability (μm)	X; Y; Z orthogonality (mrad)	X; Y; Z alignment to laser beam (mrad)	Stage runout ($\mu\text{m}/\text{mm}$)	Maximum speed (mm/s)	Drive size step (μm)	RMS-drive open loop accuracy (μm)
X and Y translation	± 5	± 5.5 (3.0 rms)	25	± 4	± 5	0.50	0.50	0.1	1	2	6.0
Z translation	± 15	± 5.5 (3.0 rms)	25	± 4	± 5	0.50	0.50	0.1	1	2	9.5

and screen, thereby eliminating the necessity of accurate angular positioning of the screen. This is done by using an array of small corner cubes as a reflective screen instead of a flat mirror.

To facilitate the location of the screen center, it has in its center a 25-mm-aperture solid corner cube. The screen is made of replicated plastic triangular pieces, 75 mm/side (see Figs. 2-162 and 2-163). The reflective surface of each piece is made up of hollow first-surface reflective corner cube ele-

ments, of approximately 1-mm aperture each. The triangular pieces are mounted on a flat plate, and an aluminum reflective coating enhanced at $\lambda = 1.06 \mu\text{m}$ is then deposited.

The screen reflects 60% of the light within a 3-mrad cone, which is collected by the PFC system. The reflectivity of the center corner cube is about 90% with a divergence of 0.1 mrad. Therefore, the image of this center corner cube and its edges is clearly distinguishable from the rest of the screen

Fig. 2-161. The target positioner for cryogenic targets can position a 300-kg cryogenic system and target to 5- μm accuracy while resisting the 600-kg vacuum load on the pylon.

Fig. 2-162. The lens drive has a ± 15 -mm range with $5\text{-}\mu\text{m}$ accuracy. The centering screen can be positioned with 0.25-mm accuracy.

Fig. 2-163. The retroreflecting plastic module is replicated from a metal die, aluminum vapor plated, and enhanced for maximum first surface reflectivity.

image and can be used for centering purposes. Filters can be placed on the center cube to lower its reflectivity when required.

For the centering operation, the screen is in the inserted position with its center in coincidence with the focusing lens center within 0.5 mm. After beam centering is achieved, the screen is retracted out of the laser beam path, and the beam focusing and pointing operations are performed.

Figure 2-162 shows the prototype centering screen. The top of the screen is the reflecting side assembled on the flat base plate. The screen and its base are attached through two brackets onto two parallel shafts. One of the shafts serves the purpose of a guide. It is rigidly bolted to the brackets and slides in a linear ball bushing. The other shaft is the moving member of a reversible linear induction motor, and it is flexurally mounted to the brackets to allow for small misalignments. The linear induction motor drives the shaft, moving the screen in and out of the laser beam path. The velocity can be adjusted by varying the voltage applied to the motor windings.

Adjustable air dashpots at the end of each travel absorb the excess kinetic energy of the screen, providing a smooth deceleration to the final stop. Once in this position, a set of microswitches cuts the motor current, avoiding overheating and thermal distortions on the structure. The screen is held in the final position by permanent magnets. The starting force of the linear motor is greater than the holding force of the magnets.

The linear motor and linear ball bushings are mounted on an aluminum base, which is attached to the X-Y stage of the lens positioner. By this means the screen and lens, once centered during assembly, will keep their relative position to each other, since both will move as a unit in the x-y plane. The focusing of the lens along the z axis does not move the screen.

References

68. E. Bliss, Lawrence Livermore Laboratory, private communication (September 1976).
69. J. B. Trenholme, Lawrence Livermore Laboratory, Internal Document, *Focal Zoom and Spot Size*, TDA 76-279 (1976).

Authors

W. C. O'Neal
J. A. Monjes

Major Contributors

J. I. Stewart, EG&G
A. Richmond, EG&G
F. Rienecker, Jr.
S. S. Glaros

2-2.14 Target Diagnostic System

The target diagnostic control and data acquisition system for Shiva is an upgrade of the Argus system (Section 3) and will be fully integrated into the overall Shiva control and data-acquisition system. Three primary requirements are addressed by this subsystem: target diagnostic data acquisition, immediate data analysis and display, and data archival. Additional requirements imposed on the system design for reliability and capability are local stand-alone data acquisition capability, peripherals shared with other Shiva systems, and compatibility with existing target diagnostic data acquisition systems on the Argus and Janus lasers. These requirements will be fulfilled by the distributed processing and acquisition system shown in Fig. 2-164.

The standard of the CAMAC serial highway interface will be used as in Argus but will be connected to an LSI-11 front-end processor (FEP). In the layout, the FEP resides in an instrumentation alcove in the target bay and is connected to the control room PDP-11/34 by a fiber-optic serial link. The CAMAC crates are distributed around the target area as near to the instrumentation as possible (see Fig. 2-165). This LSI-11 system can acquire and record the data from a target shot without use of the PDP-11/34.

Under normal operating procedures, the LSI-11 communicates with the PDP-11/34 to obtain control signals and transmit recorded data for analysis and archiving in the larger machines. The PDP-11/34 computer's function is to coordinate control of the target diagnostic block and process the acquired data. This processor connects to the control panel through an LSI-11 FEP for operator interaction.

The analysis capability is handled by two graphics terminals and a printer/plotter in the analysis room next to the control room. Target shot data will be processed immediately, much in the same manner as the Argus system but with improved software capability. The PDP-11/70 system coordinates and archives the target shot data and laser diagnostic data. The data can be written on magnetic tape on the PDP-11/70 system for transport to the LLL Octopus system for permanent retention and comparison with LASNEX code predictions.

The software operating systems for the processors will be the RSX-11M operating system. Most control and processing programs will be identical to the Argus codes written in BASIC and FORTRAN.

Assembly-language CAMAC handler and communication packages will be common with the rest of the Shiva system, as well as the Argus and DDG computer systems.

Fig. 2-164. The Shiva target diagnostic subsystem consists of the CAMAC fiber-optic serial highway, LSI-11 FEP, and PDP-11/34 control and analysis system. The connection between the PDP-11/34 and PDP-11/70 over the parallel link allows data archiving and supervisory monitoring and control.

Fig. 2-165. The target diagnostic CAMAC subsystem is distributed throughout the target bay with connections to the neutron time-of-flight facility. The primary control console and PDP-11/34 reside in the control room with a fiber-optic link to the local control LSI-11 at the target chamber. Remote analysis terminals are connected directly to the PDP-11/34 in the control room.

Authors

J. R. Greenwood

D. Campbell

J. E. Pollack

J. Severyn

2-3 SHIVA NOVA

2-3.1 Overview

Shiva Nova, an upgrade of the Shiva laser-fusion facility, is a several-hundred-terawatt system planned for operation in the early 1980s. With this system, we calculate that we can reach the final scientific milestone necessary for a commitment to a prototype laser-fusion reactor; that milestone is to prove the scientific feasibility of laser fusion as an energy source by achieving high-gain microexplosions. Shiva Nova was made possible by recent advances in glass laser system technology. When the original Shiva Nd:glass laser system was first conceived, in 1972, it was considered to be nearly the largest solid-state laser system that could reasonably be built from both technological and cost considerations. However, subsequent advances in laser materials permitting increases in flux, power, and energy in solid state lasers—as well as advances in the system optical design and performance, and in control of large laser systems—have made accessible performance levels an order of magnitude higher, in the several-hundred-terawatt regime. The evident practicality of these performance advances has encouraged us to devote a serious effort to the design and development of an upgraded Shiva system. To this end ERDA has supported a Construction Planning and Design study for the Shiva Nova project in 1976 and 1977 and beginning line-item funding in 1978. The proposed project phases are briefly described in the following sections.

Project Strategy and Scope

The primary objectives of the Nova project are to achieve scientific breakeven (gain = 1) and scientific feasibility (high gain). To build a laser facility producing the 200 to 300 TW necessary for these objectives will require significant development over existing technology. The project will draw from our experience with the Shiva laser facility—the most advanced system of its kind—with both the scientific team that designed and built Shiva and the associated manufacturing capability being dedicated to the Nova project. In fact, the Shiva laser and facility will be physically incorporated and reused in the Nova system, which will decrease the

cost and time necessary to achieve the final 200-to-300-TW laser performance. Finally, since approximately 6 years will be required to complete a project of this complexity, Nova will be executed in phases so that portions of the laser can be utilized as soon as they are completed. These considerations have led to the following scenario, which is depicted in Fig. 2-166.

Nova I. The Nova I system is being designed to operate at 100 TW, to achieve scientific breakeven, and to be completed in FY 1981 provided that the project is limited only by construction and manufacturing rates, and not by funding rates. Laser system options which might increase the laser performance within this cost and schedule are being examined, but the 100-TW projection is based upon a conventional Shiva-like design, utilizing laser optical materials which are commercially available although not yet optimized for this application. The Nova I system will be installed in a new laser building attached to a new target room adjacent to the Shiva target room, thus allowing the Nova I system to go into operation without previously shutting Shiva down, and also providing for the incorporation of the Shiva system into Nova II.

A typical Nova chain design is shown in Fig. 2-167 in comparison with the Shiva chain design. The Shiva chain is optimized to operate with a pulse duration shorter than 500 ps, for which beam breakup due to nonlinear effects constrains the performance. The Nova chain is designed to operate over a wider range of pulses, from 100 ps to 3 ns, and thus has the added requirements of maximizing the stored optical energy, operating well into saturation, and propagating at the damage threshold of thin film coatings. As a result the Nova chain has a larger volume of laser glass to increase the stored energy for long pulses, and both a larger aperture and laser glass with a lower nonlinearity to increase power for short pulses. This Nova chain will operate at about $3.3\times$ the power of the Shiva chain and will cost about $2.3\times$ as much, giving a $1.4\times$ improvement in performance/cost. However, the Nova design is not yet optimized and will further improve before the design is frozen. The typical Nova chain design is discussed below.

Nova II. The second phase of Nova can operate at 200 to 300 TW, achieve scientific feasibility, and be

completed in FY 1983. Since the building modifications for Nova II will be small, the expenditures for this phase are almost entirely for laser and target system components, with the result that a 2X to 3X

improvement in capability is achieved at a cost comparable to that of phase I. At this time the Shiva components will be reused. The laser performance will be increased by increasing the number of laser

Shiva (20 TW, 1977)

Objectives: Significant thermonuclear burn
Compression to 1000X liquid density

Shiva (20 TW) and Shiva Nova I (100 TW, 1981)

Objective: Scientific breakeven

Shiva Nova II (200-300 TW, 1983)

Objective: Scientific feasibility

Fig. 2-166. The Nova project will be executed in two phases to minimize system downtime and bring completed lasers into use on laser fusion targets as soon as possible. Nova I will operate at 100 TW in 1981 and should achieve scientific breakeven. Nova II will operate at 200-300 TW in 1983 and should achieve scientific feasibility (high-gain microexplosions). Nova II incorporates the original Shiva system.

Fig. 2-167. A typical Nova chain is larger than a Shiva chain, has more amplifiers per stage to compensate for saturation-depleted gain, and is designed to operate with longer pulses at higher energy.

chains of the same design as used in Nova I. The target systems required for the high-yield experiments ($\sim 10^{19}$ neutrons) are more complex than for Nova I. The salient features of the Nova II target chamber are described below.

Construction Planning and Design (CP&D)

During FY 1976 and FY 1977 LLL is pursuing a CP&D study to define the scope, cost, and feasibility of the Nova project and to do preliminary design and critical component assessment studies to the extent necessary to confirm cost and feasibility. In FY 1976, approximately 1000 pages of study reports and memoranda on Nova target and sub-system designs were produced and summarized in the "CP&D Preliminary Report: Shiva Upgrade/Nova, September 1976." In FY 1977 specific baseline designs, costs, and execution plans will be produced for the Nova project.

Author

T. J. Gilmartin

2-3.2 Laser Chain Design

The design and optimization of large laser systems, described in detail in § 2-3.10, is a highly refined but inherently evolutionary process. Although the laser is designed to be non-target-specific and to operate over a reasonable range of power, energy, polarization, pulse shape, and illumination parameters, the level of understanding of the physics of laser-target coupling evolves (and so, accordingly, does target design), causing changes in the laser performance requirements. The Nova laser must be designed to operate over a wider range of pulse duration than was Shiva. The methods for staging and operating the laser components undergo significant innovation as time goes on. Shiva's final design, for example, was modified to incorporate imaging relays which were first demonstrated on Argus (its immediate predecessor). The design must be flexible enough to incorporate such new technology as it evolves. Finally, even if one could assume stable requirements and methods

of operation, the design optimization process itself is still very complex (see § 2-3.10). The following general discussion of a typical Nova chain is therefore presented with the understanding that it is a tentative representation of this high-energy, high-power laser chain. Before the Nova system is designed and its construction begun, major variations from this example will certainly occur.

The design is most strongly influenced by the nonlinear refractive index of the glass for short pulses, by the thin-film damage threshold for a wide range of intermediate-length pulses, and by the energy storage for long pulses. These high-leverage parameters are the object of highly directed research and development programs described in other Solid

State Program sections of this annual report. It is certain that better glasses and coatings than are being used on Shiva will be available for Nova.

The performance and cost of a laser chain are examined using an array of computer codes developed at LLL and normalized to operating systems' performance. An example of the results of such calculations is shown in Fig. 2-168. In this case a fluorophosphate-type laser glass, a borosilicate lens and substrate glass, and currently available Faraday rotator materials are used. The damage limits are those of currently available thin-film optical coatings. The nonlinear properties of the laser glass are similar to those of FK-51; the pumping and saturation properties are similar to those of Nd in

Fig. 2-168. The code SPACE is used to examine the performance of chains constructed of optimized components and to calculate the costs. The input values and assumptions are listed at the top, the chain components on the left, and the performance results on the right. This code will also list costs and compute cost effectiveness. The example given is the performance of the typical Nova chain with a 1-ns pulse.

INPUT POWER PULSE DURATION SATURATION FLUX LASER WAVELENGTH COST OF LASER GLASS SPATIAL FILTER F & B VALUE SPATIAL FILTER CUTOFF POWER NUMBER OF RADIAL ZONES										10 1 3.24 1.054 1.5 2 8 10										GIGAWATTS NANOSECONDS JOULES PER SQUARE CENTIMETER MICRONS ED-2									
#	I.D.	DIAM	#	THICK	INDEX	N2	BRD	GRIN	G-SAT	POWER	E-E-INC	B-TOT	FLUX	COST															
		CM		CM		ESU	KJ			GH			J/CM2	K\$															
0	PR-A						20			12.0	2.00*	2.00	40*																
1	SF	9.4	1*	0.6	1.500	1.24	0	0.99	0.99	17.8	0.01	2.01	0.49	5															
2	DISK	9.4	6*	2.4	1.483	0.71	160	4.70	4.19	24.7	0.15	2.16	1.97	72															
3	POL	9.4	2*	0.6	1.500	1.24	0	0.94	0.94	70.2	0.05	2.21	1.96	6															
4	FR	9.4	1*	0.6	1.670	2.10	20	0.98	0.98	68.8	0.05	2.26	1.84	19															
5	POL	9.4	2*	0.6	1.500	1.24	0	0.99	0.94	54.7	0.02	2.30	1.80	6															
6	DISK	9.4	6*	2.4	1.483	0.71	160	4.70	3.43	221.7	0.47	2.77	5.26	72															
7	SF	9.4	1*	0.6	1.500	1.24	0	0.99	0.96	219.4	0.09	2.85	5.26	5															
8	SF	15.0	1*	1.0	1.500	1.24	0	0.99	0.99	217.2	0.04	2.90	3.04	8															
9	POL	15.0	2*	1.0	1.500	1.24	0	0.94	0.94	204.2	0.06	2.96	2.02	12															
10	FR	15.0	1*	1.0	1.670	2.10	50	0.98	0.98	200.1	0.06	3.02	1.90	34															
11	POL	15.0	2*	1.0	1.500	1.24	0	0.94	0.94	158.1	0.06	3.08	1.86	12															
12	DISK	15.0	4*	3.0	1.483	0.71	140	2.75	2.29	431.0	0.32	3.40	3.81	114															
13	DISK	15.0	4*	3.0	1.483	0.71	140	2.75	1.99	395.6	0.65	4.08	7.04	114															
14	SF	15.0	1*	1.0	1.500	1.24	0	0.99	0.98	247.0	0.14	4.19	2.04	8															
15	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	384.7	0.14	4.30	3.89	10															
16	POL	20.0	2*	1.3	1.500	1.24	0	0.94	0.94	276.5	0.16	4.46	3.85	15															
17	FR	20.0	1*	1.3	1.670	2.10	90	0.90	0.98	270.2	0.15	4.60	2.42	53															
18	POL	20.0	2*	1.3	1.500	1.24	0	0.94	0.94	254.5	0.15	4.79	3.55	19															
19	DISK	20.0	3*	2.2	1.483	0.71	100	2.02	1.66	1201.6	0.41	5.16	5.32	154															
20	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	1184.8	0.14	5.31	5.32	10															
21	SF	20.0	1*	1.3	1.500	1.24	0	0.99	1.00	1189.1	1.11	6.20	1151																
22	DISK	20.0	3*	3.2	1.483	0.71	10	2.02	1.54	1215.2	0.63	6.07	7.68	154															
23	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	1207.1	0.21	6.28	7.49	10															
24	SF	25.0	1*	1.7	1.500	1.24	0	0.99	1.00	1266.7	0.57	7.11	1136																
25	DISK	25.0	3*	3.5	1.483	0.71	465	1.95	1.52	2310.7	0.63	7.08	7.08	228															
26	SF	25.0	1*	1.7	1.500	1.24	0	0.99	0.99	2068.0	0.71	7.37	7.37	154															
27	FR	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	2655.6	0.20	7.53	4.86	17															
28	POL	30.0	1*	2.0	1.500	1.24	0	0.97	0.97	2576.0	0.15	7.63	4.61	20															
29	FR	30.0	1*	1.5	1.670	2.10	200	0.92	0.99	2509.4	0.22	7.80	4.57	112															
30	POL	30.0	1*	2.0	1.500	1.24	0	0.97	0.97	2448.7	0.15	8.07	4.58	20															
31	DISK	30.0	2*	4.0	1.483	0.71	420	1.52	1.72	3744.4	0.41	9.05	7.25	227															
32	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	3680.0	0.22	9.19	5.17	17															
33	SF	30.0	1*	2.0	1.500	1.24	0	0.97	0.99	3166.4	0.23	8.97	5.65	17															
34	DISK	30.0	2*	4.0	1.483	0.71	420	1.52	1.29	4007.7	0.71	9.40	7.40	237															
35	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	4021.8	0.24	9.73	7.06	17															
36	SF	50.0	1*	2.0	1.500	1.24	0	0.99	0.99	3698.4	0.24	9.73	7.06	17															
37	DISK	30.0	2*	4.0	1.483	0.71	420	1.52	1.26	5009.5	0.63	10.65	8.52	227															
38	SF	30.0	1*	2.0	1.500	1.24	0	0.94	0.99	4395.9	0.25	11.00	8.52	17															
39	FR	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	4364.0	0.24	11.70	7.04	2517															
40	FR	37.5	1*	15.0	1.500	1.24	0	0.91	0.91	4513.4	1.59	12.55	5.37	143															
41	FR	37.5	1*	15.0	1.500	1.24	0	0.91	0.91	4456.1	1.59	12.70	7.04	2658															
TOTAL										3995	247.27	247.01	12.59	2559															
Z-FACTOR										0.75233664										TERMINANTS: F+ REPER									
Z-VALUE										1.6725521										TERMINANTS: PER III									
FINAL FILL FACTOR										0.33415229																			
TOTAL NE COST										593.1										K\$									
TOTAL OPTICS COST										977.6										K\$									
TOTAL RE COST										1.8										K\$									
TOTAL ALIGN COST										250.0										K\$									

ED-2. In other words, this is a conservative design which relies on small improvements in the laser-glass energy storage. If the cost of fluorophosphate lens and substrate material can be reduced to be closer to that of borosilicate glasses, and if the fluorophosphate or phosphate laser glasses with lower n_2 -values can be commercialized, the chain performance would increase significantly. If better antireflection coatings, selected examples of which have yielded damage thresholds more than twice as high as the assumed 3 J/cm^2 at 100 ns, can be commercialized, the performance/cost would be greatly improved. Even though this chain represents a 40% improvement over Shiva in power/cost and almost 100% in energy/cost, still further improvements will occur as the technology develops.

This chain illustrates the principal features of large, high-performance glass lasers. It is long, large in output aperture, sequentially spatial-filtered and image-relayed, well isolated, and tapered to give near-optimal performance over a wide range of pulse durations. The size of the output aperture, which determines the minimum chain length, is found by optimizing the performance per unit cost. Disk amplifiers optimize at about 17 cm for 100-ps pulses, 21 cm for 3-ns pulses, and 25 cm for 3-ns pulses when the fixed costs associated with chain alignment, control, and diagnosis are included. The example chain was cost-balanced around the 25-cm optimum using present fixed-cost estimates. It may be possible to reduce these costs. The length of a chain is a function of the output aperture and pulse duration. For short pulses with minimal saturation, small-signal gain is emphasized and relatively short, rapidly tapered chains, such as Shiva's, are optimum. For long pulses, saturation-depleted gain must be made up by adding amplifiers with the resultant slower taper. Finally, as chains are split closer to the output, the cost decreases because more amplifiers of the most optimal size are used; but the increased chain length can increase the ΣB for the whole chain. The chain shown is a conservative balance of these considerations, split for the last time before the 10-cm sections.

The use of spatial filtering and image relaying along the chain is fundamental to high performance. Image relaying, a very recent invention within the context of high-power laser design, prevents diffraction by periodically reconstituting the input beam profile (see § 2-1.3). This allows the use of nearly uniform intensity profiles which greatly im-

Fig. 2-189. Growth of power-conditioning requirements for the sequence of glass lasers in LLL's laser program. The Shiva 23-MJ electrical system is scheduled for completion by the end of 1977. The projected Nova system reduces the slope of the growth curve from an 8-mo to a 21-mo doubling time.

proves extraction. The use of spatial filters is required to suppress beam breakup due to the non-linear growth of small-scale aberrations. By clever design the same optics which perform the spatial filtering will also provide the image relay. This concept has been demonstrated on Argus and recently incorporated in Shiva.

The need for isolation to prevent damage due to reflected amplified pulses and parasitic loss of stored energy is obvious, but the cost is high due to two principal factors. First, the rotators and polarizers are expensive. Second, these elements are lossy by reflection, absorption, and beam breakup; to compensate for the loss, more amplification is needed which further increases the cost. These

points are particularly true at large apertures where isolation is very expensive and gain low. The first 30-cm amplifier stage in Fig. 2-169, which costs more than \$400 thousand with the isolation, would be eliminated if isolation were not necessary. The tradeoff of risk and performance against cost is critical when designing the chain isolation.

The chain cost is inversely proportional to the taper rate. High-power chains taper fast and are less costly for a given output aperture. High-energy chains taper more slowly and are more expensive. To increase the taper rate, the energy stored in the glass should be increased. To first order, the stored energy is proportional to the product of the small-signal gain and the saturation parameter, although increased gain generally results in some decrease in stored energy due to fluorescence loss. The optimum long-pulse performance is obtained by increasing the stored energy as much as possible and then adjusting the cross section of the laser glass to obtain a balance between gain and saturation which results in the maximum energy output per unit cost.

In addition to the saturation limit for long pulses, the aperture taper rate is influenced by small-scale beam breakup in the short pulse regime and damage to thin-film optics in the intermediate pulse regime around 500 ps. These constraints must be applied in designing Nova chains.

Finally, the requirements of precision alignment of the beams onto the target, extensive beam diagnostics, and control of the laser components influence not only the chain size but its staging. Typically the chain has an input pointing system and a final pointing, centering, and focusing system. The alignment function is therefore not strongly influenced by the size of a single chain. As a result, the cost of alignment pushes the design toward large chains to achieve a given performance. The major diagnostic functions are performed at the laser output, with less than 20% of the cost of diagnostics distributed along the chain. Again this consideration biases the design toward fewer and therefore larger chains. The cost increase for controls is proportional to something in between the unit count (low side) and the energy stored (high side), which favors large components.

All of these considerations must be accounted for in finding the optimum design. The chain shown here is illustrative of the application of LLL design techniques; however, it will change substantially before a final system is fixed.

2-3.3 Optics

As described above, the performance of Nova is most strongly influenced by three optics parameters: the nonlinear refractive index of all the beam-line optics, the pump efficiency and energy storage of the laser glass, and the damage threshold of thin-film optical coatings. Of course, the benefits of improvements in these parameters can be utilized only if the costs of the new materials are near to or less than the costs of Shiva materials; analysis of the relative benefit versus cost and risk is necessary to determine the true value of a new material to the Nova project. The program designed to apply new optical materials technology to Nova is described in § 2-4.5. Finally, the improvements demonstrated on the scale of research and development must be achieved in large-scale production.

2-3.4 Mechanical Systems

The mechanical components of the Nova laser system including the space frame, laser hardware, optical mounts, and gas cooling system represent 20 to 25% of the total project cost. In general these elements of the system must be reliable, optically stable, ultraclean, and designed to minimize cost when manufactured in large quantities and to facilitate assembly and maintenance. These criteria were used in the design of Shiva hardware, which is described in § 2-2.3. A typical array of components required for a Nova chain is given in Table 2-36, which indicates that most of the Nova hardware already exists as Shiva components, prototype designs used for component performance experiments, or detailed designs interpolated from existing components. Of course, design improvements which will lower cost and improve performance have already been suggested, but the exercise of these concepts will be chosen on the basis of total system optimization.

While a space frame has not yet been used as part of an operating system, the Shiva space frame has been built and experimentally exercised thermally and acoustically. These measurements are described in § 2-2.7. Stability of the Shiva space frame is well within the allowed tolerances. Similarly, all of the

Shiva optical mounts and gimbals have performed within specification. Shiva has required substantial innovation in mechanical hardware design, assembly, and maintenance, the realization of which provides a firm technical and cost basis for Nova. The assembly and maintenance of a system of Nova's size will fully utilize the techniques already developed for Shiva and described in § 2-2.6.

2-3.5 Power Conditioning

The full two-phase Nova laser calls for an order of magnitude more energy than is contained in the Shiva power-conditioning system and represents about 25% of the total cost of Nova. The overview summary in Table 2-37 shows the two principal load elements—flashlamps and Faraday rotators—and

Table 2-36. Status of component development for Shiva Nova. A design already exists for most of the components of the typical Nova chain; they have either been built for other systems, have been prototyped and tested, or are a straightforward interpolation between existing designs. The few components for which no design exists are expected to offer no serious problems: the 25-cm amplifier and 30-cm isolator will both be scaled directly from the 20-cm design, the blast plate will have been used on Shiva in a 20-cm size, and the spatial filters are straightforward in design

Component	Design exists?	Cost (\$10 thousand, FY 1976)
Blast plate	No	11
Window	Yes	21
Focus lens	No	35
Alignment sensor	Yes	49
Pointing mirror	Yes	70
Centering mirror	Yes	37
Spatial filter	No	34
30-cm disk amplifier	Yes	227
30-cm isolator	No	200
Spatial filter	No	30
25-cm disk amplifier	No	228
Spatial filter	No	23
20-cm disk amplifier	Yes	154
20-cm isolator	Yes	91
Spatial filter	Yes	18
15-cm disk amplifier	Yes	114
Spatial filter	Yes	13
10-cm disk amplifier	Yes	72
10-cm isolator	Yes	31
Spatial filter	Yes	11
5-cm rod amplifier	Yes	25
5-cm Pockels switch	Yes	15
Aberration corrector	Yes	20
Spatial filter	Yes	8
2.5-cm rod amplifier	Yes	18
2.5-cm Pockels switch	Yes	11
Apodizer	Yes	3
Path length compensator	Yes	10
Entering sensor	Yes	22

the electrical demands of each. The 72- and 175-MJ Nova I and II requirements necessitate large but manageable extensions beyond the 23-MJ Shiva. The growth in the LLL electrical system to this level has been continuous for the past four years, as depicted in Fig. 2-169. The initial prototype 600-kJ capacitor bank, including power supplies and switches, was tested to 30,000 shots in 1974. Since then the Janus, Cyclops, and Argus lasers have operated reliably, and now the Shiva power-conditioning system is under construction.

Flashlamps and Faraday rotators are distinctly different loads. Flashlamps can be characterized as nonlinear resistors, while rotators are large inductors. At present, both loads are driven with capacitor bank modules. The technique works best for flashlamps because of their large number and small individual energy requirement. For example, a four-capacitor 20-kJ bank will drive a series pair of 110-cm flashlamps. In contrast, Faraday rotators are

large discrete loads that each require a large energy source — up to 500 kJ for a Nova 30-cm rotator.

While the baseline Nova system utilizes capacitors to drive flashlamps, an interesting alternative may be applicable. An inductive store driven as the self-excited coil of a homopolar generator is under development by B. Robeson of the Naval Research Laboratory.⁷⁰ This store is switched into a load with an explosive-switch/fuse combination. The switch requires only a few grams of explosive primer cord to open a circuit of more than 100 kA current in 50 μ s. This technology is being closely followed because of the large potential cost saving to Nova, e.g., possibly $7¢/J \times 150 \text{ MJ} = \10 million . A computer program that models the self-excited homopolar/fuse/flashlamp circuit has been developed at LLL.

A survey of all possible methods to drive Faraday rotators has also been made. Three systems which have the degree of development and reliability

Table 2-37. Overview of power-conditioning system for Shiva Nova. The two major load elements (Faraday rotators and flashlamps) require a total of 0.2 MJ or more in the final phase. The impulse time for flashlamps must be a fraction of a millisecond to keep pace with the decay rate of the laser glass. This takes very high power as shown. The Faraday rotators are larger individual loads than flashlamps but they are much fewer in number. Even though they can be pulsed rather slowly, the power required is too high for reasonable conversion from a utility line, and thus energy storage is still necessary —

	Nova I	Nova II
Energy required:		
Rotators	9-18 MJ	22-44 MJ
Flashlamps	63 MJ	153 MJ
Delivery time:		
Rotators	1/2 s (max)	1/2 s (max)
Flashlamps	1/3 ms	1/3 ms
Power required:		
Rotators	>18 MW	>44 MW
Flashlamps	189 GW	456 GW
Number of loads:		
Rotators	36	88
Flashlamps	2954	7208

necessary for Nova have been selected for further study. These are the conventional capacitor bank, dc power supplies, and homopolar generators. A homopolar generator converts rotating inertial energy into pulsed electrical energy. It was invented by Michael Faraday about 1831; but because it becomes economical only in large sizes, it is only now finding its way into pulsed power use as a source for very large pulsed magnets. Since fast switching is not required for the Faraday rotators, it appears that little development is necessary to engineer homopolar generators for this application. A comparison of the efficiency and cost elements of capacitor banks, dc power supplies, and homopolar generators has been made for equivalent systems that would drive 22 MJ of Faraday rotators for the Nova laser. It is estimated that a homopolar generator system would cost \$1 million less than a capacitive discharge system, while a dc-powered system would cost at least \$1 million more.

In summary, the Nova laser's power-conditioning system is the next large step in LLL's series of high-power pulsed systems requiring ever-increasing discharge energies. The baseline design will use a capacitive energy store to drive flashlamps because of the record of success of capacitors in large glass-laser systems. However, the size of the Nova electrical system is so large that a close look at feasible, economical alternatives could lead to significant cost savings. The most promising departure from present practice will be to drive groups of large Faraday rotators with a single homopolar generator.

2-3.6 Alignment and Controls

The Shiva alignment system (§ 2-2.10) and controls (§ 2-2.9 and 2-2.11) have been either fully or partially prototyped and tested. Their performance and costs are well established. These systems represent the next generation of control systems and include significant advances over techniques used on previous LLL lasers. They are very flexible and modularly expandable to allow the incorporation of improvements and the superposition of the Nova system on the Shiva system.

2-3.7 Target Chamber

The Shiva Nova system places new requirements on the target chamber for the microexplosions, which are expected to produce yields of up to 10^{19} neutrons from the DT reactions. This high yield level requires careful attention to questions of strength, material activation, and radiation damage on diagnostics and windows for the laser beams.

The target chamber must satisfy the following basic requirements:

- Have activation and shielding characteristics adequate for thermonuclear neutron yields of 10^{17} and 10^{19} for Nova I and Nova II respectively.
- Provide a vacuum on the order of 10^{-6} Torr.
- Support a small cryogenic target at a fixed point in space and verify its position within 5 μ m.
- Contain an adjustable beam-focusing system capable of delivering a number of laser beams onto the target within 5 μ m.
- Provide access for diagnostics to observe the fusion microexplosion.
- Have flexibility to allow changes in targets, focusing optics, and diagnostics while providing mechanical stability and strength appropriate to the extreme conditions of a variety of experiments.

Since the 10^{19} -neutron-yield experiments of Nova II present the more severe design requirements, the majority of the design effort has been spent on the second-phase target chamber which is described in the following. A separate chamber shown in Fig. 2-170—smaller in size, with less local shielding, lower strength requirements, and generally less complexity, but utilizing similar materials and construction techniques—will be constructed for Nova I.

The Nova II target chamber shown in Fig. 2-171 will be constructed of low-Z materials containing such elements as C, O, H, and Si. Prime candidates are Kevlar-epoxy composite and silica. The chamber will be spherical with an inner radius of 2 m. A local borated-water shield, 70 cm thick, located directly on the target chamber will be used to minimize the activation of the lens and target positioners, diagnostics instrumentation, valves, surrounding space frame, and building concrete. The penetrations through the chamber walls necessary for laser beams, diagnostics ports, and vacuum pumps will be backed up as closely as possible by shadow shields. The impulse load will be absorbed by a liner, or first wall, of plastic or of graphite plates. Beam-focusing lenses are outside

the chamber windows which are protected by debris shields. Beam ports and diagnostic ports will be protected by fast-closing valves. A pressure of 10^{-6} Torr is required to avoid excessive material condensation on cryogenic targets, to allow unobstructed paths for electrons, ions, and low-energy x rays to their respective detectors, and to avoid electrical arcing within the detectors.

The high neutron, x-ray, and plasma fluences inside the target chamber will require most of the diagnostics to be placed in line-of-sight pipes attached to the outside of the target chamber, so that they are protected by the water shield.

A summary of characteristics of the Nova I and Nova II target chambers is given in Table 2-38.

Fig. 2-170. Shiva Nova I target chamber is a 2.8-m-i.d. double-wall spherical vessel. The low-Z fiber-epoxy walls minimize neutron activation, while the annular water-filled volume absorbs about 90% of the neutrons, thus protecting exterior metal systems from activation.

Fig. 2-171. Nova II target chamber, constructed of material that is little activated by neutrons and with a local water shield, will allow experiments yielding 10^{19} neutrons with substantial design margin. The 4-m-i.d. vessel is resistant to radiation-induced shock and provides triple containment of the fusion reaction products and double containment of gas.

2-3.8 Activation and Shielding Considerations

Detailed neutronics and radiological analyses have been carried out to define the materials and shielding required for the Nova target chamber and target room. This section discusses the neutron-induced radioactivity in materials for the target chamber, primary and secondary shielding, and the shielding required to limit the integrated radiation levels to 5.0 rem per year inside the 0.5 rem per year outside the target room. The recommended primary-protection safe level is 5.0 rem per year.

The simulation models used to perform the activation and neutron and gamma transport calculations are shown in Figs. 2-172 and 2-173. The laser fusion target (neutron source) is located in the center of the target chamber, which is surrounded by the primary water shield, the steel space frame supporting the laser turning mirrors and target chamber, and the secondary shield provided by the concrete building wall.

Monte Carlo procedures^{70,71} and the ACTIVE code⁷² were used to calculate the neutron and gamma transport and activation. The calculations assumed operation of the laser fusion facility under

Table 2-38. Characteristics of Shiva Nova target chamber

	Nova I	Nova II
Spherical vessel characteristics:		
Inside diameter (m)	2.8	4.0
Structural material	Kevlar-epoxy or fiberglass-epoxy	Kevlar-epoxy or silica
External shield	Probably some local shield	70-cm-thick H ₂ O shield
First wall	Optional (some disposable material)	Disposable graphite
Containment:		
	Single	Double for burst, triple for gas
Design neutron yield:	10^{17}	10^{19}
Energy absorbed in chamber (MJ)	1	100
Pressure requirements:		
Vacuum (Torr)	10^{-6}	10^{-6}
Equilibrium pressure (bar)	1/2	27
X-ray-induced shock in first wall (kbar)	1	20

Fig. 2-172. Simulation geometry for calculating neutron-induced radioactivity and radiation levels for Shiva Nova.

three sets of conditions: (1) one burst of 10^{19} neutrons, (2) 60 days at 2×10^{19} neutrons per day, and (3) 365 days at 2×10^{19} neutrons per day. The target chamber must be capable of attaining a high vacuum, containing target debris, and withstanding the microexplosion impulse, and it must have only short-term residual activation. Two materials it could be built of are Kevlar-epoxy composite or silica (SiO_2). The gamma decay rate from the neutron-induced radioactivity in these and other possible materials is shown in Fig. 2-174 as a function of cool-down time. The resulting dose-

equivalent rate is calculated for the inside of the target chamber.

The water shield on the target chamber both attenuates and moderates the primary neutrons to limit the activation of the mild-steel space frame, room air, and concrete to residual levels acceptable for unrestricted access into the target room following a few hours of cool-down time. The gamma decay and dose rates from the induced radioactivity in the space frame and concrete walls are shown in Figs. 2-175 and 2-176 as a function of cool-down time for various operations.

Fig. 2-173. Simulation geometry for calculating neutron and secondary gamma shielding for Shiva Nova. The 14-MeV neutron source is assumed to be in the center of the target chamber 4.5 m above the basement floor.

Fig. 2-174. Calculated neutron activation of the target chamber walls for various wall materials. Total decay rate of residual gamma radiation vs cool-down time is given for three different run times. Dose equivalents are on the inside surface of the vessel.

Fig. 2-175. Calculated neutron activation of the mild-steel space frame, assuming a 70-cm-thick annular primary water shield outside the target chamber. Dose equivalents are inside the target room.

Fig. 2-176. Calculated neutron activation of the concrete shielding walls of the target room, assuming a 70-cm-thick annular primary water shield outside the target chamber. Dose equivalents are inside the target room.

The penetration of neutrons through shielding materials and beam port openings, the nuclides resulting from nuclear transmutation reactions,^{73,74} and the secondary nuclear reactions in water induced by recoiling charged particles⁷⁵ have also been calculated and found to be either negligible or amenable to standard practice.

In conclusion, it has been found that neutron yields of 2×10^{19} per day can occur continuously if the target chamber is Kevlar-epoxy or silica, the primary shield of 70 cm of borated water is immediately on the target chamber, and the building wall concrete is 180 cm (~6 ft) thick. These precautions result in safe exposure levels inside the target room after a few hours of cool-down for each 10^{19} -

neutron shot, 1/10 of the safe exposure level immediately outside the target room, and 1/100 of the natural background level at the nearest site boundary.

2-3.9 Buildings

The Shiva Nova facility shown in Figs. 2-177 through 2-179 consists of an 84,000-ft² addition to the existing HELF building which is almost a mirror image of the existing building with a larger

target room and a longer laser bay. The larger target room (75-ft-square vs 60-ft-square inside dimensions) provides the additional shielding required for the higher neutron outputs of the Nova design. The length of the laser bay is increased by 60 ft to handle the longer laser chain designs of the Nova options. A basement below the laser bay and lab areas houses the energy storage system as well as a diagnostics area closely coupled to the target room's laser-plasma diagnostics. A 41,000-ft² office building to house 150 scientific and support personnel is functionally coupled but structurally separated to minimize operations and construction conflicts. With the exception of mechanical and electrical tie-ins, construction can proceed independently of the HELF building, thereby providing for continued and virtually uninterrupted operation of Shiva experiments until the Nova laser system is operational at 80 to 120 TW.

The Shiva and Shiva Nova experiments are unique in their large size, need for highly stable and precise alignment, and the cleanliness required to minimize the destructive effects of surface contamination. These impose stringent environmental

requirements that have caused us to regard the building as an integral part of the experimental apparatus. Hence the laser bay and target room will be class 10,000 or better laminar-flow clean rooms with temperature controlled to $\pm 1^\circ\text{F}$ or better in order to ensure the laser's mechanical stability. These design objectives are met by a recirculating air-handling system that moves about 1.5 million cfm through HEPA filters and a high-capacity air-conditioning system. Neutrons from the fusion reaction will be contained by a local shielding together with the concrete in the target room walls. This conceptual integration of building and experiment led directly to the selection of 6-ft-thick walls.

There will be a class 100 laminar-flow clean room adjacent to the laser bay for assembling laser components. In addition, there will be shop and laboratory areas on the first floor supporting the laser assembly and operation, a control and data reduction room, and four lofts for the recirculating air-handling system. A large basement will have space near the target room for target fabrication and diagnostics, and 14,500 ft² devoted to capacitors for energy storage.

Fig. 2-177. Shiva Nova building perspective. The existing building is shown here to the left of the new target room, the highest element in the new building. The new laser bay extends east (to the right) of the new target room, with laboratory and support space along the south side of the building addition.

Fig. 2-178. Plan view of first floor of the Shiva Nova building. The eastern limits of the existing Building 391 are shown at the left. Access to the new addition will be through the east end of the laser bay, the double doors on the south side, and the visitors' lobby, all of which will be controlled through security booths.

Fig. 2-179. Plan view of basement of the Shiva Nova building. This area is predominantly for energy storage. Major access points into the target room are provided through openings that can be plugged with shielding doors. Freight access to the basement is through rollup doors on the north side, adjacent to the target room.

References

70. E. F. Plechaty and J. R. Kimlinger, *TARTNP: A Coupled Neutron-Photon Monte Carlo Transport Code*, Lawrence Livermore Laboratory, Rept. UCRL-50400, Vol. 14 (1976).
71. T. D. Wilcox, Lawrence Livermore Laboratory, Internal Document MOR-6 (1972).
72. R. M. Lessler, W. E. Alley, and J. B. Greene, *The ACT and ACTIVE Codes for Calculating Neutron-Induced Activation*, Lawrence Livermore Laboratory, Rept. UCRL-51292 (1972).
73. M. S. Singh, "Radiological Safety Design Considerations for a Laser Fusion Facility," Fifth International Conference on Reactor Shielding, Knoxville, Tennessee, April 18-23, 1977, Paper H-5.
74. M. S. Singh, *Activation of Concrete and Gypsum by 14-MeV Neutrons*, Lawrence Livermore Laboratory, Rept. in preparation.
75. M. S. Singh and L. Ruby, "Production and Release of Positron Emitters from Water-Moderated Power Reactors," *Nucl. Technol.* 17, 104 (1973).

Authors

T. J. Gilmartin
C. W. Meier
B. M. Carder
W. F. Hagen
S. M. Hibbs
C. A. Hurley
W. C. O'Neal
M. S. Singh
J. B. Trenholme

2-3.10 Design Procedures

Fusion laser systems have become larger and more expensive with demands for higher and higher performance levels. Thus, there is growing incentive to choose cost-optimal designs — those producing maximum output (power or energy) per dollar expended — for all components in the amplifier chain, especially for laser amplifiers. Cost-optimal methodology is needed not only for designing with present laser glasses but also for evaluating new glasses, since proper comparison requires each glass to be evaluated at its maximum potential.

Optimal design is achieved by varying the doping and thickness of the laser disks, the duration of the flashlamp pumping pulse, the stored energy in the capacitor bank, and the clear aperture of the system amplifiers. The whole process must be carried out

for many different laser pulse widths, since a given glass may be good for short pulses but poor for long pulses, or vice versa. The process is first applied to individual amplifier components, then to whole amplifier chains including spatial filters, isolation, focusing optics, alignment and beam relay components, controls, and laser diagnostics.

In designing for Nova, the largest laser fusion system yet considered, we are automating these procedures as much as possible to allow the widest set of options to be examined initially and finally to obtain maximum performance from the chosen design. Our analytical tools, which must be general enough to access the full range of possibilities and specific enough to handle practical design questions, have evolved through constant interplay between theoretical models and normalization and correction by experimental data. The material presented below follows this theme, first defining the models and then applying them to the design of optimized amplifiers for Nova chains. It should be emphasized that the designs described here are examples of current results and not final designs. The final Nova design will be optimized using these procedures and the detailed characteristics of the best available laser materials.

Our general conclusion, however, is that optimal systems for pulse durations of about 1 ns are simultaneously B-limited by small-scale beam breakup and flux-limited by damage and saturation. For short pulse operation, the performance is dominated by nonlinear effects; the nonlinear refractive index n_2 is the limiting parameter. With increasing pulse length to the nanosecond regime, damage to thin-film coatings constrains the power and energy; this damage is generally caused by beam hot spots arising from beam breakup, again demanding low- n_2 materials. For very long pulses, the primary limits are damage and saturation: that is, the energy storage capability of the laser glass. In this regime the nonlinear effects are of secondary importance. Thus, the most versatile design will stress B and flux limits for nanosecond pulses and will require both a low n_2 and high energy storage to maximize performance.

Authors

T. Gilmartin
W. Hagen
J. Trenholme

Laser System Design and Analysis

The laser systems and components discussed here were mainly designed for laser pulse durations in the nanosecond regime, although the methods are generally applicable for other pulse durations.

To optimize a laser system, one must have reasonably accurate performance and cost models. Without cost constraints, there would be no optimum, and amplifier chains would consist of the largest possible components so as to avoid both nonlinear and flux limitations. Evaluating performance and cost are the methods applied to specify detailed component designs as well as proper staging and taper of an amplifier chain.

To determine the most cost-effective amplifier

designs, the performance and costs are evaluated as indicated in Fig. 2-180. The variables are disk thickness, neodymium doping, pump pulse duration, and energy input for various clear apertures and laser glasses. Since there are two distinct regimes of operation for Nd:glass lasers, corresponding to short and long pulses, the cost effectiveness is evaluated for maximum $\alpha \ln G/C$ or $\ln G/C$ corresponding, respectively, to B- or flux-limited operation.

Those optimized amplifiers and components are then assembled into amplifier chains by selecting a near-optimal output stage and determining sequentially the most cost-effective driver stages. Finally the system is assembled from several chains, their

Fig. 2-180. Methodology for designing optimized laser systems. The highest performance-to-cost ratio is determined for each variable, resulting in optimized amplifiers. Then these amplifiers are used to assemble optimized laser chains and systems.

number and size depending primarily on the available funding and desired illumination geometries.

During this design phase, we simplify the beam propagation to reduce the number of variables. The beam profile is assumed to be parabolic with a fill factor of 0.5; changes in the profile and in the temporal pulse shape due to saturation are ignored. These simplifications are eliminated during the analysis phase, to permit selection of the most cost-effective chain design.

We assume collimated beams and uniform gain distributions in the amplifiers. The flux is limited to 10 J/cm^2 for 1-ns pulses and scaled as the square root of the pulse duration. The flashlamp loading is maintained below 20% of the explosion energy, for reliable system operation. Losses in optical materials are conservatively assessed at 0.5/m. Saturation is treated similar to a two-level system, with a saturation flux (Φ) of $h\nu/2\sigma$.

All amplifier chains have been designed and analyzed using performance models normalized to Argus performance at 1.5 TW per beam, which now appears quite conservative. To reduce the loading on the spatial filters, we have designed the individual amplifier stages for relatively low ΔB values.

This conservative design approach should provide a reasonable safety margin such that the cited output powers can be considered typical performances and not only-once-observed peak performances.

Performance Models. The performance models have evolved primarily from the data base of rod and disk amplifiers. These models separately take into account the glass properties, flashlamp efficiency, cavity efficiency, and parasitic limits.

The flashlamps are characterized by a pump efficiency equivalent to their radiative efficiency within the spectral range of effective absorption in Nd:glass. The effects of spectral blue shift and lamp opacity are taken into account collectively in a form correlated to the optical output power density of the lamps. Also included are losses in pump efficiency for short pump pulses due to the finite time required for development of the arc. This approach makes the flashlamp pump efficiency independent, to the first order, of cavity geometry and glass properties, so long as similar geometries (disks or rods) and glasses are being compared.

The absorption characteristics can be obtained directly by measuring the absorbed flashlamp light in Nd:glass samples of various thickness or by numerically integrating the measured absorption spectrum with the calculated flashlamp spectrum. Quite suitable for this purpose is the dual-absorber model

$$\epsilon_A = \epsilon_1 (1 - e^{-a_1 w t}) + \epsilon_2 (1 - e^{-a_2 w t}), \quad (28)$$

in which pumplight fraction ϵ_1 denotes absorption with a high-absorption coefficient a_1 , corresponding to strong absorption lines, and pumplight fraction ϵ_2 denotes absorption with a second coefficient a_2 , about an order of magnitude lower. This four-parameter model reduces to a three-parameter fit where the ratio a_1 to a_2 is constant, which has been true for the glasses thus far investigated. Figure 2-181 shows typical absorption characteristics for various glasses normalized to the experimentally measured characteristics of ED-2 laser

Fig. 2-181. Absorption characteristics of various laser glasses for radiation emitted from xenon flashlamps at 1 kA/cm^2 . These data can be approximated quite well by the dual-absorber model described in the text.

Table 2-39. Laser glass properties

		Glass			
	Parameter	ED-2	LHG-6	FK-51	B-2
λ	Laser wavelength, μm	1.062	1.053	1.054	1.047
n	Index of refraction	1.555	1.529	1.483	1.343
n_2	Nonlinear index, 10^{-13} esu	1.41	1.01	0.71	0.4
γ	Nonlinear coefficient, 10^{-20} m ² /W	3.79	2.76	2.00	1.25
σ	Cross section, 10^{-20} cm ²	2.9 ^a	3.7	2.52	2.9
ϵ_1	High-absorption fraction	0.18	0.15	0.19	0.13
ϵ_2	Low-absorption fraction	0.39	0.35	0.375	0.35
a_1	Absorption coefficient, cm x wt% ⁻¹	0.8	0.8	0.8	0.6
a_1/a_2	Absorption coefficient ratio	10	10	10	10
τ_0	Zero doping lifetime, ms	0.44	0.39	0.42	0.72
w_0	Quenching concentration, wt% Nd	4.8	9.1	4.3	6.1
k	Decay ratio	3.5	3.5	5	5

^a Latest results 2.7×10^{-20} cm²

glass.⁷⁶ Table 2-39 lists the corresponding parameters, along with other properties of interest.

Instead of a single equivalent decay for fluorescence, we use a double exponential decay of the form

$$I/I_0 = (1 - \Delta) e^{-t/\tau_F} + \Delta e^{-kt/\tau_F} \quad (29)$$

with

$$\tau_F = \tau_0/[1 + (w/w_0)^2]$$

and

$$1 - \Delta = e^{-\Delta t/\tau_F},$$

where $\Delta t \approx 80 \mu\text{s}$ for the glasses thus far investigated, w is the neodymium doping in weight percent, w_0 the neodymium doping for which the fluorescence lifetime τ_F is half the lifetime at zero doping τ_0 , and k is the ratio of the initial fast-decay rate to the final slow-decay rate τ_F^{-1} . This approximation allows the fluorescence decay of any particular Nd:glass to be specified by the three parameters τ_0 , w_0 , and k .

The cavity efficiency takes into account both the cavity geometry and material properties. It is primarily determined by (a) the diameter of the flashlamp circle with respect to the clear aperture of the device, (b) the lamp spacing with respect to the bore diameter of the lamps, and (c) the end effects caused by reduced pumping of the end disks. Included also are corrections for differences in cavity efficiency due to reflector geometries (crenulated vs cylindrical), reflectivity of the cavity material, and losses from the uv shields. The cavity efficiency includes a normalization constant that is the same for all disk amplifiers of similar design.

Parasitic losses are separated into bulk and face parasitics, which are correlated to their respective effective reflectivities at the edge coating. These effective reflectivities incorporate Fresnel reflections at the disk-edge coating interface and contributions from the edge coating/air interface for partially transmitting coatings, as well as scattering in the edge coating or interface. The modeling of fluorescence amplification and parasitics has been normalized to disks with typical edge coatings and should provide a reasonable approximation so long as similar edge coatings are applied.

Figure 2-182 presents results of the performance model used for this analysis, along with experimental data.

Cost Modeling of Chains. Table 2-40 summarizes the functional forms for scaling the cost of the

Fig. 2-182. Experimental data and modeling of disk amplifier performance. The performance model considers laser glass properties, flashlamp pump efficiency, cavity efficiency, and parasitic limits.

various components. These estimates are based mainly on the cost of Shiva components including labor and initial spares but not inflation or contingency. Individual component costs are broken down into mechanical hardware, optics, and electronics; these costs are primarily scaled with respect to the clear aperture of the component. Fixed costs include fixtures, cooling, handling, etc. The fixed cost for energy storage is, to the first order, proportional to the clear aperture of the amplifiers assuming fixed length. This fixed bank cost includes flashlamps, cables, terminal boxes, and the like.

In Table 2-40, the material cost for the disks is based on the cost of silicate laser glass and is, to the first order, proportional to the volume of the disks. The costs for spatial filters and polarizers assume BK-7 glass. Although FK-51 fluorosphate glass is preferred for most of the nonlasing passive optical elements, its high material cost as compared with BK-7 drives the optimization toward the less expensive material. The Faraday rotator cost is based on FR-5 glass.

Preamplifier section costs includes those for the rod amplifiers, Pockels cells, apodized aperture, etc. These costs have been held constant for purposes of this analysis.

Table 2-40. Functional forms for scaling component costs (thousands of dollars FY 1976)^a

Component	Mechanical hardware cost	Optics	Electronics cost
Disk amplifier	$(1 + 0.017 D^2) N_D$	$0.0064 (1 + t) D^2 N_D$	$D + 0.20 E$
Spatial filter	$4 + 0.5 D$	$0.2 + 0.016 D^2$	0
Polarizer	$1 + 0.005 D^2$	$0.2 + 0.016 D^2$	0
Faraday rotator	$8 + 0.1 D^{1.5}$	$1 + 0.028 D^2$	$0.25 E$
Focusing optics	$0.8 D$	$0.08 D^2$	0.0
Preamplifier	80	50	20

^a Alignment, control, and diagnostics — \$250,000 total per chain.

D = clear aperture in cm.

t = thickness in cm.

N_D = number of disks per amplifier.

E = energy storage bank in kJ per amplifier.

The cost of the focusing optics includes half the output spatial filter, two mirrors, an $f/7$ focusing lens, two windows, and a blast plate. To reduce the flux loading on these components, a standard beam expansion ratio of 1.25 is assumed for these components with respect to the final amplifier.

Performance Characteristics of Unsaturated Amplifiers. The performance of Nd:glass lasers operating in the short pulse regime (<0.1 ns) is generally B-limited, which typically results in flux levels well below the saturation flux and damage limits. In this regime, where saturation can be ignored, disk amplifier performance can be uniquely described by the specific power capability

$$X_A = \frac{\lambda}{8} \frac{n}{\gamma} \alpha D^2 = \Delta P_A / B_A, \quad (30)$$

where λ is the laser wavelength, n is the index of refraction, γ is the nonlinear index coefficient, α is the gain coefficient, and D is the clear aperture of the device. This specific power capability can then be combined with the specific cost of the amplifier (C_A) to determine its cost effectiveness:

$$Z_A = X_A / C_A. \quad (31)$$

The specific cost is then defined as the amplifier cost per neper of net gain (G) in the form

$$C_A = C / \ln G. \quad (32)$$

This normalization frees the specific power capability, specific cost, and hence, the cost effectiveness from dependence on the number of amplifiers or disks. In other words, the cost effectiveness of a single amplifier is the same as for several amplifiers in series.

Figure 2-183 shows the results obtained by optimizing Z_A for various disk amplifiers and laser glasses. The results for the individual amplifiers with various disk thicknesses are shown in dashed lines. Along these dashed lines, the disk thickness decreases from about 6 to 0.4 cm, going from low to high X values. For every disk thickness, the optimum Z_A value is found by varying the neodymium doping, pump-pulse duration, and bank energy, applying a sequential three-dimensional search for the optimum. Thin disks provide high power capabilities because of high gain coefficients but have a low cost effectiveness because of the low gain per disk and, hence, high specific cost. Conversely, very thick disks provide high gain per disk but at a low gain coefficient; hence, they provide low power capability, which again reduces their cost effectiveness.

From this figure, one can determine the optimum disk thickness for the various amplifiers at the point where their envelope is tangent to their performance curve.

The envelope curves over the various amplifiers for the different laser glasses provide a good comparison of the short-pulse performance characteristics of these glasses. The improved performance of LHG-6 over ED-2 is due mainly to its higher

Fig. 2-183. Performance characteristics (X_A vs Z_A in terawatts per million dollars of cost) of unsaturated amplifiers using different laser glasses. Results for the individual amplifiers are shown (dashed lines) for decreasing disk thicknesses from 6 to 0.4 cm, going from low to high X values. FK-51 and B-2 are superior materials for large, high-power lasers with apertures larger than about 12 and 5 cm, respectively.

cross section and lower nonlinear index of refraction. The improvements of B-2 and FK-51 are due mainly to their much lower n_2 values. However, this comparison is only valid in the regime where saturation and flux limits can be ignored.

Saturation. For laser pulses lasting longer than 0.1 ns, flux levels can be obtained in typical amplifier chains that approach or exceed the saturation flux and eventually reach the damage limit of the coatings.

The performance characteristics of saturated amplifiers cannot be described in the unique, normalized form possible for unsaturated amplifiers. Now these characteristics depend on the required gain or required number of disks, as well as on the output flux and beam profile. This complicates the comparison of different laser glasses without going through a complete chain design.

To calculate the saturated gain (G_s) for a parabolic beam profile, we first apply the Frantz-Nodvik equation for a number of radial zones. From this, to hasten the speed of calculation, we determine an "effective" flux that is 1.22 times the average flux, or 61% of the peak flux. This approximation is accurate to within 2% of the accurate solution for peak flux levels of up to three times the saturation flux.

To provide a measure of cost effectiveness similar to that discussed above, we define a specific cost and power capability for saturated amplifiers in the form

$$C_s = C/\ln G_s \quad \text{and}$$

$$X_s = (\lambda/8)(n/\gamma) \alpha_s D^2 = \Delta P_s/B_s,$$

resulting in

$$Z_s = X_s/C_s.$$

The effective saturated-gain coefficient α_s is determined by

$$\alpha_s = \ln G_s / \ell \quad (33)$$

where ℓ is the optical pathlength in the laser glass of the amplifier. This effective saturated-gain coef-

ficient approximates the nonexponential flux distribution along the axis of a saturated amplifier by an equivalent exponential flux distribution. This allows integration of the intensity along the beam as required for the determination of the amplifier's B value.

As shown in Fig. 2-184, this approximation underestimates the B contribution of typical amplifier stages by less than 5%. However, in the actual case, the peak beam intensity is somewhat lower because of temporal pulse distortions caused by saturation; hence, the above approximation should be even in closer agreement with the actual case for low-gain ($G < 10$) stages. For flux levels much above or below the saturation flux, the approximation is quite accurate even for high-gain stages.

Figure 2-185 shows the results for saturated amplifiers with ED-2 laser glass for a saturated gain of 2, ΔB value of 2, and fill factor (f) of 0.5. The unsaturated performance envelope corresponds to the performance characteristic shown in the previous figure. The lower envelopes correspond to laser pulse durations of 0.1, 1, and 3 ns, where saturation becomes increasingly important. Along each curve for the individual amplifiers, shown in dashed lines,

Fig. 2-184. Approximated saturated B values vs integrated results for various small-signal gains. The approximations (dashed lines) underestimate the integrated results (solid lines) by less than 3% for typical disk amplifier gains less than 5.

Fig. 2-185. Performance characteristics (X_s vs Z_s in terawatts per million dollars of cost) of saturated ED-2 disk amplifiers operating at various pulse durations. These results assume a fixed saturated gain of 2 to a beam with a parabolic radial profile, operating at a ΔB value of 2. The unsaturated performance envelope corresponds to the characteristics shown in Fig. 2-183.

the disk thickness decreases from about 6 to 0.4 cm, going from low to high X values. Comparing these results with those in Fig. 2-184, one can see that, at 3 ns, the optimum γ -size disk thickness increases with increasing saturation from about 1.5 cm for the unsaturated case to about 4 cm for the saturated case.

The maximum of each envelope curve normalized to the unsaturated ED-2 performance is plotted in Fig. 2-186 for different pulse durations and laser materials. This figure emphasizes the performance characteristics of γ -size amplifiers because of their relatively high cost effectiveness. Optimal chains are usually dominated by larger amplifiers, but the results are similar.

In Fig. 2-186, all materials are assumed to cost the same. The performance of existing silicate, phosphate, fluorophosphate, and beryllium fluoride materials is compared with a hypothetical superglass assumed to have the best properties of all existing glasses. As indicated, substantial improvements in system performance could be realized with improved optical materials, especially for short-pulse operation.

For long-pulse operation, the differences in overall laser-material performance are relatively small for the materials investigated thus far. In this

pulse regime, the cost effectiveness is determined primarily by the energy storage capability of the glass. In other words, for saturated amplifiers the efficiency of storing energy in the glass at low cost is as important as the nonlinear effects: the more deeply saturated, the more dominant the role of energy storage.

Performance Characteristics of Flux-Limited Stages. In designing amplifier chains, it is more practical to determine the performance characteristics of individual stages than to use the normalized characteristics of amplifiers. This plan also allows selection of an integral number of disks or amplifiers, which is a more practical approach than hypothecating idealized amplifiers with fractional numbers of disks.

Presentation of the performance characteristics in this form differs mainly from that described above in that we select a specific number of amplifiers or disks rather than maintaining a constant saturated gain. Allowing the gain to vary by aperture size is more realistic because cost-optimized amplifier chains require low-gain output stages, medium-gain driver stages, and high-gain preamplifier stages.

The results for saturated stages (ED-2 laser glass) are shown in Fig. 2-187 using two amplifiers per

Fig. 2-186. Relative peak performance of B to γ amplifiers assuming identical costs for the laser materials. For short pulses, the advantage of phosphate (LHG-6) or fluorophosphate (FK-51) glass over silicate (ED-2) glass is 50 to 70%. Beryllium fluoride (B-2) glass is superior for all pulse durations; superglass is considered the upper bound. For long pulse durations, the performance can be improved only by raising the energy storage capability of the glass.

Fig. 2-187. Performance characteristics (P_{ss} vs Z_m in terawatts per million dollars of cost) of saturated ED-2 amplifier stages. These results correspond to stages consisting of two standard disk amplifiers between spatial filters operating either at a ΔB value of 2 or a flux level limited by damage to coatings. Again assumed is a parabolic beam profile. Flux and energy-storage limitations dominate the performance for pulse durations longer than 1 ns.

stage and constant values of $\Delta B = 2$ and $f = 0.5$. Included here are spatial filters and flux limitations of 10 J/cm^2 at 1 ns scaled by the square root of the pulse duration. For short pulses ($< 1 \text{ ns}$), the cost effectiveness is determined primarily by nonlinear effects (B-limited). For pulses of about 1 ns in duration, the limits set by nonlinear effects and flux limitations are about equally important for ED-2, whereas, for longer pulses, flux and energy storage limitations become dominant even for very thick disks.

In general, the best performance characteristics are obtained for the highest B values and highest flux limits. In other words, the most cost-effective designs are both B- and flux-limited in the sub-nanosecond regime.

Energy Storage Capability. For Nd:glass lasers operating at pulse durations longer than 1 ns , flux levels can be obtained that significantly exceed the saturation flux and, hence, extract a major portion of the stored energy. Thus, for long-pulse, high-flux operation, the energy storage capability of the laser material is as important as its power capability. The cost effectiveness of storing energy is another

necessary descriptive characteristic of amplifiers and laser glasses for long-pulse operation.

The combination of cost effectiveness in generating focusable power and cost effectiveness in storing energy gives us a pair of quantities that completely describe amplifiers and laser materials for both high-energy and high-power lasers. These quantities are independent of variables relating to beam propagation, beam profiles, damage limits, laser-pulse durations, required gains per stage, number of amplifiers, or saturation flux. They correspond to the two extremes of operating the amplifiers in either the unsaturated B-limited regime or the fully saturated flux-limited regime. The transition occurs in the time domain of sub-nanoseconds, and it is there that normalized quantities are hard to find.

Optimizing the energy storage capability of an amplifier or glass is equivalent to optimizing the quantity $\ln G/C$, as discussed previously with reference to the flux-limited design. In Fig. 2-188, the cost-optimized energy storage capability of ED-2 glass is plotted with respect to the cost effectiveness of generating focusable power Z_A , which

Fig. 2-188. Composite plot of the cost effectiveness— Z_A in terawatts per million dollars vs E_g/C in kilojoules per million dollars—of storing energy and generating focusable power for various ED-2 disk amplifiers. The disk thickness decreases in a clockwise direction from about 6 to 0.4 cm. Very thin disks are not cost effective for energetic or powerful lasers. The solid and dashed lines show the results of optimizing energy storage or power capability.

Fig. 2-189. Composite plot of the cost effectiveness- Z_A vs E_s/C -of storing energy and generating focusable power for various laser glasses, using disk lasers. This plot shows the superior power capability of the low- n_2 materials as well as the similarity in energy storage capability of the glasses investigated. For 1-ns pulses, the improved glass is most desirable.

provides a unique description of amplifiers and glasses. The dashed lines in this case are the curves obtained by optimizing the quantity $\alpha \ln G/C$ for maximum focusable power per unit cost. This figure clearly shows that Z_A optimization results in a slight shift from energetic to more powerful lasers.

In this figure, the disk thickness decreases from about 6 to 0.4 cm in a clockwise direction. Very thin disks are not cost effective for energetic or powerful lasers. The optimum disk thickness for powerful laser is about 1 to 2 cm, whereas disks about three times thicker are optimal for energetic lasers.

The envelope curves for the different laser glasses are shown in Fig. 2-189. This plot shows, in condensed form, the power and energy capabilities of Nd:glass disk lasers. The performance capabilities of rods, slabs, and active mirrors, as well as other pulsed lasers, can be described in the same basic form for side-by-side comparison of various laser materials and components.

Figure 2-189 again shows the superior performance characteristics of low- n_2 materials for high-power lasers, as well as the very similar performance characteristics of the laser glasses investigated thus far for high-energy lasers. The performance of improved laser glass, described below, is also shown here in form of dashed lines. Such a glass could

potentially provide a 50% improvement in energy storage capability as compared with the other glasses.

Evaluating these curves in the transition regime of subnanosecond pulses is equivalent to requiring both high power and high energy and, hence, an optimum in a direction diagonal to the two axes. Such a compromise will allow high power as well as high energy extraction, without sacrificing the optimum power or optimum energy design by more than about 10%.

Improved Glass Properties. With the techniques described above, we can now investigate which properties of the laser glass are more desirable. An improved glass would have high absorption with broad absorption bands over the full flashlamp spectrum, a long fluorescence lifetime with little or no quenching at high neodymium concentrations, and a low nonlinear index of refraction. The optimum emission cross section would depend, however, on the regime of operation. For short pulses, a high cross section is desirable, but for longer pulses, where saturation is important, a high energy storage capability of the glass is desirable and, hence, a lower cross section.

Since the desired qualities are not independent of each other, a tradeoff between these variables is

necessary. The coupling of these variables is given by⁷⁷

$$\sigma \Delta\lambda \tau_R n^2 = \frac{b \lambda^4}{8\pi c^2} \approx \text{constant}, \quad (34)$$

where σ is the peak emission cross section, $\Delta\lambda$ is the effective fluorescence linewidth, τ_R is the radiative lifetime, and b is the fluorescence branching ratio. Because the branching ratio and the laser wavelength do not change appreciably, the product $\sigma \Delta\lambda \tau_R n^2$ is essentially constant for the various glasses considered.

The radiative lifetime is proportional to the zero-doping fluorescence lifetime τ_0 , while the total absorption $\epsilon = \epsilon_1 + \epsilon_2$ seems to correlate with the effective fluorescence linewidth $\Delta\lambda$ in the form $\epsilon \sim \sqrt{\Delta\lambda}$. However, the correlation of the quenching concentration with any of the glass properties is still elusive. Because of this lack of correlation, a quenching concentration somewhat above the average value of the glasses thus far investigated has been assumed for the improved glass.

These correlations are crucial for an effective tradeoff of the various glass properties. Also, the relative change of the cost effectiveness (Z) of a system has to be determined with respect to the relative change of the various glass properties. Using ED-2 as the reference material, we have determined the relative change in cost effectiveness by

varying the fluorescence lifetime, absorption, and cross section individually by a factor of 1.5 above and below the nominal value. Figure 2-190 shows the results of these calculations. The change in cost effectiveness with fluorescence lifetime and absorption is, to the first order, independent of the regime of operation, saturated or unsaturated, whereas the optimum cross section depends on the degree of saturation.

These results for 3-ns operation can be approximated by

$$Z \sim \tau_0^{0.4} \epsilon^{0.8} \left[1 - \left(\frac{\sigma}{\sigma_0} - 1 \right)^2 \right] \quad (35)$$

where $\sigma \approx 2.5 \times 10^{-20} \text{ cm}^2$. From the correlations discussed earlier, we can write

$$Z \sim \tau_0^{0.4} \Delta\lambda^{0.4} \left[1 - \left(\frac{\sigma}{\sigma_0} - 1 \right)^2 \right] \sim \left(\frac{\sigma}{\sigma_0} \right)^{0.4} \left[1 - \left(\frac{\sigma}{\sigma_0} - 1 \right)^2 \right], \quad (36)$$

since $\tau_R^{0.4} \Delta\lambda^{0.4} \sim \sigma^{-0.4}$ for $n \approx \text{constant}$. This expression indicates an optimum cross section of about $2 \times 10^{-20} \text{ cm}^2$ for an improved laser glass operating at 3 ns.

Fig. 2-190. Relative system performance at 3 ns for various changes in laser glass properties. The performance increases with improved absorption and fluorescence lifetime proportional to about the 0.8 and 0.4 powers of the relative changes in absorption and lifetime. At 3 ns, the system shows optimum performance for an emission cross section of $\sigma = 2.5 \times 10^{-20} \text{ cm}^2$ when correlations are neglected and only σ is optimized.

From these considerations, an improved laser glass for the 3-ns regime would have the following specifications:

$\sigma \approx 2 \times 10^{-20} \text{ cm}^2$	(saturation)
$\Delta\lambda \tau_0 > 20 \text{ nm} - \text{ms}$	(absorption and decay)
$w_0 > 8 \text{ wt.}\%$	(quenching)
$k < 3.5$	(fast decay ratio)
$n < 1.5$	(parasitics)
$n_2 < 1 \times 10^{-13} \text{ esu}$	(nonlinear effects)
$\text{Cost} < \$2/\text{cm}^3$	(cost effectiveness)

However, these specifications depend critically on the desired laser pulse duration. In general, for short-pulse lasers, higher cross sections and lower n_2 values are required.

The characteristics of the improved glass are quite realistic because they are within the range of existing laser glasses.

The next step is to determine which glass compositions could provide the desired material properties and which tradeoffs have to be made to arrive at an ideal composition. The procedure discussed above provides a basic approach of defining ideal characteristics; however, the approximation and results are rather tentative at this time. More detailed analysis is required to determine how these glass specifications would change for a system operating at different laser pulse durations.

Amplifier Chain Design. Previously we have described a large number of optimized components that can be compared in a general sense. The next step is to assemble amplifier chains from these components. The method used here is to select an output stage and then determine sequentially the most cost-effective driver stages. This approach generally results in many options that differ in number of stages, isolation characteristics, flux distribution in the chain, etc.

The designs of lowest cost have limited isolation and many stages with only few disks per stage; they operate at high flux levels throughout the chain. Such designs, however, also have a high associated risk, and the initial cost savings may be paid several

times over in high maintenance costs, including the stocking of many spare parts of different sizes. The general trend, thus, is to reduce the complexity by choosing amplifier chain designs that have only few stages of different-size components. This reduces the requisite number of spares and lowers the cost because of quantity discounts. The risk is reduced by lowering the flux loading in the driver and preamplifier stages, where the cost impact is relatively small. In addition, commonality in components such as flashlamps is desirable, because it also simplifies requirements on the energy storage banks. These general guidelines significantly reduce the number of options.

The dimensions and characteristics of the output stage can be approximated by adding a fixed cost (C_F) for preamplifiers, alignment, control, and diagnostics to that of a chain consisting of identical stages. Identically staged chains cost about twice as much as appropriately staged chains. For a staged chain, therefore, one can approximate the cost as

$$C_c \approx \frac{1}{2} C N + C_F, \quad (37)$$

where C is the cost per stage and N is the number of stages required to amplify the signal from the preamplifiers (P_0) to the full output power capability (P_s) of the stage being considered. Thence, $N = \ln G_{co} / \ln G_{so}$, where G_{co} and G_{so} are the net small-signal gains of the chain and stage, respectively. From the chain's output flux and the required saturated gain $G_{co} = P_s / P_0$, the value of G_{so} can be easily determined using the Frantz-Nodvik equation. This approach provides an approximation for the chain's cost effectiveness in the form $Z_c \approx P_s / C_c$. The results of this approximation are shown in Fig. 2-191 for the case of $C_F = \$400,000$ and $P_0 \approx 10 \text{ GW}$. Comparing these results to those described previously, one observes a significant shift of the peak Z values from B-size stages toward output stages of about 30 cm aperture for 3-ns pulses.

The selection of an output stage with a clear-aperture D_0 , consisting either of one or several identical optimized amplifiers, defines G_0 and X_0 of the output stage. The power capability X_1 and clear-aperture D_1 of the first driver stage can then be estimated by

$$X_1 \geq 1.06 X_0/G_0 \quad \text{and} \quad D_1 \approx D_0/G_0^{0.3} \quad (38)$$

as described in more detail in last year's Annual Report. Specifying X_1 and D_1 defines G_1 and, hence, completely determines the first driver stage. The same process is then repeated sequentially for each driver and preamplifier stage. These approximations provide a rough outline of a chain design. Components are then selected that match closest to the desired specification but also include considerations such as commonality of subcomponents. The individual components are then fine-tuned to provide fully optimized chains within the design constraints.

Amplifier chains with spatial filters can be considered basically as a series of stages that provide focusable power to each other. Since the focusable power of each stage is limited, it is important to match the individual stages quite carefully, such that they can provide sufficient drive power to each other. In other words, each link of the chain should be equally strong. A weak link reduces the chain's overall performance, whereas an excessively strong link will not improve the performance but increase

the cost and, hence, diminish the system's cost effectiveness.

Analysis of Laser Systems. A system analysis code—SPACE (Saturated Performance and Cost Estimates)⁷⁸ is used to determine the chain's performance and cost. Before describing the results, we must know the assumptions and limitations on system performance.

SPACE calculates the saturated gain and beam breakup of spatial zones of the beam, hence takes into account variations in the beam profile due to saturation and B limitations. The input beam profile is assumed to be parabolic (or with an equivalent distribution of the beam intensity). The final fill factor is also calculated by this code and printed in the summary statements. From this analysis, it becomes apparent that the beam profile changes significantly from the input to the output of a chain, improving the fill factor from 0.5 for the parabolic input beam to a value close to unity for the output beam. This improvement in the fill factor, due mainly to saturation, allows significantly higher performance than obtainable for the fixed-fill factor of 0.5 previously assumed. However, there are limitations because of diffraction that limit the fill factor to an estimated value of less than 0.8. In

Fig. 2-191. Approximate cost effectiveness (P_s vs Z_c in terawatts per million dollars of cost) of saturated ED-2 amplifier chains consisting of identical stages with two amplifiers per stage operating at either $\Delta B = 2$ or the flux limit. The input power to the chains is 10 GW; the fixed cost is \$400,000.

Table 2-41. Sample SPACE output for ED-2 laser chain

INPUT POWER		13		GIGAWATTS										
PULSE DURATION		1		NANOSECONDS										
SATURATION FLUX		3.24		JOULES PER SQUARE CENTIMETER										
LASER WAVELENGTH		1.062		MICRONS										
COST OF LASER GLASS		1		* ED-2										
SPATIAL FILTER 1/E B VALUE		2.5												
SPATIAL FILTER CUTOFF POWER		8												
NUMBER OF RADIAL ZONES		10												
#	1.D.	DIAM	#	THICK	INDEX	N2	BANK	GAIN	G-SAT	POWER	B-INC	B-TOT	FLUX	COST
		CM		CM		ESU	KJ			GW			J/CM2	K\$
0	PA+R						20			13.0	2.00*	2.00		400
1	SF	9.4	1*	0.8	1.500	1.24	0	0.99	0.99	12.9	0.01	2.01	0.36	5
2	DISK	9.4	6*	2.4	1.556	1.41	160	4.70	4.33	55.7	0.20	2.20	1.48	68
3	POL	9.4	2*	0.8	1.500	1.24	0	0.94	0.94	52.4	0.04	2.24	1.46	5
4	FR	9.4	1*	0.8	1.670	2.10	20	0.98	0.98	51.3	0.03	2.27	1.39	19
5	POL	9.4	2*	0.8	1.500	1.24	0	0.94	0.94	48.3	0.03	2.31	1.36	6
6	DISK	9.4	6*	2.4	1.556	1.41	160	4.70	3.67	177.2	0.65	2.96	4.32	68
7	SF	9.4	1*	0.8	1.500	1.24	0	0.99	0.99	175.5	0.07	3.03	4.32	5
									1.00	175.4	1.03*	0.28	TW/M\$	577
8	SF	15.0	1*	1.0	1.500	1.24	0	0.99	0.99	173.7	0.03	3.06	1.68	8
9	POL	15.0	2*	1.0	1.500	1.24	0	0.94	0.94	163.3	0.05	3.11	1.66	12
10	FR	15.0	1*	1.0	1.670	2.10	50	0.98	0.98	160.0	0.05	3.16	1.56	34
11	POL	15.0	2*	1.0	1.500	1.24	0	0.94	0.94	150.4	0.05	3.21	1.53	12
12	DISK	15.0	4*	3.0	1.556	1.41	240	2.75	2.37	356.5	0.47	3.69	3.26	105
13	DISK	15.0	4*	3.0	1.556	1.41	240	2.75	2.03	740.3	1.00	4.68	6.31	105
14	SF	15.0	1*	1.0	1.500	1.24	0	0.99	0.99	732.9	0.13	4.81	6.31	8
									0.98	717.9	1.78*	0.74	TW/M\$	881
15	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	710.8	0.09	4.90	3.29	10
16	POL	20.0	2*	1.3	1.500	1.24	0	0.94	0.94	668.1	0.13	5.03	3.26	19
17	FR	20.0	1*	1.3	1.670	2.10	80	0.98	0.98	654.8	0.12	5.15	3.06	53
18	POL	20.0	2*	1.3	1.500	1.24	0	0.94	0.94	615.5	0.12	5.28	3.00	19
19	DISK	20.0	3*	3.2	1.556	1.41	330	2.02	1.73	1040.3	0.62	5.90	4.65	142
20	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	1033.4	0.12	6.07	4.65	10
									1.00	1037.0	1.23*	0.81	TW/M\$	1134
21	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	1026.6	0.12	6.15	4.59	10
22	DISK	20.0	3*	3.2	1.556	1.41	330	2.02	1.59	1628.8	0.93	7.12	6.93	142
23	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	1612.5	0.18	7.31	6.93	10
									1.00	1609.1	1.28*	1.11	TW/M\$	1276
24	SF	25.0	1*	1.7	1.500	1.24	0	0.99	0.99	1592.0	0.15	7.46	4.37	13
25	DISK	25.0	3*	3.5	1.556	1.41	465	1.95	1.56	2483.6	1.01	8.47	6.93	207
26	SF	25.0	1*	1.7	1.500	1.24	0	0.99	0.99	2458.8	0.23	8.69	6.93	13
									1.00	2448.6	1.39*	1.39	TW/M\$	1510
27	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	2424.1	0.18	8.87	4.45	17
28	POL	30.0	1*	2.0	1.500	1.24	0	0.97	0.97	2351.3	0.14	9.02	4.40	20
29	FR	30.0	1*	1.5	1.670	2.10	200	0.98	0.98	2304.3	0.20	9.21	4.27	113
30	POL	30.0	1*	2.0	1.500	1.24	0	0.97	0.97	2235.2	0.14	9.35	4.18	20
31	DISK	30.0	2*	4.0	1.556	1.41	420	1.52	1.34	2983.9	0.66	10.01	5.33	204
32	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	2959.0	0.22	10.23	5.33	17
									0.99	2929.2	1.54*	1.31	TW/M\$	1901
33	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	2899.9	0.21	10.44	5.17	17
34	DISK	30.0	2*	4.0	1.556	1.41	420	1.52	1.30	3793.7	0.83	11.28	6.56	204
35	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	3745.9	0.27	11.54	6.56	17
									1.00	3734.5	1.31*	1.49	TW/M\$	2139
36	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	3697.1	0.26	11.81	6.46	17
37	DISK	30.0	2*	4.0	1.556	1.41	420	1.52	1.27	4704.5	1.04	12.84	8.00	204
38	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	4657.4	0.33	13.17	8.00	17
									0.98	4577.0	1.63*	1.66	TW/M\$	2376
39	FO	37.5	1*	15.0	1.500	1.24	0	0.91	0.91	4176.5	1.44	14.61	4.31	143
									0.99	4146.2	1.44*	1.66	TW/M\$	2519
TOTAL							3555		319.94	4146.2		14.61		2519
X-FACTOR		0.283781251		TERAWATTS PER NEPER										
Z-VALUE		1.646022366		TERAWATTS PER M\$										
FINAL FILL FACTOR		0.844321193												
TOTAL ME		COST		583.1										
TOTAL OPTICS		COST		737.5										
TOTAL EE		COST		948.3										
TOTAL ALIGN.		COST		250.0										

addition, we have allowed no spatial dip in the beam profile.

Since the loading of the pinholes in the spatial filters is also of critical importance, we have assumed a maximum tolerable loading of 100 J without plasma formation and premature closure of the pinhole. Data are needed to determine the accuracy of these assumptions.

To reduce the impact of the focusing optics on system design, we have assumed that the optics can be designed such that they do not limit the system performance in either the B-limited or flux-limited regime. This is considered possible by adding the optics in form of a separate stage following the output stage and by expanding the beam to reduce the flux loading.

Because there are significant potential variations on the focusing optics alone, depending on the assumed target yield, standardized focusing optics have been assumed for these chain designs to permit better side-by-side comparison of different chains. These standardized optics are assumed to have a clear aperture 1.25 times the clear aperture of the output stage, so as to reduce the flux loading as well as B. The assumed configuration includes one blast plate, two vacuum windows, one f/7 focusing lens, two turning mirrors, and one spatial filter lens. The total effective thickness (t_F) of all these components is estimated to be 40% that of the clear aperture. The transmission loss is estimated at $5\% + 0.25 \text{ m}^{-1} \times t_F$ taking into account reflection losses and scattering as well as absorption.

To reduce the impact of isolation on the system design, we have generally located the isolators on the input side of the various stages to reduce the flux loading. In addition, an effective target reflectivity of less than 30% has been assumed for the designs discussed here. If significantly higher isolation were required, then the focusing optics could contain an isolator; the impact on all systems would probably be of a similar magnitude. Finally, the designs have been adjusted to maximize the focusable energy over the range 100 ps to 3-ns.

Typical Results. Table 2-41 presents a sample SPACE output for an ED-2 laser chain operating at 1 ns. This chain is used primarily for reference in determining the relative merit of other materials and components.

Besides a detailed listing of each component in the chain, some general input data are required such

as: input power from the preamplifier section, pulse duration, saturation flux of the laser glass, operating wavelength, relative cost of the laser material in comparison to ED-2, spatial filter transmission characteristics, and number of spatial zones for which the chain is to be evaluated. Every component is entered or recalled from storage, specifying the clear aperture, number of subcomponents, and physical thickness of each transmitting subcomponent. Also entered are the linear and non-linear index, plus the required bank energy and corresponding gain or transmission of each component. These seven pieces of input data and the abbreviated component name are sufficient to calculate the saturated gain, output power, and incremental B contributions, as well as the total B accumulation, peak flux, and component cost (see Table 2-41). Usually, several iterations are needed to find the appropriate input power for maximizing the chain performance within the ΔB or damage constraints.

The abbreviated component name is needed primarily to recognize which cost estimates are applicable. The component cost is then calculated from the given physical dimensions and required energy storage. The abbreviation "Disk, Pol or B-" recognizes components that are oriented at Brewster's angle and determines the appropriate optical pathlength, as well as flux in the optical medium. The abbreviation "SF" recognizes a spatial filter lens and initializes an appropriate transmission calculation after each input spatial filter lens. The resulting transmission is printed in the G-sat column. The stage's B accumulation is shown in the B-inc column and denoted by *. The chain could be terminated at this point, and provide the focusable power at the accumulated cost, as shown. Its cost effectiveness up to this point, including the appropriate standard focusing optics, is also calculated in units of terawatts per million dollars.

Comparing the chain's cost effectiveness at various stages indicates that long, large-aperture chains are more cost-effective, because of the high fixed costs, than shorter, small-aperture chains. For this analysis, the fixed cost for preamplifiers is assessed at \$150,000 and the cost for alignment, control, and diagnostics at \$250,000 per chain. These costs may change somewhat with the size of the chain, but this correlation has not yet been well established. However, it would require a large

reduction in these fixed costs to make a noticeable difference in system design.

The results for the chain are summarized, showing the total required bank energy, effective gain, focusable output power, total B accumulation, and

total cost. Also provided are the focusable power divided by the chain's whole-beam B value, and the final fill factor. The chain costs are broken down separately for mechanical components, optics, electronics, and alignment, as shown.

Table 2-42. Sample SPACE output for high-energy laser chain deep in saturation

INPUT POWER		1.95		GIGAWATTS										
PULSE DURATION		3		NANOSECONDS										
SATURATION FLUX		3.24		JOULES PER SQUARE CENTIMETER										
LASER WAVELENGTH		1.062		MICRONS										
COST OF LASER GLASS		1		ED-2										
SPATIAL FILTER 1/E B VALUE		2.5												
SPATIAL FILTER CUTOFF POWER		8												
NUMBER OF RADIAL ZONES		10												
#	I.D. DIAM CM	#	THICK CM	INDEX	N2 ESU	BANK KJ	GAIN	G-SAT	POWER GW	B-INC	B-TOT	FLUX J/CM2	COST K\$	
0	PA+R					20			2.0	2.00*	2.00		400	
1	SF	9.4	1*	0.8	1.500	1.24	0	0.99	0.99	1.9	0.00	2.00	0.16	5
2	DISK	9.4	6*	3.0	1.556	1.41	170	5.20	4.98	9.6	0.04	2.04	0.77	72
3	DISK	9.4	6*	3.0	1.556	1.41	170	5.20	4.33	41.6	0.18	2.22	3.14	72
4	SF	9.4	1*	0.8	1.500	1.24	0	0.99	0.99	41.2	0.02	2.24	3.14	5
									1.00	41.2	0.24*	0.07	TW/M\$	554
5	SF	15.0	1*	1.0	1.500	1.24	0	0.99	0.99	40.8	0.01	2.25	1.22	8
6	DISK	15.0	4*	3.5	1.556	1.41	250	2.95	2.57	104.6	0.16	2.41	2.96	110
7	POL	15.0	2*	1.0	1.500	1.24	0	0.94	0.94	98.3	0.03	2.44	2.96	12
8	FR	15.0	1*	1.0	1.670	2.10	50	0.98	0.98	96.4	0.03	2.47	2.78	34
9	POL	15.0	2*	1.0	1.500	1.24	0	0.94	0.94	90.6	0.03	2.50	2.73	12
10	DISK	15.0	4*	3.5	1.556	1.41	250	2.95	2.28	206.9	0.32	2.82	5.46	110
11	SF	15.0	1*	1.0	1.500	1.24	0	0.99	0.99	204.8	0.04	2.85	5.46	8
									1.00	204.8	0.62*	0.21	TW/M\$	847
12	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	202.8	0.03	2.88	3.04	10
13	DISK	20.0	3*	4.0	1.556	1.41	350	2.16	1.78	361.7	0.28	3.16	5.13	152
14	DISK	20.0	3*	4.0	1.556	1.41	350	2.16	1.63	589.8	0.47	3.63	7.92	152
15	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	583.9	0.07	3.70	7.92	10
									1.00	583.9	0.85*	0.44	TW/M\$	1172
16	SF	25.0	1*	1.7	1.500	1.24	0	0.99	0.99	578.0	0.06	3.76	5.02	13
17	DISK	25.0	3*	4.5	1.556	1.41	500	2.07	1.59	919.8	0.50	4.26	7.56	226
18	POL	25.0	2*	1.7	1.500	1.24	0	0.94	0.94	864.6	0.14	4.40	7.56	29
19	FR	25.0	1*	1.4	1.670	2.10	130	0.98	0.98	847.3	0.10	4.50	7.10	78
20	POL	25.0	2*	1.7	1.500	1.24	0	0.94	0.94	796.4	0.13	4.62	6.96	29
21	DISK	25.0	3*	4.5	1.556	1.41	500	2.07	1.51	1281.2	0.65	5.27	9.44	226
22	SF	25.0	1*	1.7	1.500	1.24	0	0.99	0.99	1199.2	0.11	5.38	9.44	13
									0.98	1169.9	1.68*	0.57	TW/M\$	1786
23	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	1158.2	0.08	5.46	5.23	17
24	DISK	30.0	2*	5.0	1.556	1.41	440	1.58	1.31	1515.4	0.42	5.89	7.90	220
25	DISK	30.0	2*	5.0	1.556	1.41	440	1.58	1.27	1921.0	0.55	6.42	9.00	220
26	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	1901.8	0.13	6.55	9.00	17
									1.00	1899.5	1.17*	0.72	TW/M\$	2250
27	FO	37.5	1*	15.0	1.500	1.24	0	0.91	0.91	1733.3	0.61	7.16	6.19	143
									1.00	1733.3	0.61*	0.72	TW/M\$	2491
TOTAL						3620		888.88	1733.3		7.16		2491	
X-FACTOR		0.242140755		TERAWATTS PER NEPER										
Z-VALUE		0.721814959		TERAWATTS PER M\$										
FINAL FILL FACTOR		0.832956156												
TOTAL ME COST		489.4 K\$												
TOTAL OPTICS COST		714.1 K\$												
TOTAL EE COST		947.8 K\$												
TOTAL ALIGN. COST		250.0 K\$												

Also available, as another option, is a more detailed cost breakdown of individual components.

The strength of the SPACE code is its detailed analysis of the chain with respect to saturation and B accumulation. Its limitation, is that it ignores diffraction and whole-beam B effects. This limitation is now being reduced by adding an approximation for the growth of large-scale ripples. However, even without this modification, the code provides a powerful tool for side-by-side comparisons of various systems so long as it is properly normalized to existing laser systems. It was normalized to Argus performance at 1.5 TW per beam, which now appears conservative. The addition of large-scale ripple growth and renormalization of the code are discussed elsewhere, where the performance evaluation of the Argus laser is presented.

Comparison of Chain Designs. During the initial phase of the Nova design effort, 3-ns operation was emphasized in order to provide data on high-energy chains deep in saturation. Such a design, for silicate laser glass, is characterized in Table 2-42. Since B limitations at 3 ns do not dominate the performance, only three spatial filters would be required for such a chain. Two beam-expanding telescopes would be required, which have been configured into spatial filters. This chain would provide the greatest cost effectiveness for 3-ns operation but would be limited by nonlinear effects for significantly shorter pulses.

To extend the dynamic operating range from 100 ps to 3 ns we were led to careful examination of the 1-ns pulse laser, i.e., the hybrid between long- and short-pulse laser chains. This resulted in chain designs with a larger number of spatial filters and thinner disks, as listed in Table 2-41. This chain has about an 80% higher short-pulse performance than the 3-ns design; its long-pulse performance is about 10% lower because of higher cost, greater transmission losses through the additional spatial filters, and lower energy storage of the thinner disks.

To determine the impact of a low- n_2 laser material, we evaluated the performance of the laser chain characterized in Table 2-41 for a laser material identical to ED-2 except for the linear and nonlinear indices of FK-51. This material is designated ED-2*. Experimental samples of such a glass have been measured. The results, shown in Table 2-43, indicate some improvement in focusable

power but with a cost increase due to an assumed 50% higher material cost. The cost effectiveness of these two materials would be essentially the same at 1 ns because flux limitations begin to dominate nonlinear effects in this regime. However, the 16% lower whole-beam B value of this chain should help to reduce the growth of large-scale ripples and, hence, provide a beam of higher optical quality. At 100 ps, the ED-2* chain significantly outperforms the ED-2 chain.

To make significant improvements in system performance for pulse durations of 1 ns or longer, a material with improved energy storage capability is desirable. To evaluate the improvement available from higher energy storage, we evaluated the performance of an amplifier chain using the improved laser glass discussed previously. Since the saturated gains of the amplifiers are significantly higher, fewer amplifiers are needed than for the previous chains (see Table 2-44). The chain would be significantly shorter because the number of spatial filters would also be reduced. It would provide about twice the isolation against target reflection as in previous cases, since only two amplifiers would be used in the final output stage. A significant improvement in cost effectiveness at 1 ns could be expected from this chain as compared with the previous 1-ns chains, because of the higher energy storage in the glass.

Laser chains were evaluated for different pulse durations. Figure 2-192 shows some results, plotting cost effectiveness of generating focusable energy vs laser pulse duration. In this figure, each system has a particular characteristic curve whose shape is determined by the chain design.

Amplifier chains optimized for a particular pulse duration exhibit a relatively narrow range of the transition from approximately constant power to constant energy. This accrues from the optimization procedure, which tends to avoid the limitations imposed on the system and, hence, finds an operating condition where all or most limitations are of equal importance. Since the performance of a fully optimized system is usually limited simultaneously by several constraints, the elimination of a single constraint does not improve the performance unless the system is redesigned to take full advantage of the improved situation.

The performance characteristics in Fig. 2-192 correspond to the systems described in Tables 2-41 through 2-44. For comparison, the performance

Table 2-43. Sample SPACE output for ED-2⁺ laser chain

INPUT POWER		18		GIGAWATTS										
PULSE DURATION		1		NANOSECONDS										
SATURATION FLUX		3.24		JOULES PER SQUARE CENTIMETER										
LASER WAVELENGTH		1.054		MICRONS										
COST OF LASER GLASS		1.5		ED-2										
SPATIAL FILTER 1/E B VALUE		2.5												
SPATIAL FILTER CUTOFF POWER		8												
NUMBER OF RADIAL ZONES		10												
#	I.D.	DIAM	#	THICK	INDEX	N2	BANK	GAIN	G-SAT	POWER	B-INC	B-TOT	FLUX	COST
		CM		CM		ESU	KJ			GN			J/CM2	K\$
0	PA+A						20			18.0	2.00*	2.00		400
1	SF	9.4	1*	0.8	1.500	1.24	0	0.99	0.99	17.8	0.01	2.01	0.49	5
2	DISK	9.4	6*	2.4	1.483	0.71	160	4.70	4.19	74.7	0.15	2.16	1.96	72
3	POL	9.4	2*	0.8	1.500	1.24	0	0.94	0.94	70.2	0.05	2.21	1.96	6
4	FR	9.4	1*	0.8	1.670	2.10	20	0.98	0.98	68.8	0.05	2.26	1.84	19
5	POL	9.4	2*	0.8	1.500	1.24	0	0.94	0.94	64.7	0.05	2.30	1.80	6
6	DISK	9.4	6*	2.4	1.483	0.71	160	4.70	3.43	221.7	0.47	2.77	5.26	72
7	SF	9.4	1*	0.8	1.500	1.24	0	0.99	0.99	219.4	0.09	2.85	5.26	5
8	SF	15.0	1*	1.0	1.500	1.24	0	0.99	1.00	219.4	0.85*	0.34	TW/M\$	585
9	POL	15.0	2*	1.0	1.500	1.24	0	0.94	0.94	217.2	0.04	2.90	2.04	8
10	FR	15.0	1*	1.0	1.670	2.10	50	0.98	0.98	204.2	0.06	2.96	2.02	12
11	POL	15.0	2*	1.0	1.500	1.24	0	0.94	0.94	200.1	0.06	3.02	1.90	34
12	DISK	15.0	4*	3.0	1.483	0.71	240	0.94	0.94	188.1	0.06	3.08	1.86	12
13	DISK	15.0	4*	3.0	1.483	0.71	240	2.75	2.29	431.0	0.32	3.40	3.81	114
14	SF	15.0	1*	1.0	1.500	1.24	0	2.75	1.99	855.6	0.65	4.05	7.04	114
15	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	847.0	0.14	4.19	7.04	8
16	POL	20.0	2*	1.3	1.500	1.24	0	1.00	1.00	845.2	1.34*	0.85	TW/M\$	886
17	FR	20.0	1*	1.3	1.670	2.10	80	0.99	0.99	836.7	0.10	4.30	3.89	10
18	POL	20.0	2*	1.3	1.500	1.24	0	0.94	0.94	786.5	0.16	4.46	3.85	19
19	DISK	20.0	3*	3.2	1.483	0.71	330	0.98	0.98	770.8	0.15	4.60	3.62	53
20	SF	20.0	1*	1.3	1.500	1.24	0	0.94	0.94	724.5	0.15	4.75	3.55	19
21	SF	20.0	1*	1.3	1.500	1.24	0	2.02	1.66	1201.8	0.41	5.16	5.32	154
22	DISK	20.0	3*	3.2	1.483	0.71	330	0.99	0.99	1189.8	0.14	5.31	5.32	10
23	SF	20.0	1*	1.3	1.500	1.24	0	1.00	1.00	1189.1	1.11*	0.90	TW/M\$	1151
24	SF	25.0	1*	1.7	1.500	1.24	0	0.99	0.99	1177.3	0.14	5.45	5.26	10
25	DISK	25.0	3*	3.5	1.483	0.71	465	2.02	1.54	1815.2	0.63	6.07	7.68	154
26	SF	25.0	1*	1.7	1.500	1.24	0	0.99	0.99	1797.1	0.21	6.28	7.68	10
27	SF	30.0	1*	2.0	1.500	1.24	0	1.00	1.00	1796.7	0.97*	1.19	TW/M\$	1326
28	POL	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	1778.7	0.17	6.45	4.87	13
29	FR	30.0	1*	1.5	1.670	2.10	200	1.95	1.52	2710.7	0.63	7.08	7.08	228
30	POL	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	2683.5	0.25	7.33	7.08	13
31	DISK	30.0	2*	4.0	1.483	0.71	420	1.00	1.00	2683.5	1.05*	1.46	TW/M\$	1581
32	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	2655.6	0.20	7.53	4.86	17
33	SF	30.0	1*	2.0	1.500	1.24	0	0.97	0.97	2655.6	0.20	7.53	4.86	17
34	DISK	30.0	2*	4.0	1.483	0.71	420	0.97	0.97	2576.0	0.16	7.68	4.81	20
35	SF	30.0	1*	2.0	1.500	1.24	0	0.98	0.98	2524.4	0.22	7.90	4.67	113
36	SF	30.0	1*	2.0	1.500	1.24	0	0.97	0.97	2448.7	0.15	8.05	4.58	20
37	DISK	30.0	2*	4.0	1.483	0.71	420	1.52	1.32	3234.4	0.41	8.46	5.75	227
38	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	3202.1	0.24	8.70	5.75	17
39	FO	37.5	1*	15.0	1.500	1.24	0	1.00	1.00	3190.4	1.37*	1.36	TW/M\$	1995
								0.99	0.99	3158.4	0.23	8.93	5.65	17
								1.52	1.29	4067.5	0.51	9.44	7.06	227
								0.99	0.99	4026.8	0.29	9.73	7.06	17
								1.00	1.00	4025.1	1.04*	1.53	TW/M\$	2256
								0.99	0.99	3984.9	0.29	10.02	6.98	17
								1.52	1.26	5005.9	0.63	10.65	8.52	227
								0.99	0.99	4955.9	0.35	11.00	8.52	17
								1.00	1.00	4945.1	1.27*	1.70	TW/M\$	2517
								0.91	0.91	4512.4	1.59	12.59	5.37	143
								0.99	0.99	4450.1	1.59*	1.70	TW/M\$	2659
TOTAL							3555		247.23	4450.1		12.59		2659
X-FACTOR		0.353390644		TERAWATTS PER NEPER										
C-VALUE		1.67359245		TERAWATTS PER M\$										
FINAL FILL FACTOR		0.833415286												
TOTAL ME		COST		583.1 K\$										
TOTAL OPTICS		COST		877.6 K\$										
TOTAL EE		COST		948.2 K\$										
TOTAL ALIGN.		COST		250.0 K\$										

characteristic of the present Shiva chain is also included. The Shiva chain was designed primarily for short-pulse operation and, consequently, has significantly poorer performance at 1 ns than chains specifically optimized for this pulse duration.

This brief description covers only a small fraction of the many amplifier chains investigated to date. The effort of completely specifying the Shiva Nova chains requires many more additional tradeoffs, as well as more careful considerations of beam

Table 2-44. Sample SPACE output for improved glass laser chain

INPUT POWER	17.8	GIGAWATTS
PULSE DURATION	1	NANOSECONDS
SATURATION FLUX	5	JOULES PER SQUARE CENTIMETER
LASER WAVELENGTH	1.06	MICRONS
COST OF LASER GLASS	0.6 *	ED-2
SPATIAL FILTER 1/E B VALUE	2.5	
SPATIAL FILTER CUTOFF POWER	8	
NUMBER OF RADIAL ZONES	10	

#	I.D.	DIAM	#	THICK	INDEX	N2	BANK	GAIN	G-SAT	POWER	B-INC	B-TOT	FLUX	COST
		CM		CM		ESU	KJ			GW			/CM2	K\$
0	PA+H						20			17.8	2.00*	2.00		400
1	SF	9.4	1*	0.8	1.500	1.24	0	0.99	0.99	17.6	0.01	2.01	0.49	5
2	DISK	9.4	6*	3.0	1.500	0.70	200	6.30	5.67	99.9	0.22	2.22	2.62	74
3	POL	9.4	2*	0.8	1.500	1.24	0	0.94	0.94	93.3	0.07	2.29	2.62	6
4	FR	9.4	1*	0.8	1.670	2.10	20	0.98	0.98	92.0	0.06	2.35	2.47	19
5	POL	9.4	2*	0.8	1.500	1.24	0	0.94	0.94	86.5	0.06	2.41	2.42	6
6	DISK	9.4	6*	3.0	1.500	0.70	200	6.30	4.34	375.5	0.06	3.28	8.79	74
7	SF	9.4	1*	0.8	1.500	1.24	0	0.99	0.99	371.8	0.14	3.42	8.79	5
										1.00	370.6	1.42*	0.57	TW/M\$ 589
8	SF	15.0	1*	1.0	1.500	1.24	0	0.99	0.99	366.9	0.07	3.49	3.38	8
9	DISK	15.0	4*	3.5	1.500	0.70	300	3.30	2.52	924.7	0.72	4.21	7.97	112
10	SF	15.0	1*	1.0	1.500	1.24	0	0.99	0.99	915.5	0.16	4.37	7.87	8
										1.00	915.3	0.95*	1.12	TW/M\$ 717
11	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	906.2	0.12	4.49	4.38	10
12	POL	20.0	2*	1.3	1.500	1.24	0	0.94	0.94	851.8	0.18	4.67	4.34	19
13	FR	20.0	1*	1.3	1.670	2.10	80	0.98	0.98	834.8	0.16	4.83	4.08	53
14	POL	20.0	2*	1.3	1.500	1.24	0	0.94	0.94	784.7	0.17	5.00	3.99	19
15	DISK	20.0	3*	3.5	1.500	0.70	400	2.30	1.91	1495.9	0.52	5.52	6.86	147
16	SF	20.0	1*	1.3	1.500	1.24	0	0.99	0.99	1480.9	0.18	5.70	6.86	10
										1.00	1477.6	1.33*	1.31	TW/M\$ 975
17	SF	25.0	1*	1.7	1.500	1.24	0	0.99	0.99	1462.8	0.15	5.85	4.32	13
18	DISK	25.0	4*	4.0	1.500	0.70	760	3.10	2.27	3318.6	1.00	6.85	9.14	278
19	SF	25.0	1*	1.7	1.500	1.24	0	0.99	0.99	3285.4	0.32	7.16	9.14	13
										0.99	3267.4	1.47*	2.17	TW/M\$ 1280
20	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	3234.8	0.25	7.42	6.19	17
21	POL	30.0	1*	2.0	1.500	1.24	0	0.97	0.97	3137.7	0.20	7.62	6.13	20
22	FR	30.0	1*	1.5	1.670	2.10	200	0.98	0.98	3075.0	0.28	7.89	5.95	113
23	POL	30.0	1*	2.0	1.500	1.24	0	0.97	0.97	2982.7	0.19	8.08	5.83	24
24	DISK	30.0	2*	4.0	1.500	0.70	500	1.62	1.41	4201.1	0.51	8.59	7.78	202
25	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	4159.1	0.32	8.91	7.78	17
										0.98	4059.1	1.75*	2.04	TW/M\$ 1669
26	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	4018.5	0.30	9.21	7.28	17
27	DISK	30.0	2*	4.0	1.500	0.70	500	1.62	1.37	5487.6	0.65	9.86	9.63	202
28	SF	30.0	1*	2.0	1.500	1.24	0	0.99	0.99	5432.7	0.39	10.25	9.63	17
										1.00	5413.8	1.34*	2.41	TW/M\$ 1904
29	FO	37.5	1*	15.0	1.500	1.24	0	0.91	0.91	4940.1	1.79	12.04	6.06	143
										0.96	4766.2	1.79*	2.41	TW/M\$ 2047
TOTAL							3180		267.76	4766.2		12.04		2047

X-FACTOR	0.395956566	TERAWATTS PER NEPER
Z-VALUE	2.328768244	TERAWATTS PER M\$
FINAL FILL FACTOR	0.808437872	

TOTAL ME	COST	464.2	K\$
TOTAL OPTICS	COST	526.7	K\$
TOTAL EE	COST	805.8	K\$
TOTAL ALIGN.	COST	250.0	K\$

Fig. 2-192. Performance characteristics (pulse duration vs $z\tau$ in kilojoules per million dollars of cost) of various chain designs and laser glasses. The sharp transition from approximately constant power to constant energy results from the procedure that optimizes performance for a specified pulse duration. The cost of the laser materials is assumed to be constant.

propagation for the dynamically changing beam profile.

Author
W. F. Hagen

Cost-Optimum Design of Laser Amplifiers

Performance Models. As explained above, an amplifier's performance usually is limited by nonlinear optical processes for short pulses, by flux limitations at intermediate pulse widths, and by energy storage and saturation effects for long pulses. The nonlinear effects are well characterized by the B integral

$$B = \frac{2\pi}{\lambda} \int \gamma I \, dl, \quad (39)$$

where γ is the nonlinear index coefficient that relates the rise in the refractive index produced by an intense laser beam to the intensity of that beam:

$$n = n_0 + \gamma I.$$

Typical materials have γ values in the range 2 to $4 \times 10^{-20} \text{ m}^2/\text{w}$ (see the description of refractive index nonlinearity elsewhere in this report). The small-scale and whole-beam distortions due to B accumulation in a laser chain are complicated, but things get monotonically worse with increasing B. We shall therefore require that our designs not exceed a specified B value. We shall also require that a flux limit not be exceeded, whose value will increase as τ^p where τ is the laser pulse duration and $p = 0.4$ to 0.5 (see the description of laser-induced damage in this report).

The amplifier design is based on laser-glass properties, of which the most important for amplification are pump absorption, inversion decay, emission cross section, emission branching ratio, fluorescence line shape, and refractive index. These properties are combined with those of the capacitor bank, lamp circuit, and laser cavity in a computer simulation of the pumping process in the laser cavity. Careful measurement of the glass properties and normalization of the computer program assure

accurate results (typically $\pm 10\%$). We may then vary the doping and pump pulse duration on the computer and find the best choice of these parameters for a number of combinations of disk thickness and bank energy. Amplifiers of constant gain can then be designed and their costs and performances established, leading to selection of the most cost-effective designs.

We begin the simulation process with the flashlamp circuit (see Fig. 2-193). The current equation,

$$L \frac{dI}{dt} = V - \frac{1}{C} \int_0^t I(t') dt' - IR - \frac{KI}{\sqrt{I}} \quad (40)$$

is solved by numerical integration to get $I(t)$; from this, we get the power into the lamps as a function of time. Lamp power is converted with about 80% efficiency into photons that travel around the laser cavity. Some of the pump photons are lost by absorption in various portions of the cavity, some are lost out the ends, and some strike the glass. Because the lamps reabsorb light by an amount that increases rapidly with increasing input power, and because their output shifts toward the blue with a loading-induced increase in lamp opacity, the fraction of lamp input power that gets to the glass (the cavity transfer efficiency) drops steadily with lamp

Fig. 2-193. Single-mesh flashlamp circuit. Capacitor C is initially charged to voltage V . When the switch closes, the capacitor discharges through inductor L , resistor R , and the flashlamp. The relation between voltage and current in the flashlamp is nonlinear and approximated by the expression shown. K is about $1.3 L/D$ volts per root ampere, where L is the arc length and D the inner diameter of the lamp.

Fig. 2-194. Cavity transfer efficiency in a disk amplifier as a function of lamp current density. The rapid decrease at high current density results from an increase of lamp opacity, that causes the lamp to reabsorb more and more cavity photons.

current density. By use of a three-dimensional Monte Carlo optical-ray trace program and by fitting experimental results on actual disk amplifiers, we have found that a function of the form

$$\eta(J) = \frac{A(1 - e^{-BJ})}{J^C} \quad (41)$$

fits the cavity transfer efficiency, where J is the lamp current density. The constant C is typically in the range 0.8 to 1.0, and the cavity transfer efficiency is usually about 0.5 at 1000 A/cm^2 (see Fig. 2-194). The exponential term in the numerator is needed to drop the efficiency at low current densities; it is not really necessary, since its influence is negligible in the normal operating regime of disk amplifiers.

The light that strikes the glass is absorbed with an efficiency $\epsilon(wt)$ that depends on the disk's doping-thickness product (wt). The shape of the absorption curve as a function of wt is found by numerically running a spectrum typical of flashlamps in laser cavities into the absorption spectrum of the glass, as digitized on a spectrophotometer. This is done by the VODAC program.⁷⁹ Each absorbed photon is converted into an excitation at the upper laser level, so lamp power in the blue is weighted less heavily than lamp power in the red. The weighting is just

λ/λ_L , where λ_L is the laser wavelength. Since there are many absorption coefficients in the glass ranging from very large at the center of strong absorption lines to very weak in the regions between lines, the absorption curve as a function of wt is not a simple exponential. Instead, it is a combination of many exponentials with different absorption coefficients and weights. This multiexponential curve is very well fitted by a double exponential of the form⁸⁰

$$\epsilon(wt) = \epsilon_0 \left[f \left(1 - e^{-a_1 wt} \right) + (1 - f) \left(1 - e^{-a_2 wt} \right) \right], \quad (42)$$

where the coefficients are found separately for each glass (Table 2-45) by use of a nonlinear least-squares fitting program.

The total pumping power going into the upper laser level as a function of time is thus

$$P(t) = L(t)\eta(J)\epsilon(wt), \quad (43)$$

where $L(t)$ is the lamp power. This upper-level power increases the laser's gain coefficient. Since the gain coefficient is $\alpha = N\sigma$, where N is the inversion density and σ is the cross section, and since the

stored energy density is $Nh\nu$, the gain coefficient rate of increase is

$$\alpha = \frac{L\eta\epsilon}{h\nu V} \sigma, \quad (44)$$

where V is the volume of laser glass in the amplifier and ν is the laser light frequency.

By also calculating the loss processes for the gain coefficient, we may write a differential equation for the gain coefficient that can be solved to find the peak gain in the laser. The first such loss process is normal fluorescence decay of the upper level inversion. Even at low doping, this decay in glasses is not well modeled by a single exponential; as the doping increases, the decay curve deviates more and more from an exponential (see Fig. 2-195). We assume that the gain decay has the same shape as the fluorescence decay and have modeled the actual multicomponent system by a three-population model. Each population decays with a simple exponential, so the gain coefficient obeys

$$\alpha(t) = \alpha_0 \sum_{i=1}^3 f_i e^{-t/\tau_i} \quad (45)$$

The fractions in each population group, and their decay times, are found by the nonlinear least-squares fit of a triple exponential decay function to

Table 2-45. VODAC efficiency coefficients

Glass	$\frac{\text{ions/cm}^2}{\text{wt\%}} \times 10^{-20}$	ϵ_0	f	a_1	a_2
ED-2	0.909046	0.108720	0.712782	0.134343	1.116400
LG-650	0.9398	.099830	.865985	.140246	1.296667
LHG-5	0.957200	.105971	.685956	.144165	1.306095
LHG-7N	0.929600	.109493	.698578	.140658	1.297771
LG-710	1.059187	.099238	.723195	.159769	1.434416
LG-700	0.977234	.103883	.694314	.143020	1.231262
Q-88	0.97100	.10844	.765353	.170637	1.782619
EV-2	0.959259	.098495	.681025	.144144	1.239097
LG-802	1.35030	.104261	.713142	.126258	0.976677
B-101	0.784490	0.086469	0.803472	0.160180	1.376036

the measured decay curves at various dopings. This model is useful for single simulations of laser amplifiers but cumbersome for optimization searches involving thousands of designs. So we have determined equivalent single-exponential decay times at dopings corresponding to experimental glass samples. This is done by running an amplifier simulation with the actual nonexponential decay and finding the single exponential that gives the same peak gain. The equivalent decay time increases by 10% or so as the pump duration changes from 400 μ s to 1 ms. It is useful for optimization because it can be easily interpolated to dopings for which experimental data are not available. For example, Fig. 2-196 shows equivalent single-exponential decays for various glasses and the best fit by curves of the form

$$\tau_{eq}(w) = \frac{\tau_R}{1 + \left(\frac{w}{w_Q}\right)^P} \quad (46)$$

where w is the doping, τ_R is the zero-doping (radiative) equivalent single-exponential decay time at 600- μ s pump, w_Q is the quenching value of the doping at which the equivalent lifetime is reduced to half the zero-doping value, and P is a power that is usually close to 2. The fitting, as usual, is done by nonlinear least squares.

Fig. 2-196. Equivalent single-exponential decays as a function of doping for several laser glasses. The points are found by matching the nonexponential decay of samples with single exponentials that produce the same gain. Then best-fit curves are extended through the points.

Fig. 2-195. Inversion decay in glass is not exponential, as demonstrated here. After a short excitation pulse, this curve would be a straight line if it were a single exponential.

Fluorescence amplification within single laser disks increases the loss rate beyond that calculated from the decay curves of small samples. Any production of gain in the disk amplifies the inversion decay that is radiated in the spectral regions where gain is present, thus increasing the loss rate. This effect becomes very serious in large laser disks because the gain across the disk becomes very large (see Fig. 2-197). The three-dimensional Monte Carlo ray trace program has been used to calculate this effect.⁸¹ If the gain coefficient is α and the disk

Fig. 2-197. Monte Carlo values of the ratio A (stimulated to spontaneous loss) as a function of the product β of the gain coefficient and major axis for an elliptical disk whose minor axis is 50% and thickness 14.3% of the major axis. The inside-outside refractive index ratio is 1.56. Curves are shown for three different line profiles of the gain coefficient. When the ratio A is unity, the effective decay time is halved.

long axis is L , then we set $\beta = \alpha L$ and approximate the decay rate as

$$\frac{d\alpha}{dt} = -\frac{\alpha}{\tau_{eq}} (1 - b) + b \exp(c_1\beta + c_2\beta^2 + c_3\beta^3), \quad (47)$$

where b is the fraction of the decays appearing in the 1.06- μm band (the other bands being ignored as negligible) and the c_i are coefficients found by fitting the Monte Carlo results for an elliptical disk with uniform inversion and a Gaussian line profile:

$$c_1 = 0.2087$$

$$c_2 = 0.0135$$

$$c_3 = 0.0031$$

Parasitic oscillation can also increase the loss rate and limit the gain. The principal offenders here are bulk- and face-mode parasites (see Fig. 2-198). These modes are simulated by increasing the decay

rate rapidly as β approaches the parasitic limit, by the factor

$$K \approx 1 + \frac{W}{1 - \frac{\beta}{\beta_p}} \quad (48)$$

where W is the relative width of the parasitic onset and β_p is the parasitic limit. K is kept below 10 to avoid numerical problems. If the unpumped gain of the threshold bulk mode is G_B , then the bulk mode cannot exceed

$$\beta_B = \frac{-\ln G_B}{n}, \quad (49)$$

where n is the refractive index, and the face mode cannot exceed

$$\beta_F = \frac{-\ln G_F}{\xi}, \quad (50)$$

where ξ is the doping-dependent ratio of surface gain to bulk gain. For the two-exponential deposition profile discussed above, this is

Fig. 2-198. Parasitics limit the gain when light amplified in the disk reflects off the edge and returns into the disk for reamplification. Bulk parasites fill the whole disk while bouncing off the faces by total internal reflection. Face parasites result from the higher gain coefficient near the disk faces.

$$\xi = \frac{wt}{2} \frac{[fa_1(1 + e^{-a_1 wt}) + (1-f)a_2(1 + e^{-a_2 wt})]}{[f(1 - e^{-a_1 wt}) + (1-f)(1 - e^{-a_2 wt})]} \quad (51)$$

We then use, as the parasitic limit, whichever of these is worse:

$$\beta_p = \min(\beta_B, \beta_F) \quad (52)$$

The width of parasitic onset W is larger for face modes than for bulk modes, but a single value of 0.05 to 0.1 is customarily used in the calculations.

The differential equation for the gain coefficient is now of the form

$$\frac{d\alpha}{dt} = \frac{\eta\epsilon\sigma}{Vh\nu} L(t) - \frac{\alpha}{\tau_{eq}} [(1-b) + bS] K, \quad (53)$$

where L is the lamp power, η is the current-dependent cavity transfer efficiency, ϵ is the fraction of lamp input appearing in the laser upper level, V is the glass volume, τ_{eq} is a single-exponential representation of the natural decay, S is the fluorescence amplification factor, b is the radiative branching ratio, and K is the decay increase factor due to parasitics. This equation may be integrated to find the maximum gain achieved by the amplifier (see Fig. 2-199).

The optimum pump pulse duration and doping are found by carrying out the simulation for a number of different values of these parameters and plotting the results (Fig. 2-200). Since changes can be made in both parameters with negligible cost change to the laser, we may operate the amplifier at optimum unless the flashlamp loading becomes too high, in which case we must accept a somewhat lower gain coefficient at longer pump-pulse duration.

Gain values for different combinations of disk thickness and bank energy can now be found (see Fig. 2-201). At each thickness-bank combination, we optimize the doping and pump duration as outlined above. Thus, we derive a two-dimensional

matrix of maximum gain values, each of which has been optimized over a two-dimensional space.

Gain coefficients can now be found for various amplifier sizes. Smaller amplifiers will have gains that are limited by lamp life considerations, whereas larger disks will suffer more from fluorescence amplification and parasitics. In all cases we can increase the amplifier gain almost indefinitely by making disks thicker and pumping harder (with longer pump-pulse duration, to avoid lamp-life problems). This is undesirable with respect to cost effectiveness, because short-pulse performance is being limited by the increased glass thickness and because the benefits — even at long pulse — rise less rapidly than the costs. What we have to do is find the amplifier of highest cost effectiveness. To do so, we must evaluate cost and performance for the amplifiers whose gains we have found.

Cost Modeling of Amplifiers. The cost of a disk amplifier, as discussed earlier, is the sum of the mechanical, optical, and electrical costs. Each of these must be determined by experience with actual laser hardware. The extensive data available from experience at LLL have been condensed to the linear form

$$\text{Cost} = K_1 + K_2 E + K_3 V \quad (54)$$

where the K_i are constants that depend on the diameter of the disk amplifier's clear aperture, E is the stored energy in the drive bank, and V is the volume of laser glass in the head. Thus, in the above expression, K_1 is the fixed cost of mechanical and electrical hardware plus glass polishing; K_2 is the cost of adding energy to the bank once the power supplies, cables, and flashlamps (which are included in K_1) are paid for; and K_3 is the cost of thickening the disk once the faces have been polished.

Disk-amplifier performance is determined by fixing the gain and B integral in the amplifier and then establishing the resulting output power. To avoid complications introduced by the laser beam shape, we simply use a uniform profile that fills the entire clear aperture of the amplifier. The actual output of a laser system thus will be considerably less than the output used in these comparisons, but this does not influence the relative merits of various amplifiers.

Saturation. Saturation in the amplifier complicates the calculation of gain and the B integral.

Fig. 2-199. The lamp circuit, pumping, and decay equations are integrated in time to simulate the rise and fall of gain in the laser amplifier. The instantaneous lifetime is reduced at high gain by the effects of fluorescence amplification.

Fig. 2-200. Repeated simulation while varying the doping and pulse duration allows the selection of optimum values for these parameters. Also shown are the processes that reduce gain if we deviate from the optimum.

Fig. 2-201. Maximum gain coefficient as a function of disk thickness and bank energy. At each point, the doping and pump duration have been optimized as in the previous figure. For thin disks and large banks, the gain is limited by parasitics.

All the amplifiers to be compared must have the same saturated gain (G_s), so we use the Frantz-Nodvik formalism⁸² to find the unsaturated gain (G_0) as

$$G_0 = \frac{e^{R_{out}} - 1}{e^{R_{in}} - 1} \quad (55)$$

where R is the ratio of the pulse energy density inside the glass to the saturation energy density. This ratio is found by requiring the B integral to have a specified value B . The B integral is

$$B = \frac{2\pi}{\lambda} \int \gamma I \, dz \quad (56)$$

and, if we assume that the pulse shape is not greatly changed by saturation, the intensity and energy density per unit area are related by

$$I \cong \frac{F}{\tau}, \quad (57)$$

where τ is the equivalent laser pulse width (1.0645

times the FWHM for a Gaussian). The energy density found from Frantz-Nodvik is

$$F = \Phi \ln \left[1 + G_0(z) (e^{R_{in}} - 1) \right], \quad (58)$$

where Φ is the saturation energy density. If the gain is uniformly distributed along the optical path (true for rods and approximately true for disks), we have

$$G_0(z) = e^{\alpha z}, \quad (59)$$

so the B integral is approximately

$$B \cong \frac{2\pi\gamma\Phi}{\lambda\tau} \int_0^L \ln \left[1 + e^{\alpha z} (e^{R_{in}} - 1) \right] dz. \quad (60)$$

The constant-pulse-shape approximation overestimates the B integral (for Gaussian pulses), while the uniform-gain approximation underestimates it. However, we may hope that these errors will compensate each other. By changing to the variable

$$r = \ln \left[1 + e^{\alpha z} (e^{R_{in}} - 1) \right], \quad (61)$$

we have

$$B \cong \frac{2\pi\gamma\Phi}{\lambda\tau\alpha} \int_{R_{in}}^{R_{out}} \frac{r dr}{1 - e^{-r}}. \quad (62)$$

Since $R_{out} = G_s R_{in}$, we may write this as

$$B \cong \frac{2\pi\gamma S}{\lambda\tau\alpha} I(R_{out}, G_s) \quad (63)$$

where

$$I(R, G) = \int_{R/G}^R \frac{r dr}{1 - e^{-r}} = I(R, 0) - I(R/G, 0).$$

This integral is simplified by writing

$$\frac{1}{1 - e^{-r}} = 1 + \frac{1}{e^r - 1}$$

so that

$$I(R, O) = \frac{R^2}{2} + \int_0^R \frac{rdr}{e^r - 1}$$

The integral on the right of this expression is tabulated⁸³ and has the power series expansion

$$\int_0^R \frac{rdr}{e^r - 1} \approx R - \frac{R^2}{4} + \frac{R^3}{36} - \frac{R^5}{3600} + \frac{R^7}{211680} \pm \dots$$

which converges for $R < 2\pi$. We want to approximate $I(R, O)$ to some moderate accuracy with an expression that is fast to evaluate. Some numerical experimentation yields the result

$$\int_0^R \frac{rdr}{e^r - 1} \approx \frac{R^2}{2} + 4 \left(1 - \frac{1}{1 + \frac{R}{4}} \right),$$

which gives an approximation for $I(R, O)$ that matches the exact result to order R^2 for small values of R and gives

$$I(R, O) \rightarrow \frac{R^2}{2} + 4$$

as $R \rightarrow \infty$ instead of the exact result⁸⁴

$$I(R, O) \rightarrow \frac{R^2}{2} + \frac{\pi^2}{6} = \frac{R^2}{2} + 1.64.$$

Thus, the approximation is very good for small amounts of saturation, slightly overestimating the B

integral deep in saturation. The final approximation is

$$B \approx \frac{2\pi\gamma\Phi}{\lambda\tau\alpha} \left[\frac{R_{out}^2}{2} \left(1 - \frac{1}{G_s^2} \right) - \frac{4}{1 + \frac{R_{out}}{4}} + \frac{4}{1 + \frac{R_{out}}{4G_s}} \right] \quad (64)$$

Since we have fixed B , we next want to solve this equation for R_{out} . Rather than tackling a cubic equation, we make an initial guess and then improve it by Newton iterations. The initial guess is based on

$$I(R, O) \approx R + \frac{1}{2} R^2,$$

so

$$R_0 = \frac{1}{1 + \frac{1}{G_s}} \left[\sqrt{1 + 2 I_0 \frac{\left(1 + \frac{1}{G_s} \right)}{\left(1 - \frac{1}{G_s} \right)}} - 1 \right] \quad (65)$$

where

$$I_0 = \frac{\lambda\tau\alpha B}{2\pi\gamma\Phi}.$$

We then find

$$R_{N+1} = R_N + \frac{I_0 - I(R_N, G_s)}{I'(R_N, G_s)} \quad (66)$$

where the derivative is

$$I'(R, G) = R \left(1 - \frac{1}{G^2} \right) + \frac{1}{\left(1 + \frac{R}{4} \right)^2} - \frac{1}{G \left(1 + \frac{R}{4G} \right)^2}$$

Two Newton iterations are enough to reduce the error to negligibility. For example, if we start with $G_s = 2$ and want an R value that yields $I = 2.5988$, we get

$$R_0 = 2.0489 \quad I = 2.1136$$

$$R_1 = 2.3417 \quad I = 2.6276$$

$$R_2 = 2.3261 \quad I = 2.5988$$

Typical Cost and Performance Calculation. We now have everything needed to evaluate amplifier cost and performance using a disk with a known bank energy and resulting gain coefficient. To demonstrate the complete process, we will run through an actual example. An ED-2 amplifier of 20-cm clear aperture and 2.5-cm disk thickness was simulated with 60-kJ/disk pumping input. The resulting gain coefficient was 6.31 m^{-1} . The fixed cost is around \$17,000 per disk and, at 20¢ per joule, the bank variable cost is \$12,000 per disk. The glass variable cost depends on the glass volume. With a 3-mm margin for holding the disk, the short axis is 20.6 cm. The long axis is found from the formula

$$L = D \sqrt{1 + n^2} + \frac{t}{n} + 2M, \quad (67)$$

where D is the clear aperture, n the refractive index, t the thickness, and M the margin. These terms allow for the beam spread on a disk at Brewsters angle, the sideways shift caused by the skew path of the beam in the disk, and the margin for mechanical holding. The long-axis calculation (with $n = 1.556$) yields the result $L = 36.99 + 1.61 + 0.6 = 39.2 \text{ cm}$. Assuming the disk is elliptical, the volume is then $V = \pi/4(D + 2M)Lt = 1586 \text{ cm}^3$, so, at $\$3/\text{cm}^3$, the glass variable cost is \$4,760. The total cost of the amplifier is then \$33,760. The gain per disk is

$$G_1 = e^{at \sqrt{1 + 1/n^2}} \quad (68)$$

(the square root factor allows for the extra length of the skew beam path at Brewsters angle), which yields (per disk)

$$G_1 = e^{0.1875} = 1.20625$$

For ED-2 at line peak, λ is $1.062 \mu\text{m}$. The cross section is $2.7 \times 10^{-20} \text{ cm}^2$, so the saturation energy density (adopting a simplistic two-level model of the actual gain process in glass) is

$$\phi_s = \frac{h\nu}{2\sigma} = 3.464 \text{ J/cm}^2 \quad (69)$$

The nonlinear coefficient is γ is $3.8 \times 10^{-20} \text{ m}^2/\text{W}$, so if B is 2, G is 2, and the laser pulse duration is 1.6 ns, we must have

$$I(R, G) = \frac{\lambda \tau \alpha B}{2\pi \gamma \Phi} = 2.60$$

This corresponds to the example given previously, so we know that R_{out} is 2.33. The small-signal gain needed to produce the saturated gain of 2 is then

$$G_0 = \frac{e^{2.33} - 1}{e^{2.33/2} - 1} = 4.21$$

so we must use

$$N = \frac{\ln G_0}{\ln G_1} = 7.66$$

disks at a total cost of about \$259,000 to do the job. (Of course, an actual design will not use fractional disks, but we must do so for comparison of various disks.) The output energy density is

$$n\Phi R_{\text{out}} = 12.56 \text{ J/cm}^2$$

which is at or above the damage level at this pulse width. If we were more cautious, we would set R_{out} to a safer value and recompute the number of disks and cost at this lower output level. Let us press on regardless and find the output power to be

$$P_{\text{out}} = \frac{\pi D^2 n}{4\tau} R_{\text{out}} \Phi = 2.47 \text{ TW}$$

This is with unity fill factor, of course. We can then determine the cost effectiveness (CE):

$$CE = \frac{2.47 \text{ TW}}{\$259,000} = 9.54 \text{ MW/dollar}$$

Optimum Bank Energy and Disk Thickness. We can now compare this disk with other disks on an equal basis. For each bank energy and disk thickness (with optimized doping and pump duration), we calculate the output power that will give the fixed B-integral and gain values, then find the number of disks and thus the cost required to give the necessary small-signal gain. This gives us a cost effectiveness, permitting comparison of the disks by their relative cost effectiveness.

The comparison is illustrated in Fig. 2-202, which shows a plot of a mesh of bank-thickness possibilities. Each combination of bank and thickness is plotted horizontally by its unity-fill output power and vertically by its cost effectiveness. Increasing the disk thickness while maintaining constant bank, B-integral and saturated gain values steadily reduces the power output because the gain coefficient is reduced. This increases the total length

of glass needed to supply the specified gain, which in turn increases the B integral unless the power is reduced. Cost initially declines faster than power because of the large number of thin disks needed to produce the gain. Since each disk requires supporting hardware and stored energy, the amplifier cost is large. The result of the rapid decrease of disk count with disk thickness is that the cost effectiveness initially rises. As the disks become thicker, the cost advantage becomes less; the steady performance decrease causes the cost effectiveness to drop. Thus, there is an optimum thickness at the balance between the excessive cost of thin disks and the low performance of thick disks.

Increasing the bank energy while maintaining a constant disk thickness steadily increases the power output because of the resulting rise in the gain coefficient. The cost effectiveness also rises because the bank is initially a small fraction of the amplifier cost. However, as the bank becomes larger, the added increases of gain coefficient become smaller and smaller because of lamp reabsorption and superfluorescence, while the bank cost becomes a larger and larger fraction of the amplifier cost. Thus, the power increases become less and costs more; the cost effectiveness drops. There is an optimum bank

Fig. 2-202. Disk cost effectiveness calculated for the gains in the previous figure. We find the maximum output power for a fixed B-integral contribution, then determine the cost from the number of disks needed to provide the specified gain. Saturation is included in both calculations. For each combination of bank energy and disk thickness (mesh node), the power per dollar is plotted as a function of the power.

size at the balance between added performance and added cost.

Parasitics can affect the optimum thickness and bank. A rapid-onset bulk parasitic limits the gain coefficient and thus the power output. The result is unavailability of the region of thin disks and large banks, where the gain coefficient would exceed the parasitic limit. If the optimum thickness and bank lie in this region without parasitics, the optimum is moved to lower bank and thicker disks when the parasitic is active, reducing the maximum cost effectiveness. The reduction can be severe in the case of large amplifiers, where parasitic suppression is especially important.

Optimum Amplifier Aperture

The mesh of disk-thickness and bank-size possibilities described above can be produced for amplifiers of various laser-beam diameters. Typical results for the LLL 39-, 91-, 200-, and 300-mm amplifier apertures are shown in Fig. 2-203. A smooth curve has been drawn through the tops of the meshes. This curve shows the highest achievable cost effectiveness as a function of output power. The point where this curve touches each mesh is the

optimum thickness-bank combination for that diameter; note that this is not necessarily the top of the mesh.

There is an aperture that generates power in the most cost effective manner. In the case shown, the optimum comes at about 170 mm — between the 91- and 200-mm sizes. A laser chain must have a variety of apertures, so the optimum diameter of the chain output will be slightly larger than the most cost effective amplifier. This is why the Shiva chains terminate at 200-mm aperture.

Laser Pulse Width Variation. The envelope curve may be produced for a variety of different laser pulse widths. Figure 2-204 shows the result of this process for pulse widths of 30 ps to 10 ns. Ticks on the curves denote 39-, 91-, 200-, and 300-mm apertures.

When the pulse duration is short, the amplifiers are unsaturated and the best performance comes with a high gain coefficient, which minimizes the glass in the beam. The best amplifiers are around 100 mm in diameter and have thin disks and a large bank. Larger amplifiers suffer because of fluorescence amplification and parasitic limitations on their gain coefficient. Note also that the cost effectiveness drops rather rapidly if we use the wrong amplifier diameter.

Fig. 2-203. The dependence of cost effectiveness on diameter is found by plotting the mesh of the previous figure for various diameters. A smooth curve can then be drawn through the tops of the meshes, which defines the maximum cost effectiveness as a function of diameter. The point where the curve touches the mesh defines the best thickness-bank diameter.

Fig. 2-204. The dependence of cost effectiveness on laser pulse width is found by repeating the calculations of the previous figure for different laser pulse durations. Note that power per dollar becomes nearly constant below 10 ps whereas energy per dollar is constant about 1 ns.

Fig. 2-205. The improvement available by changing glass properties is found by plotting the maximum values of the curves from the previous figure as a function of laser pulse width. The entire optimization process is then performed with the changed glass properties, and another curve is plotted. Here we see the improvement available by halving and quartering the nonlinear index of the laser glass. This improvement is large for short pulses but negligible for long pulses.

When the pulse duration is long, the amplifiers are heavily saturated. The best performance comes with the stored energy of lowest cost. The optimum shifts to larger apertures and becomes less sensitive to diameter. The disks are thicker and the banks smaller. Unsaturated and saturated amplifiers are therefore different in optimum aperture, disk thickness, and bank size. If a multipurpose system is needed to cover both cases, it will be closer to a short-pulse system in aperture but will have the extra disks needed for storing the long-pulse energy.

In the short-pulse case, the lasers converge on a constant-power capability as the pulse is shortened. Unsaturated lasers are thus power-limited devices. When the pulses are long, the peak power per dollar becomes inversely proportional to the pulse width, so the energy per dollar becomes constant. Saturated lasers are thus energy-limited.

Glass Parameter Variation. Given the cost-optimal amplifier design method outlined above, what can we learn about the effect of the laser-glass parameters on the cost effectiveness of a laser system? We can plot the power per dollar of a representative output amplifier stage as a function of laser pulse width (Fig. 2-205). Three curves are shown. The first is for a silicate glass such as used in Shiva. The second and third curves are for this same glass with its nonlinear refractive coefficient γ decreased to 50% and then to 25% of the actual value. The glass cost is assumed to be unchanged. For very short pulses, the power per unit cost is

found to be inversely proportional to γ ; we get twice and four times the baseline power as γ is halved and quartered. For very long pulses, however, there is no effect. The energy per dollar does not depend on γ . In the 100-ps to 1-ns regime in which we expect to operate Shiva, γ has a modest effect but reduced considerably from the short-pulse result.

References

76. *Laser Fusion Program Semiannual Report, July-December 1973*, Lawrence Livermore Laboratory, Rept. UCRL-50021-73-2 (1974), p. 39.
77. W. F. Krupke, *IEEE, QE-10* (1974).
78. The propagation, data input, and storage sections of the SPACE code were developed by J. Trenholme of Lawrence Livermore Laboratory. See the theory and design analysis portion of this report for propagation code information.
79. *Laser Program Annual Report — 1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), p. 269.
80. *Laser Program Annual Report — 1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p. 205.
81. W. Hagen, Lawrence Livermore Laboratory, private communication (1976).
82. J. Trenholme, NRL Memorandum Rept. 2480 (1972).
83. L. M. Frantz and J. S. Nodvik, *J. Appl. Phys.* 34, 2346 (1963).
84. M. Abramowitz and I. Segun, *Handbook of Mathematical Functions* (U.S. Government Printing Office, Washington, D.C., 1968), Sec. 27.1.
85. H. Dwight, *Tables of Integrals and Other Mathematical Functions* (Macmillan, New York, 1961), Integral 860.31.

Authors

J. B. Trenholme
E. J. Goodwin

2-4 Optical Materials

2-4.1 Overview

Intense laser pulses change the refractive index of the optical material they pass through—both optical glass and laser glass—by an amount that varies with the pulse intensity. This effect limits the performance of high-power lasers including “self-focusing,” which leads to beam breakup and loss of focusable energy. Both small-scale and whole-beam self-focusing are governed by the nonlinear refractive index coefficient, n_2 , of the optical medium. A direct way to increase the performance of a given laser system is to reduce the n_2 of all the

optical materials in the system. In 1973 we began a program to identify and develop optical materials with lower n_2 -values. This program as it applies to developing improved glasses and materials for Shiva Nova and future laser systems is discussed below.

Our present laser systems for fusion experiments use commercial silicate-based glasses doped with neodymium. These glasses were not developed for today's power-limited laser systems, nor are they expected to be optimum for projected laser systems of the future. We now know that improved glass compositions are possible which can provide significant

Table 2-46. Various types of fluoride-containing glasses. Those marked with an asterisk have been investigated for possible fusion-laser application

Pure Fluoride Glasses*

Network	Modifier Ions
BeF_2	MF ($\text{M}^+ = \text{Li, Na, K, Rb, Cs}$)
AlF_3	MF_2 ($\text{M}^{2+} = \text{Mg, Ca, Sr, Ba, Zn, Cd, Pb}$)
ZrF_4	MF_3 ($\text{M}^{3+} = \text{Al, Y, La, Bi}$)
	MF_4 ($\text{M}^{4+} = \text{Zr, Th}$)

Fluoride Glasses Containing Phosphate ($\text{F/O} \gtrsim 1$)*

Oxide Glasses Containing Fluorine ($\text{F/O} \lesssim 1$)

Fluoroborate
 Fluorosilicate
 Fluorophosphate*
 Fluorogermanate

Fig. 2-206. Variation of the refractive index of beryllium fluoride glasses with the addition of alkali fluorides (left) and alkaline earth fluorides (right). Solid portions of curves denote regions of glass formation. (Data from W. Vogel and K. Gerth, *Glastech. Ber.* 31, 15 (1958) and *Silikattechnik* 9, 353 (1958).)

performance advantages over present laser glasses, especially in power-limited laser systems.^{85,86} Among these are phosphate glasses, which we have been investigating for several years and which are being considered for fusion-laser systems here and elsewhere, and various fluoride glasses, which are discussed in last year's Annual Report⁸⁷ and in more detail below. In addition, fluoride crystalline materials have been identified that possess very high figures of merit.

Fluoride glasses and crystals have been demonstrated to have smaller refractive index non-linearity than their oxide counterparts, and hence they are of interest for high-power lasers where focusable energy is important. Table 2-46 gives examples of fluoride-containing glasses. Of the pure

fluoride glasses, the lowest refractive indices belong to glasses with beryllium fluoride as their network former. Adding various alkali and alkaline-earth fluorides as network modifiers increases the refractive index as shown in Fig. 2-206. From such studies of the compositional dependence of the refractive index and dispersion, one can tailor glasses to reduce their n_2 -values.

It has been shown⁸⁸ that estimates of n can be based on the linear index n_d and the reciprocal dispersion given by the Abbe number ν_d . A plot of these relationships for known glasses is shown in Fig. 2-207. The approximate location of the glasses in Table 2-46 is determined by the fluorine-to-oxide ratio and the presence of high-atomic-number cations having large polarizabilities.

Fig. 2-207. Glasses can be grouped using their refractive index n and Abbe number ν as coordinates. Here regions of known oxide- and fluoride-containing glasses are shown together with lines of constant nonlinear refractive index n_2 estimated from n_d and ν . Increasing the fluorine content results in low-index, low-dispersion glasses.

While the nonlinear index n_2 is an important factor in the performance of both transmitting optical material and lasing material, for lasing material other properties such as the optical pumping efficiency, excited-state lifetimes, stimulated-emission cross section, and resultant gain coefficient are also important considerations. As an example, for longer pulse operation, the stored energy and saturation flux may assume greater importance and the nonlinear index less. These properties are affected by the spectroscopic properties of the Nd^{3+} ion, which in turn are dependent on the composition of the glass host. Large variations in spectroscopic properties with network-forming and network-modifying ions have been reported.⁸⁹ To investigate the range of spectroscopic properties possible for fluoride glasses, measurements have been made as a function of glass composition. Results for a number of fluorophosphate, fluoroberyllate, and fluorozirconate glasses are presented later in this section.

Using spectroscopic data obtained from small Nd:glass samples sample material in various optical pumping configurations and amplifiers. These results are then applied to derive optimized amplifier chains and the most cost-effective laser fusion system based upon the use of specific materials. To determine how accurately the gain coefficient of a new material can be predicted, we have made detailed comparisons of calculated versus measured gain coefficients in a disk amplifier. Two significant features of this study are (1) the use of a special liquid-edge-clad disk holder to reduce uncertainties arising from parasitic losses, and (2) the investigation of glasses having a wide range of spectroscopic properties, thereby providing a more severe test of the calculations. The results, presented later in this section, indicate that the gain characteristics of new materials can be predicted to within $\pm 10\%$.

The computerized facilities for optical spectroscopy of Nd laser materials have been improved further to provide a more rapid and convenient evaluation of new compositions, in a form useful for direct input to the computer codes used to model the gain characteristics.⁹⁰ The data generated has been compiled into volumes of "Nd Laser Glasses Data Sheets," described later which have been distributed to laser glass companies to assist them in the development of new glasses.

To investigate more fully the properties of paramagnetic ions in glasses, particularly the properties that can affect laser performance, several

additional studies have been undertaken. This research includes studies of fluorescence sensitization, saturation fluence, fluorescence line narrowing, fluorescence quenching, and nonradiative decay by multiphonon processes in glasses. These experiments are described in a later subsection. Three following subsections present discussions and properties of other optical materials of interest: Faraday rotator materials, lens materials, and oscillator crystals.

All optical materials are subject to laser-induced damage. Antireflection coatings, in particular, are presently the weak link in many system designs. Progress in the area of thin-film coatings is especially important in order to optimize the long-pulse performance of future glass-laser systems. The performance level of many laser systems will increase greatly with more damage-resistant coatings and materials. Some results of the continuing investigation of damage thresholds for optical components are summarized in the next-to-last subsection.

Studies of nonlinear optical properties of materials are discussed at the end of this section. They include measurements of the refractive index nonlinearity using time-resolved interferometry. Extensions of these techniques to studies of other optical materials, the spatial and frequency dispersion of n_2 , and the dependence of n_2 on pulse duration are planned. An investigation of multiphoton absorption phenomena has also been initiated. Finally, an upgrade of the Nonlinear Optics/Laser Damage Facility to provide for these investigations is under way. The essential features of this upgrade are outlined at the conclusion of this section.

References

85. M. J. Weber, "Optical Materials for Neodymium Fusion Lasers," in *Critical Materials Problems in Energy Production*, C. Stein, Editor (Academic Press, New York, 1976), pp. 261-279.
86. M. J. Weber, C. B. Layne, R. A. Saroyan, and D. Milam, *Opt. Commun.* 18, 171 (1976).
87. *Laser Fusion Annual Report-1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75, pp. 192-201.
88. *Laser Fusion Annual Report-1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74, pp. 256-260.
89. R. R. Jacobs and M. J. Weber, *IEEE J. Quant. Electron.* QE-12, 102 (1976).
90. R. A. Saroyan and M. J. Weber, *Proc. SPIE Conference on Unconventional Spectroscopy* 82, 169 (August 1976).

Author

M. J. Weber

2-4.2 Fluoride Glasses

Fluorophosphates

Investigations of fluorophosphate glasses, some results of which were reported in last year's Annual Report, continue to point the way toward lasers of even higher power than those now being built. A variety of glasses were prepared by the Inorganic Glass Section of the National Bureau of Standards (NBS). By using cations of low atomic number and increasing the fluorine-to-oxygen ratio, we have produced small melts of glasses with estimated n_2 values of $<0.6 \times 10^{-13}$ esu. Commercially available optical glasses such as Schott's FK-51 and FK-52 have n_2 values of $\approx 0.7 \times 10^{-13}$ esu. Large melts of these lower-index glasses have not yet been attempted, and, therefore, the difficulties in obtaining high optical quality remain to be established.

The effects of chemical composition on the spectroscopic properties of Nd^{3+} were explored for a large number of melts. Tables 2-47 and 2-48 show the results of systematically varying the alkali and alkaline earth network modifier ions. Tabulated are

(a) the density and sodium D-line index of refraction, (b) the Judd-Ofelt intensity parameters determined from a least-squares fit of measured and calculated absorption band strengths in the 400- to 950-nm region, and (c) the properties associated with the $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{11/2}$ fluorescence including the predicted radiative lifetime τ_R , the effective linewidth $\Delta\lambda_{\text{eff}}$, and the stimulated emission cross section σ .

As in the case of phosphate glasses, the fluorescence linewidth decreases with increasing size of the alkali or alkaline-earth ions. This, combined with changes in the oscillator strengths, affects the stimulated emission cross sections. For the compositions shown, however, the changes in σ are small. (The probable errors associated with the Ω determinations were typical, $\approx \pm 10\%$ for Ω_4 and Ω_6 , and $\leq \pm 10\%$ for Ω_2 .) Linewidths were found to increase monotonically with Al^{3+} addition. The range of spectroscopic values observed for the compositions studied thus far are given in Table 2-49; values observed for other glass types are included for comparison. Since all possible compositions have not been explored, the ranges in this table do not necessarily indicate the extremes possible.

Table 2-47. Dependence of Nd^{3+} spectroscopic properties on alkali ion variation in a fluorophosphate glass. Composition (mol%): $\text{Al}(\text{PO}_3)_3$, 235; MF, 38; BaF_2 , 38; Nd_2O_3 , 0.5. Fluorescence peak: ≈ 1054 nm

Property	Alkali ion		
	Li^+	Na^+	K^+
Density, g/cm^3	3.63	3.62	3.48
Refractive index (n_D)	1.551	1.530	1.515
Nd^{3+} intensity parameters:			
Ω_2 , 10^{-20} cm^2	2.8	3.0	3.2
Ω_4 , 10^{-20} cm^2	5.4	4.3	4.7
Ω_6 , 10^{-20} cm^2	5.8	5.2	5.2
$^4\text{F}_{3/2} \rightarrow ^4\text{I}_{11/2}$ fluorescence properties:			
$\Delta\lambda_{\text{eff}}$, nm	28.6	28.4	28.0
Lifetime (τ_R), μs	308	382	374
Cross section (σ), 10^{-20} cm^2	3.8	3.3	3.4

The centers of gravity of rare-earth J states and the wavelengths of absorption and emission bands vary with the glass network former and the network modifiers. The changes obtained by changing the latter are less, however, typically $\sim \pm 2$ nm. As an interesting example, consider a pure fluoride glass such as one based upon beryllium fluoride. The peak emission for $\text{Nd}^{3+} {}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{11/2}$ is around 1047 nm. For an oxide glass based upon phosphate, the corresponding peak emission is around 1054 nm. For many fluorophosphates with sizeable ox-

ygen content, the emission again peaks near 1054 nm. However, when the fluorine content is made very large, the fluorescence becomes very broad and straddles the spectral region of both fluoroberyllate and phosphate glasses with a peak around 1050 nm. This behavior is shown in Fig. 2-208 and reflects the different ranges of Nd^{3+} local environments.

Work on fluorophosphates is continuing. In addition to studies of spectroscopic properties, the effects of chemical composition on other physical and chemical properties are being investigated. These

Table 2-48. Dependence of Nd^{3+} spectroscopic properties of alkaline earth variation in a fluorophosphate glass. Composition (mol%): $\text{Al}(\text{PO}_3)_3$, 16.0; MF_2 , 32.0; LiF , 41.5; Li_2O , 10.0; Nd_2O_3 , 0.5. Fluorescence peak: 1055 nm

Property	Alkaline earth			
	Mg^{2+}	Ca^{2+}	Sr^{2+}	Ba^{2+}
Density, g/cm^3	2.77	2.81	3.24	3.52
Refractive index (n_D)	1.494	1.502	1.51	1.524
Nd^{3+} intensity parameters:				
Ω_2 , 10^{-20} cm^2	2.9	2.2	1.9	2.3
Ω_4 , 10^{-20} cm^2	5.0	4.6	5.4	5.4
Ω_6 , 10^{-20} cm^2	5.6	5.3	5.7	6.3
${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{11/2}$ fluorescence properties:				
$\Delta\lambda_{\text{eff}}$, nm	29.2	27.6	27.3	26.7
Lifetime (τ_R), μs	365	385	340	310
Cross section (σ), 10^{-20} cm^2	3.4	3.4	3.8	4.3

Table 2-49. Measured variations of neodymium laser glass properties

Glass	Peak wavelength (nm)	Cross section, 10^{-20} cm^2	Linewidth FWHM (nm)	Lifetime, τ_R (μs)
Silicate	1057 - 1062	1.0 - 3.1	28 - 35	330 - 950
Phosphate	1053 - 1055	1.8 - 4.7	19 - 28	320 - 560
Fluorophosphate	1051 - 1055	2.1 - 4.3	22 - 29	310 - 470
Fluoroberyllate	1047 - 1050	1.9 - 3.8	15 - 24	590 - 920

Fig. 2-208. Room-temperature ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ fluorescence spectra of Nd^{3+} in (a) beryllium fluoride-based glass, (b) mixed fluoride (no BeF_2) glass with phosphate, and (c) phosphate glass. Compositions in mol% are (a) BeF_2 47, KF 27, CaF_2 14, AlF_3 10, and NdF_3 2 (from UCLA); (b) AlF_3 37.3, MgF_2 10, CaF_2 30, SrF_2 10, BaF_2 8, YF_3 1, $Al(PO_3)_3$ 2.7, and NdF_3 1 (from Owens-Illinois); (c) P_2O_5 55, Li_2O 30, CaO 10, Al_2O_3 4.3, and Nd_2O_3 0.7 (from Kigre).

results will form the basis for selection of glass compositions to be developed in a laser glass development program.

Fluoroberyllates

The fluoride glasses of lowest index are those based upon beryllium fluoride, a well-known glass former with a structure similar to that of silica. However, because of the toxicity of beryllium fluoride, its hygroscopic character, and its relatively high cost, fluoroberyllate glasses have received much less attention than silicate glasses. Important events in the history of fluoroberyllate glasses are:

1926 — Discovery of beryllium fluoride glass (Goldschmidt).

1933 — Investigation of optical and physical properties (Heyne).

1938 — Fluorescence from rare earths reported (Tomaschek-Deutschbein).

1940's — Toxicity of beryllium compounds demonstrated.

1940's and 1950's — Compositional studies: glass formation and properties of optical glass (Sun, Vogel-Gerth, Pincus. . .).

1966 — Neodymium laser glass (Petrovskii and coworkers, Deutschbein).

Recognition of the small nonlinear refractive index of fluoroberyllate glasses and the possible application of these glasses to fusion lasers are developments in the 1970's.

More than 25 different neodymium-doped fluoroberyllate compositions have now been ex-

amined. Samples were obtained from UCLA⁹¹ and from Corning Glass. Facilities for melting and finishing small samples of fluoroberyllate glasses were also established at LLL and are reviewed below.

Table 2-50 shows a compositional study in which the alkali ion is changed from Li^+ to Cs^+ . Systematic variations are observed for the density, refractive index, intensity parameters, linewidths, and cross sections. Similar studies were made on glass of the same composition except the alkali ion (K^+) was kept constant and the alkaline-earth fluoride was changed (14 mol% Mg, Ca, or Sr). In these cases the variations in the $Nd^{3+} {}^4F_{3/2} \rightarrow {}^4I_{11/2}$ fluorescence properties did not exceed 10%.

Table 2-51 presents spectroscopic data for different beryllium fluoride glasses: (A) simple BeF_2 , (B) an alkaline earth — aluminum fluoroberyllate, and (C) and (D) a binary alkali fluoroberyllate in which a fraction of the anions are replaced by chlorine.⁹²

The properties of fluoroberyllate glasses differ from those of oxide and other fluoride glasses in several respects. The peak of the $Nd^{3+} {}^4F_{3/2} \rightarrow {}^4I_{11/2}$ emission occurs near 1047 nm at ambient temperatures. The fluorescence branching ratio for this transition is larger than in oxide glasses. As is typical of fluoride crystals as well as glasses, the Ω_2 intensity parameters for Nd^{3+} are very small. The Nd^{3+} absorption band around 580 nm, which can have a large contribution from the Ω_2 term, is correspondingly small. Because the oscillator strengths of Nd^{3+} transitions are not large in

Table 2-50. Dependence of Nd³⁺ spectroscopic properties on alkali ion variation in a fluoroberyllate glass. Composition (mol%): BeF₂, 47; MF, 27; CaF₂, 14; AlF₃, 2. Fluorescence peak: $\approx$ 1047 nm

Property	Alkali ion				
	Li ⁺	Na ⁺	K ⁺	Rb ⁺	Cs ⁺
Density, g/cm ³	2.54	2.68	2.62	2.96	3.25
Refractive index (n _D)	1.344	1.343	1.347	1.354	1.376
Nd ³⁺ intensity parameters:					
Ω_2 , 10 ⁻²⁰ cm ²	~ 0	0.11	0.20	0.37	0.22
Ω_4 , 10 ⁻²⁰ cm ²	3.6	3.7	3.9	3.9	4.4
Ω_6 , 10 ⁻²⁰ cm ²	3.7	4.3	4.6	4.8	5.3
⁴ F _{3/2} → ⁴ I _{11/2} fluorescence properties:					
$\Delta\lambda_{eff}$, nm	25.6	23.8	23.2	23.0	22.5
Lifetime (τ_R), μ s	700	661	611	590	500
Cross section (σ), 10 ⁻²⁰ cm ²	2.3	2.8	3.2	3.3	3.8

Table 2-51. Variation of Nd³⁺ spectroscopic properties with composition of fluoroberyllate glasses

Property	Fluoroberyllate glass ^a			
	A	B	C	D
Density, g/cm ³	2.13	3.25	2.386	2.387
Refractive index (n _D)	1.284	1.384	1.325	1.325
Nd ³⁺ intensity parameters:				
Ω_2 , 10 ⁻²⁰ cm ²	1.4	0.73	0.07	0.26
Ω_4 , 10 ⁻²⁰ cm ²	2.9	4.3	2.7	3.0
Ω_6 , 10 ⁻²⁰ cm ²	3.6	5.0	3.2	3.7
⁴ F _{3/2} → ⁴ I _{11/2} fluorescence properties:				
λ_p , nm	1046	1047	1050	1050
$\Delta\lambda_{eff}$, nm	27.7	28.6	19.3	19.4
Lifetime (τ_R), μ s	916	515	930	822
Cross section (σ), 10 ⁻²⁰ cm ²	1.9	2.9	2.6	2.9

^aCompositions (mol%):

A. BeF₂, 98; NdF₃, 2.

B. BeF₂, 34; AlF₃, 23; MgF₂, 19; CaF₂, 10; BaF₂, 14;

C. BeF₂, 58; KF, 40; NdF₃, 2.

D. BeF₂, 58; KF, 20; KCl, 20; NdF₃, 2.

Fig. 2-209. Absorption spectrum of 9.35 wt% NdF_3 in beryllium fluoride glass at 295 K. Sample thickness: 0.31 cm.

fluoroberyllate glasses and the linewidths are narrow, the pumping efficiency is less than in most other glasses. Beryllium fluoride glasses transmit in the ultraviolet as shown in Fig. 2-209 for Nd-doped BeF_2 glass. Investigations are underway to determine the UV absorption edge of beryllium fluoride glasses.

The long fluorescence lifetimes in Tables 2-50 and 2-51 are due in part to the small refractive index which enters as $n(n^2 + 2)^2$ in the spontaneous emission probability. The emission linewidths in fluoroberyllate glasses exhibit a monotonic decrease with increasing size of the alkali or alkaline earth ion, as is also observed in phosphate glasses. Increasing the AlF_3 content increases the linewidth.

The observed ranges of Nd spectroscopic properties for the fluoroberyllate glasses studied are included in Table 2-49. Further compositional investigations, for example, additions of CdF_2 and ZrF_4 , simple $\text{BeF}_2 - \text{AlF}_3$ glasses, and the like, are in progress.

Data on concentration quenching of the Nd^{3+} fluorescence and nonradiative decay by multiphonon processes in fluoroberyllate glasses are presented in the articles describing fluorescence quenching and multiphonon relaxation in beryllium fluoride glasses.

Melting Studies on Fluoroberyllates. The melting procedure for fluoroberyllate glasses at LLL has centered on $(\text{NH}_4)_2\text{BeF}_4$ as the source of BeF_2 . The choice of $(\text{NH}_4)_2\text{BeF}_4$ is mainly for two reasons:

- The material is available in a relatively pure form, which is not true for the vitreous BeF_2 .
- $(\text{NH}_4)_2\text{BeF}_4$ is an anhydrous salt and, as such, can be blended with other fluorides before decomposition and melting.

The main disadvantages of the $(\text{NH}_4)_2\text{BeF}_4$ are the decomposition reaction, which yields two moles of NH_3 per mole of BeF_2 ; the need for a dry box for its attendant removal; and the need for a distinct atmosphere control during melting. Atmosphere control and crucible corrosion problems are major concerns. One advantage of NH_4F vaporization is that the consequent stirring action promotes effective mixing. Figure 2-210 illustrates the enclosure and apparatus for induction-melting and casting of beryllium fluoride-based glasses.

Atmosphere control over the melt, and possibly crucible corrosion problems, are areas of immediate interest. The use of an inert atmosphere in melting of $(\text{NH}_4)_2\text{BeF}_4$ has been discontinued because of darkening of glass melts and the resulting corrosion of platinum crucibles and stirring rotors. Currently, all melting is carried out in a dry air atmosphere. The use of air has eliminated the darkening of the glass due to NH_3 reduction or entrainment and has prolonged the life of our platinum crucibles. Efforts to circumvent the crucible attack, which resulted in platinum crucible failure, led us to use graphite and glassy carbon crucibles. The graphite and glassy carbon apparently perform in a satisfactory manner even when inductively heated in air. Studies are

Fig. 2-210. Enclosed facilities for induction-melting and casting beryllium fluoride glasses.

planned using a CO_2 atmosphere over the melt to prevent external corrosion of the carbon base crucibles.

Polishing of Fluoroberyllates. The program for developing new optical glasses with BeF_2 base materials has been aided by the polishing facility shown in Fig. 2-211. Current experiments indicate that fluoroberyllates can be satisfactorily polished. Planned improvements in the facility will eliminate temperature variations as well as allow extension of size capabilities from prisms and rods to "B" size laser disks.

Hardness of Fluoroberyllates. Microhardness studies of BeF_2 and fluoroberyllate glasses have been completed using a Leitz Duriment Hardness Tester. The indentations were made using a Knoop indenter and a 100-gram load. Table 2-52 compares the BeF_2 base glasses with other laser glasses under investigation. The hardness data indicate that the fluoroberyllate glasses are comparable to the phosphate and fluorophosphate glasses, and appear promising from a polishing and strength standpoint.

Figure 2-212 shows the effect of substituting other alkali fluorides for KF in a base glass that has a composition (mol%) of 47 BeF_2 , 27 KF, 14 CaF_2 , 10 AlF_3 , 2 NdF_3 . Hardness linearly decreases with increasing size of the alkali ion. A variation of the

Fig. 2-211. Facilities for cutting and optically finishing beryllium fluoride glasses.

AlF_3 content markedly affects the hardness as well as the dissolution behavior in distilled water, particularly when one changes the alkali content at the same time. This is shown in Fig. 2-212 where the

Table 2-52. Hardness of laser glasses

Source	Type (Designation or mol%)	HK_{100} (kg/mm^2)
Owens-Illinois	Li-Al Silicate (ED-2)	544
Hoya	Phosphate (LHG-7N)	367
Schott	Fluorophosphate (FK-51)	360
Schott	Phosphate (LG-710)	240
NBS	K-871A (39.6 AlF_3 , 9.9 MgF_2 , 29.7 CaF_2 , 9.9 SrF_2 , 4.9 BaF_2 , 4.9 $\text{Ba}(\text{PO}_3)_2$, 1 NdF_3 .)	395
LLL	B803 (pure BeF_2)	300
UCLA	B102 (47 BeF_2 , 27 KF, 14 CaF_2 , 10 AlF_3 , 2 NdF_3 .)	215
Corning	B403 (34 BeF_2 , 23.5 AlF_3 , 10 CaF_2 , 13.5 BaF_2 , 19 MgF_2 , NdF_3 .)	315
UCLA	B115 (49 BeF_2 , 30 KF, 14 CaF_2 , 5 AlF_3 , 2 NdF_3 .)	205
UCLA	B116 (49 BeF_2 , 15 KF, 14 CaF_2 , 20 AlF_3 , 2 NdF_3 .)	300

Fig. 2-212. Effect of composition on microhardness of BeF_2 -base glasses (mol% BeF_2 47, LiF 27, CaF_2 14, AlF_3 10, and NdF_3 2). The composition (mol%) of the alkali-free glass is BeF_2 33.5, AlF_3 23.5, MgF_2 19, CaF_2 10, BaF_2 13.5, and NdF_3 0.45.

AlF_3 and KF content are varied. Increasing the AlF_3 from 10 to 20 mol% results in a 50% increase in hardness and a substantial improvement in moisture resistance.

Moisture Resistance of Fluoroberyllate Glasses.

The lack of moisture stability of pure BeF_2 is well known. Determining compositional changes which will improve moisture stability is one of the major goals of the program. Table 2-53 shows preliminary results of dissolution studies in distilled water. The

Table 2-53. Chemical durability of BeF_2 base glass.

Glass	Sample wt, (g)	Time, (hr)	Be (mg/g/hr)	
			20°C	70°C
B103 (solid)	14.31005	16	0.18	
B103 (powder)	0.693	24	1.01	
B403	15.10250	26	0.06	
B403 (powder)	1.612	24	0.12	
B115 (chunks)	6.498	24	0.14	
B115 (chunks)	6.564	24		0.24
B116 (chunks)	6.336	24	0.05	
B116 (20 mol% AlF_3)	6.241	24		0.22
B801	7.824	24	0.24	
B801	5.774	24		0.36

^aDissolution in unstirred distilled H_2O .

^bSample B103 lost 182 mg sample wt and 42 mg Be.

Table 2-54. Compositions (mol%) of fluorozirconate glasses as shown in

Table 2-55

Compound	Fluorozirconate glass ^a		
	I	II	III
ZrF ₄	50.0	60.6	53.0
LiF			6.9
NaF	25.0		3.4
CaF ₂			0.4
BaF ₂	23.0	33.8	22.0
PbF ₂			1.8
AlF ₃			0.6
LaF ₃		3.9	
NdF ₃	2.0	1.7	4.2
ThF ₄			7.7

^aGlass I was prepared by NBS; The other two were furnished by Prof. J. Lucas of the University of Rennes.

Table 2-55. Variation of Nd³⁺ spectroscopic properties with composition of fluorozirconate glasses. Glass compositions are given in Table 2-54

Property	Fluorozirconate glass		
	I	II	III
Density, g/cm ³	~4.5	4.64	4.83
Refractive index (n _D)	~1.56	1.524	1.531
Nd ³⁺ intensity parameters:			
Ω ₂ , 10 ⁻²⁰ cm ²	1.96	1.76	1.71
Ω ₄ , 10 ⁻²⁰ cm ²	3.64	4.00	3.25
Ω ₆ , 10 ⁻²⁰ cm ²	4.17	4.30	3.91
⁴ F _{3/2} → ⁴ I _{11/2} fluorescence properties:			
λ _p , nm	1049	1049	1049
Δλ _{FWHM} , nm	23.0	22.2	21.6
Δλ _{eff} , nm	27.1	26.4	25.8
Lifetime (τ _R)	434	437	497
Cross section (σ), 10 ⁻²⁰ cm ²	2.90	2.99	2.73

results are presented as loss of milligrams of Be per gram of sample per hour at 20°C. Some data at 70°C are shown to indicate the trend with temperature.

In future studies, we will attempt to monitor the weight continuously, and we will analyze solutions for both Be²⁺ and F content in an attempt to understand the mechanism of dissolution. We also plan to use pure BeF₂ and other standard glasses to obtain control data.

Fluorozirconates

Fluoride glasses can also be made with ZrF₄ as the network former. Three fluoro-zirconate glasses were studied: an alkali-alkaline earth fluoro-zirconate, a lanthanide-alkaline earth fluoro-zirconate, and a complex mixed fluoride. Their compositions are given in Table 2-54.

The spectroscopic properties of the glasses are given in Table 2-55. Because of the presence of larger, more polarizable cations, the refractive indices for these glasses are significantly higher than those for fluoroberyllates or for many of the fluorophosphates. Compositions with lower refractive indices are possible, but the indices probably would not be lower than the fluorophosphates explored thus far. The oscillator strengths of Nd³⁺ transitions in fluoro-zirconates are of the order of or slightly less than for fluorophosphates. Since small melts of good optical-quality fluoro-zirconate glasses have been produced, these glasses should also be considered candidates for laser materials. Further work is needed, however, to determine the characteristics of large melts and to explore more extensively the compositional space and its effect on the nonlinear optical and spectroscopic properties.

References

91. C. Baldwin made these glasses. Some of this work is described in an interim progress report (UCLA-Eng-76103, October 1976) available from the University of California at Los Angeles.
92. Chloride glasses can be made using ZnCl₂ as the network former.

2-4.3 Gain Coefficients of Neodymium-Doped Laser Glasses

To determine the relative merits of Nd-doped laser glasses for laser fusion applications, we have developed (1) a special liquid-edge-clad disk amplifier to measure the gain coefficients of new laser glasses in the absence of parasitics and (2) computer programs using spectroscopic, electronic, optical, and geometrical data to model the optical gain characteristics of new laser glasses. We have also performed measurements and theoretical calculations for Nd-doped silicate, phosphate, and fluorophosphate laser glasses. The results of these measurements and computer calculations are a self-consistent set of gain coefficients for laser glasses measured under identical experimental conditions and the potential capability of both predicting and optimizing the laser performance of new glasses based upon the spectroscopic data obtained for small (about 1 cm³) glass samples.

Experimental Measurements

We made small-signal gain measurements with elliptical 8.4 × 4.8 cm laser glass disks mounted in liquid-edge-clad holders designed to eliminate parasitic losses within the volume of the laser disks, thereby avoiding uncertainties arising from the variable properties of solid edge coatings. The inorganic immersion fluids used for each glass were selected to match the refractive indices of the individual laser glasses while possessing sufficient intrinsic absorption to suppress parasitic modes arising from disk-holder reflections. The test disks were mounted at Brewster's angle in the center of a uniformly pumped B-75 disk-amplifier pumping cavity, as shown in Fig. 2-213. The 16 flashlamps were filled with 300 Torr of xenon and had cerium-doped fused-silica envelopes. Optical pumping pulse durations of 200 and 600 μs (FWHM) (corresponding to flashlamp current densities of up to 4000 A/cm²) were used in these gain measurement experiments. A cylindrical Pyrex shield glass excluded residual uv light from the pumping cavity. The spectral absorption effects of this shield glass and of the cerium in the flashlamps were determined by removal of the

Authors
M. J. Weber
C. F. Cline

Major Contributor
R. A. Saroyan

Pyrex shield glass and replacement of the cerium-doped lamps with lamps having clear fused silica envelopes for several control experiments.

The axial small-signal gross gain at $1.064\text{ }\mu\text{m}$ was measured using a beam from a cw Nd:YAG laser oscillator aligned so that it passed through the center of each test laser disk twice (as shown in Fig. 2-214). Since the peak wavelength of the ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{11/2}$ transition varies with the glass host, the peak gain was determined by extrapolation from $1.0642\text{ }\mu\text{m}$ to the peak wavelength by using data derived from the fluorescence spectra. The validity of this approach was confirmed by specific gain measure-

ments of one of the phosphate laser glasses at the 1.052- , 1.061- , and $1.064\text{-}\mu\text{m}$ lines of a pulsed Nd:YAG oscillator. Figure 2-215 shows the results.

Small-signal gain coefficients vs input energy were measured for glasses having stimulated emission cross sections differing by a factor greater than four (from $1 \times 10^{-20}\text{ cm}^2$ to $4.7 \times 10^{-20}\text{ cm}^2$). These cross sections are derived from the spectroscopic determination of three Judd-Ofelt intensity parameters and measured fluorescence linewidths. The absorption efficiencies of the laser glasses are calculated from reductions of absorption spectra by the computer program VODAC (see § 2-4.4),

(a) Isometric view of B-75 with liquid-clad disk holders installed

(b) Side view of liquid-clad disk holders installed in amplifier

(c) Disassembled liquid-clad disk holder

(d) Twin disk holders assembled on rail

Fig. 2-213. Liquid-clad "A"-disk experimental apparatus.

Fig. 2-214. Liquid-"A" disk gain measurement apparatus.

Fig. 2-215. Comparison of measured (+) gain coefficients normalized to line center and fluorescence curve for 3.6% Nd-doped LHG-6 laser glass. Gain measurements were made at 1.052, 1.061, and 1.064 μ m using six "B" disks installed in a "B-75" disk amplifier. The amplifier was operated using 16 xenon flashlamps of 1.5-cm bore and an input energy of 140 kJ delivered in a 600- μ s pulse length.

chemical analyses of the actual concentration of Nd^{3+} ions in the glass, and the thicknesses of the glass disks. The fluorescent decay, which is nonexponential, was modeled by a triple exponential fit to the time-varying fluorescence output using the computer program DECAY. Models of the functional dependencies of flashlamp opacity and spectral output on current density are convolved with the computed data from CREEPER and VODAC, geometrical factors (such as pumping cavity efficiency, volume of laser glass), capacitor bank parameters, and the branching ratio to fluorescence. These models provide the computer program GAINPK with sufficient data for theoretical predic-

tions of the gain coefficient vs input energy curve for each laser disk.

Comparison between Theory and Experiment

A comparison between the experimentally measured data and the theoretical predictions can be seen in Fig. 2-216 for the LG-802 fluorophosphate, the LG-650 silicate, and the EV-2 phosphate laser glasses. These glasses represent, respectively, a low n_2 , moderate gain glass (LG-802), a low-gain, high saturation flux glass (LG-650), and a high-gain, moderate n_2 laser glass.

Fig. 2-216. Comparison between predicted and experimental gain coefficients vs input energy for new laser glasses; 600- μs pumping pulse duration, 1.5-cm bore lamps, Pyrex shield glass, and index-matched liquid cladding.

Table 2-56. Measured and calculated gain coefficients, spectroscopic and geometrical properties of new Nd-doped laser glasses

Glass designation	Laser glass type	Peak wavelength (μm)	Stimulated emission cross section ($\times 10^{-20} \text{ cm}^2$)	Zero-quenching decay time (μs)	Absorption efficiency ^a	Doping (Nd wt%)	Thickness (cm)	Predicted small signal gain coefficient ^b (m^{-1})	Measured small signal gain coefficient ^b (m^{-1})
ED-2	silicate	1.061	2.7	390	1.00	3.5	1.443	11.6	11.5
LG-650	silicate	1.057	1.0	800	0.78	5.0	1.502	6.8	7.9
EV-2	phosphate	1.053	4.7	370	0.99	2.5	1.501	19.0	18.3
LHG-5	phosphate	1.054	4.4	350	1.02	3.3	1.519	19.5	16.8
LHG-7	phosphate	1.053	3.7	370	0.98	3.4	1.518	19.8	14.0
Q-88	phosphate	1.054	4.2	360	0.99	3.0	1.490	19.3	19.3
LG-718	phosphate	1.054	4.5	—	1.00	8.0	1.485	16.3	15.4
FK-50	fluorophosphate	1.054	2.7	444	0.94	3.0	1.148	14.4	14.5
LG-802	fluorophosphate	1.052	2.6	460	0.93	1.9	1.621	10.7	11.0
LG-802	fluorophosphate	1.052	2.6	460	0.93	1.9	2.518	8.2	8.4

^aNormalized to ED-2.

^bFlashlamp pumping - pulse duration of 800 μs (FWHM) and 140 kJ input energy.

Table 2-56 links the measured and predicted small signal gain coefficients for nine different laser glasses and includes:

- Peak-of-fluorescence wavelength.
- Peak-stimulated-emission cross section, σ .
- Mean fluorescence lifetime in the zero-quenching limit, τ .
- Absorption efficiency per ion (normalized to ED-2) calculated from a VODAC convolution of the Nd³⁺ absorption spectrum in the 0.4- to 0.95- μm spectral region and from the xenon flashlamp spectrum (taken at a current density of 1000 A/cm²) assuming a Nd³⁺ optical depth of $5 \times 10^{20} \text{ cm}^2$.^{*} The ED-2 silicate laser glass was used to normalize the B-75 pumping cavity efficiency for all the other laser glasses; hence, the simulations of the other laser glasses depended entirely on their respective spectroscopic data with no adjustable parameters. Additional refinements to our computer models are currently being made.

The new glass data listed in Table 2-56 are not sufficient by themselves to select the optimum laser amplifier glass for a specific application since they represent only a single Nd³⁺ doping, disk size, and

thickness. The computer simulations have the capacity to extrapolate the experimental results sufficiently to permit the specification, for a given glass type and pumping cavity, the disk thickness, Nd doping, bank parameters, and anticipated gain coefficients. In turn, the results of these extrapolations can be used to optimize laser amplifier optical gain, efficiency, and lamp life for a specific application. When these optimization analyses are applied to a specific laser glass type to be used in an amplifier chain, it is then possible to obtain optimizations of the most cost-effective staging for that laser amplifier chain. These analyses and optimizations can, therefore, be conducted using only relatively small (about 1 cm³) spectroscopic samples. This permits a wide range of potential laser glass candidates to be considered.

Compensation for Flashlamp and Fluorescent Decay

Two different pumping pulse durations (200 and 600 μs) were used in these gain-measurement experiments to deconvolve the influences of flashlamp opacity and fluorescent decay processes from the attainment of high optical gain in these laser glasses. Thus, for example, in the case of LG-718 [a Schott phosphate heavily doped (8%) with Nd], the fluorescent quenching between adjacent Nd³⁺ sites within

^{*}See § 2-4.4. For several glasses, pumping also occurs by means of additional Nd bands at wavelengths less than 400 nm. When appropriate, these bands were included to the predicted pumping efficiency.

Table 2-57. Dependence of measured and calculated gain coefficients of New Laser Glasses on Pumping — pulse duration (input energy = 140 kJ)

Glass designation	Laser glass type	Pumping-pulse duration (FWHM) (μ s)	Thickness (cm)	Predicted small signal gain coefficient (m^{-1})	Measured small signal gain coefficient (m^{-1})	Zero-quenching decay time (μ s)
ED-2	silicate	200	1.443	10.4	10.1	390
		600	1.486	11.7	11.5	
LG-650	silicate	200	1.502	5.0	7.8	800
		600		6.8	8.0	
EV-2	phosphate	200	1.501	16.3	17.1	370
		600		19.0	18.3	
LHG-5	phosphate	200	1.519	16.8	16.1	350
		600		19.4	16.8	
LHG-7	phosphate	200	1.518	17.0	13.1	370
		600		19.7	14.0	
Q-88	phosphate	200	1.490	16.7	16.2	360
		600		19.3	19.3	
LG-718	phosphate	200	1.486	15.9	19.0	
		600		16.3	15.4	
FK-50	fluorophosphate	200	1.148	12.3	13.0	444
		600		14.3	14.5	
LG-802	fluorophosphate	200	1.621	8.8	10.3	460
		600		10.7	11.0	
LG-802	fluorophosphate	200	2.518	6.8	7.3	460
		600		8.2	8.4	

the glass reduced the gain coefficient attained for 600- μ s pump pulses relative to the 200- μ s data. For EV-2, on the other hand, the effects of inter-ion quenching are substantially reduced, and the greater opacity of the flashlamps (due to the higher current densities) during the 200- μ s pumping pulse makes the shorter pulse less effective than the 600- μ s pumping pulses. The measured and calculated gain coefficients for all nine glasses are listed in Table 2-57 for both 200- and 600- μ s pumping pulses. It is evident from the data in this table that the majority of

the laser glasses investigated perform better using the longer, 600- μ s pumping pulse than was observed for the 200- μ s pulse duration, providing that the doping of the laser glass is less than 5% Nd.

Author
G. J. Linford

Major Contributors
S. M. Yarema
R. A. Saroyan
M. J. Weber

2-4.4 Neodymium Laser Glass Data

Optical materials impose severe constraints on the performance of short-pulse, high-power neodymium glass lasers. Considerable research is under way on improved glass compositions: silicate, phosphate, fluorophosphate, fluoroberyllate, and fluorozirconate neodymium formulations. From that research we expect improved gain-coefficient and nonlinear optical properties.

Gain coefficients and performance characteristics of new materials can be predicted from spectroscopic data obtained from small samples. This simplifies the comparison and selection of new materials. Spectroscopic data of interest for laser design calculations include absorption and fluorescence spectra and associated cross sections, and fluorescence decay rate as a function of time and neodymium concentration. The absorption spectrum is integrated to get the Judd-Ofelt radiative intensity parameters. These are then used to calculate the radiative decay probabilities. The fluorescence branching ratios and intensities are also calculated, the latter for quantifying the fluorescence intensity and thereby the peak cross sections.

This evaluation can be extended to variations in spectroscopic parameters by glass composition. Based on these findings, the composition can be tailored to yield the most favorable spectroscopic properties for a given laser application. The potential compositional space to be explored is huge, with almost endless variations in the glass network former (silicate, phosphate, etc.) and the network modifier ions (alkali, alkaline, etc.). If conventional data collection and processing methods were used, only a small portion of the possible compositional space could be searched in a given amount of time.

For this reason, we have interfaced our spectroscopic equipment directly with a minicomputer in a data-acquisition and processing system described in Ref. 93 and last year's Annual Report. Using this system, we have produced a standard data package for glass samples that permits direct comparison of silicate, phosphate, fluorophosphate, fluoroberyllate, and fluorozirconate neodymium laser glasses. The package includes glass composition (when known), Judd-Ofelt analysis, measured absorption spectrum, measured fluorescence spec-

trum, measured fluorescence decay, and calculated flashlamp absorption efficiency. In addition, the system generates a single page containing abbreviated versions of all but the composition and absorption efficiency (see Fig. 2-217). The entire data package is computer-generated.

The availability of this information in a standard format has permitted the generation of a set of data sheets for neodymium laser glass. Three volumes of data sheets — (I) Commercial Laser Glass, (II) Fluorophosphate Glasses, and (III) Fluoroberyllate and Fluorozirconate Glasses — have been prepared and distributed to glass manufacturers participating in the glass development program, to help them in their compositional studies. Additions to these volumes, and new compilations on phosphate, silicate, and other glasses, are now being prepared.

Computerized Spectroscopy Facility

To produce the standard data packages and accelerate our analyses of new samples, we have made several important changes to the computer software:

- Created programs for correcting labeling errors, storing glass-composition information, tabulating data for a subset of samples, summarizing spectroscopic measurements for one sample, fitting decay data to functional forms, transferring data to other computers, converting decay data for analysis, and integrating absorption bands.
- Improved Judd-Ofelt output, fluorescence spectrum measurement and analysis, BASIC interpreters, and data-plotting capabilities.
- Made the programs smarter, thus reducing operator interaction.
- Combined several glass-properties programs into one.

In addition, we have improved our data acquisition procedures and demonstrated the system's flexibility in data collection and reduction.

Absorption Efficiency Calculations

We have extensively modified our Variable Optical Depth and Current (VODAC) program,⁹⁴ which simulates the absorption of flashlamp light by a neodymium glass, to accept direct input of absorption spectrum data from the computerized

spectroscopy facility. This replaces our former process of digitizing the absorption spectrum from a chart recorder and creating a few data points for VODAC.

We have changed the format of VODAC calculational results to produce graphs of the lamp-emission and glass-absorption spectra plus several efficiency curves. Formerly we got a single table of efficiency vs optical depth in cm % (product of glass thickness and neodymium wt% in the glass). Efficiency is now given in absolute efficiency (power into laser transition divided by power into lamp) and efficiency relative to the perfect absorber (uniform and infinite absorption). Optical depth is given in terms of cm % and also of ions/cm² (product of glass thickness and neodymium concentration). The cm % measure is used in design calculations whereas the ions/cm² measure is used

for glass-to-glass comparison of VODAC results. Figure 2-218 is a typical VODAC output.

A program has been written to aid in the running of VODAC. This interactive program gets absorption data from tape; sets VODAC parameters such as lamp current density, optical depth range, and absorption spectrum limits; runs VODAC; and supplies output (cathode-ray tube, 35-mm film, high-speed printer). This makes rapid production of VODAC analyses.

The thrust in all these improvements is easy and rapid updating of our laser glass data. This is important because our goal is to maintain viable data on various glasses upon which researchers can rely to be current, accurate, and complete. Ultimately, the availability of such data should obviate the need for duplicate experiments and stimulate efficient use of laser fusion resources nationwide.

Fig. 2-217. Computer-generated data summary of fluorescence, absorption, and fluorescence decay measurements and Judd-Ofelt analysis for a neodymium glass sample.

Fig. 2-218. (a) Graph of neodymium glass absorption spectrum and the xenon flashlamp emission model used in VODAC absorption efficiency calculations. (b) Plot of the absorption efficiency of a neodymium glass sample as a function of optical depth (ions/cm²) for a 15-mm-diam 1000-A/cm² xenon flashlamp. For reference, the efficiency curve of Owens-Illinois ED-2 is also shown (dotted line). The solid curve is a fit to the calculated efficiency data (O's) to the double exponential equation shown at the bottom of the graph.

References

93. R. A. Saroyan and M. J. Weber, "A Minicomputer and the Spectroscopist: Optical Spectroscopy of New Laser Glasses," in *Proceedings of the Society of Photo-Optical Instrumentation Engineers, San Diego, California, August 24-25, 1976; Vol. 82, Unconventional Spectroscopy*, SPIE, Palos Verdes Estates, California (1976).
94. VODAC is described in *Laser Fusion Annual Report-1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975).

Author

R. A. Saroyan

2-4.5 Glass Development Program

To achieve scientific breakeven in laser fusion requires a 100- to 300-TW fusion laser system, about 10 times the focusable power of Shiva. This increase in power can be attained (1) by increasing the number of amplifier chains, (2) by adding more amplifiers per chain, and (3) by increasing the focusable power per chain through the use of improved optical glass materials.

The present Shiva system uses commercial silicate-based laser glasses. These glasses were not developed for use in today's power-limited laser systems nor are they expected to be satisfactory for

use in the projected Shiva Nova system. Recent work at LLL^{93,96} has shown that improved glass compositions are possible that will provide significant performance advantages over present laser glasses, especially in power-limited laser systems. In this and prior annual reports,^{97,98} several possible options for improved materials are discussed, including commercial phosphate and fluorophosphate glasses as well as the less-common fluoroberyllate glasses.

LLL, in cooperation with other development groups (listed in Table 2-58), is conducting a program under ERDA and industry support to develop glasses that would provide viable alternatives to the present Shiva materials for use in the Nova laser system. The program's goal is to develop a low nonlinear index (n_2) glass that can be produced at minimum cost in the quantity and quality required for the Shiva Nova system. In addition, for laser glass an emission cross section, σ , is desired that falls between 1 and $4 \times 10^{-20} \text{ cm}^2$. The final cross section σ will be chosen to optimize the system's performance.

Table 2-58 lists the present participants and their areas of investigation in the glass development program. As it can be seen, a significant number of public and industrial institutions share the effort.

Figure 2-219 outlines the new laser glass development program. To make an informed decision on the best glass type to use in the Nova system, the glass properties listed in Table 2-59 must be known because they affect the laser design and impact the

Table 2-58. Participants in the Laser glass program

Program	Participants	Goal
Fluorophosphates	Hoya, Kigre, NBS, Owens-Illinois, Schott	Obtain lowest N_2 , high energy storage $1 \times 10^{-20} \text{ cm}^2 < \sigma < 3 \times 10^{-20} \text{ cm}^2$
Phosphates	Hoya, Kigre, Owens-Illinois, Schott	High σ glasses for rod amplifiers; low σ glasses for disk amplifiers.
Fluoroberyllates	Corning, LLL, UCLA	Develop durable large-sized glass components

Purpose	Phase	Development activities	Product
Low n_2 $\sigma \sim 2-3 \times 10^{-20} \text{ cm}^2$ Good pumping	Research	Many compositions Small melts (~100 g)	2-cm ³ samples
Initial disk melts Laser gain measurements	Development	Few compositions Medium melts (~5 kg) Edge cladding	4 × 8-cm bare-edge disks Edge-clad samples
Edge-clad High optical quality Large size	Prototype	Specific compositions Large melts (~50 kg) Edge clad Finished disks	10 × 20-cm disk 20 × 40-cm disk 30 × 60-cm disk Edge-clad and finished

Fig. 2-219. Steps through which a new laser glass must pass to end up in the Nova system. Before production of new glass components is initiated, prototypes must be fabricated and tested. The work in the preproduction stage will help in determining the cost of the new glass. The decision on the glass to be employed in Nova depends on how many kilojoules per dollar or terawatts per dollar the glass can produce.

Table 2-59. Data necessary on important glass compositions

Optical properties

Index of refraction, n_d
Index dispersion (Abbé number, ν)
 dn/dT
Stress-optic coefficient
Homogeneity
Nonlinear index, n_2

Spectroscopic properties of Nd-doped materials

Emission cross section, σ
Emission lifetime, τ
Absorption efficiency
Peak emission wavelength, λ_p
Emission linewidth, $\Delta\lambda$

Chemical properties

Analysis of composition
Chemical stability

Physical properties

Liquidus temperature
Annealing temperature
Density
Viscosity vs temperature
Thermal expansion
Thermal conductivity
Heat capacity
Hardness

Fig. 2-220. Example of a large (40-cm-diam) piece of fluorophosphate (FK-51) glass produced by Schott Glass. The high quality optics is indicated by the uniform interference fringe pattern (right).

Fig. 2-221. Gamma disk being poured from 10-litre melter at Owens Illinois, Toledo, Ohio. Melter contains about 80 kg of platinum.

Fig. 2-222. 2.4-m continuous polisher developed by Zygo and L.L.L., shown in operation at Zygo plant, Middlefield, Connecticut. Highly efficient state-of-the art techniques are used for precision surfacing of laser disks and other flat optical components.

cost of the glass. During FY 1977, compositional studies will be done to determine how the important optical and physical parameters are affected by compositional changes. The data base generated during these studies is available to the glass program participants in the form of data sheets. By the middle of FY 1977, we shall emphasize the larger melts of the more promising glasses that are identified by the compositional studies. From these melts, A-sized disks or rods will be fabricated for laser gain measurements.

Because high-precision finishing of glass components is a key process in the glass component production, work on developing finishing techniques will be initiated in FY 1977. The early phase of this work is to identify the nature and magnitude of any problems associated with the finishing of the different glass types. Although the problems associated with the production and finishing of the new fluoride glasses are large, they can be overcome with a concerted effort. Figure 2-220 shows this success by the picture of a fluorophosphate glass (FK-51) blank, which is of the size and quality desired for the Nova system.

The glass type or types chosen for system implementation will then enter preproduction experiments, which are to solve any problems that may be associated with the melting of large components. Some compositional change (less than 5%) will be allowed in order to improve melting characteristics. At this time, work on finishing techniques for laser disk edge-cladding and on thin-film coatings for the new glasses will be emphasized. Before final glass production, prototype edge-clad laser disks (about 30 by 60 cm) will be obtained for testing.

Procurement

Just as the optics procurement for Shiva rests largely on the work done for Cyclops and Argus, so will the Shiva Nova program rest on the work done for Shiva. Even though the logistical problem is greater and there may be new, more difficult glasses involved, it has been possible, based on this prior experience, to do a rather detailed preliminary analysis of the optical component manufacturing problem. This study, which will be extended in the coming year, indicates the feasibility of Shiva Nova in the proposed time frame and the key areas requiring special attention.

Equipment

Many technologies are involved in the manufacturing and test equipment for the laser components. These equipment tend to be capital-intensive. Some of these are as follows:

- Figure 2-221 shows a 10-litre melter at Owens-Illinois, containing about 80 kg of platinum.

- Figure 2-222 shows a 2.4-m continuous polisher for laser disk finishing and other flatwork developed jointly by Zygo and LLL. This machine is capable of finishing about twenty 20- by 40-cm laser disks per month on a single-shift operation.

Figure 2-223 shows a large coating tank at Optical Coating Laboratory devoted to high-technology coatings. The 20- by 40-cm polarizers are coated here. To ensure uniform deposition, the polarizers are held in rapidly rotating stainless-steel planetary tooling.

Figure 2-224 shows a dual-mode 30-cm-aperture interferometer for testing mounted components in the LLL assembly area, along with an interferogram of the "empty" cavity.

Quality

We are achieving laser chains that are not far from "diffraction limited." This has been demonstrated in Cyclops and Argus, as evidenced by Fig. 2-225.

Table 2-60 shows a typical tolerance budget for certain flat components. Manufacturers are routinely achieving and surpassing these values, demonstrating the high state of laser glass making and finishing technology. Figure 2-226 shows the results for a 10-cm laser head assembly.

Some of the surfaces planned for Shiva Nova are aspheric. The asphericity is for the correction of spherical aberration (primarily a function of the cube of the focal ratio) where it is desired to minimize the number of optical elements; these fall roughly into two categories: "steep" aspherics and "mild" aspherics. Spatial filter lenses fall into the latter category, being generally $f/10$ or slower, whereas focusing lenses might be quite fast. Figure 2-227 shows the state of correction of a typical spatial filter lens, being produced by the hundreds for Shiva, and Fig. 2-228 shows the wavefront from a very fast, large-aperture aspheric used for Argus.

Table 2-61 gives a metric comparison between Shiva and a baseline Nova preliminary design.

Fig. 2-223. 2.5-m box coater at Optical Coating Laboratory, Inc., Santa Rosa, California. Highly trained technicians coat Shiva optics in a clean-room environment. Handling and loading procedures are carefully controlled, and holding fixtures have been especially designed to minimize substrate damage during the coating operation.

30.5-cm clear aperture

Fig. 2-224. (a) Dual mode, 30-cm-aperture interferometer manufactured by Zygo Corp., Middlefield, Connecticut; (b) interferogram of the "empty" cavity.

Fig. 2-225. Interferogram of 160-surface, 20-cm-diam Cyclops chain shows achievement of very high wavefront quality through long optical trains (single pass at $1.064 \mu\text{m}$).

There are obviously some difficult problems posed here in preparing the high-technology optical industry for meeting the challenge. The basic elements are:

- High-grade chemical materials.
- Plant and facilities.
- Personnel.
- Lead time.
- Capital money.

The responses thus far to preliminary planning and interaction sessions with industry are positive,

and we expect a very high level of industrial cooperation. Because of the ERDA-funded glass program already well under way and the commitments in other areas by industrial planners, we feel that the building of optics for Shiva Nova can be done on time.

Table 2-80. Wavefront transmission tolerances for a single-pass transmission at $0.6328 \mu\text{m}$

	Peak to valley (λ)	Gradient
β disk	1/12	1/30 2/09
γ disk	1/10	1/30
δ disk	1/8	1/40
β rotators	1/10	1/25
δ rotators	1/8	1/40

Fig. 2-226. 10-cm laser amplifier assembly containing six beta disks shown in double-pass interferogram at $0.633 \mu\text{m}$.

Fig. 2-227. Aspheric spatial filter lens interferogram (double pass at $0.633\ \mu\text{m}$). Down edge outside of 8.5-cm-diam aperture gives rough indication of asphericity. Component manufactured by Tinsley Laboratories, Berkeley, California.

Fig. 2-228. 20-cm, $f/1$ single-element aspheric shown in double-pass interferograms at $1.06\ \mu\text{m}$. The departure from best-fit sphere is about 1.8 mm. Lens manufactured by Opti-Systems, Irvine, California.

Table 2-61. Comparison of Shiva and Nova total glass volume area

	Shiva	Nova I	Nova II	Total Nova
Glass volume (litres)	790	4800 (6X) ^a	7200 (9X)	12,000 (15X)
Finishing area (m ²)	63	190 (3X)	290 (4.5X)	480 (7.5X)
Coating area (m ²)	23	76 (3.3X)	114 (5X)	190 (8.3X)

^a Factor in parenthesis is the Nova number divided by the related Shiva number.

References

95. M. J. Weber, "Optical Materials for Neodymium Fusion Lasers," *Critical Materials Problems in Energy Production*, C. Stein, Ed. (Academic Press, New York, 1976), pp. 261-279.
96. M. J. Weber, C. B. Layne, R. A. Saroyan, and D. Milam, *Opt. Commun.* 18, 171 (1976).
97. *Laser Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-77 (1976).
98. *Laser Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975).

Authors

S. E. Stokowski
E. P. Wallerstein

2-4.6 Other Studies of Laser Glasses

Fluorescence Sensitization

In efforts to improve the pumping efficiency of Nd:glass, we have previously investigated Ce³⁺-to-Nd³⁺ energy transfer.⁹⁹ We found that the improved Nd pumping due to energy transfer from Ce was very small.¹⁰⁰ Subsequently, the Cr³⁺ ion was considered as a possible sensitizer. Initial calculations indicated that a high transfer efficiency (>50%) from chromium to neodymium would be necessary for a net improvement in Nd pumping.¹⁰¹

The same general approach was used to evaluate the Cr—Nd transfer: (1) transfer efficiency was deduced from sensitizer fluorescence-lifetime data, and (2) a computer program calculated absorption of a typical flashlamp spectrum by a glass with vary-

ing amounts of Nd and sensitizer ions. Two complications are present in the chromium-neodymium system that do not apply for cerium-neodymium. First, the Cr fluorescence lifetime is highly nonexponential at all Cr and Nd concentrations (see Fig. 2-229), making the determination of a transfer rate very difficult. Second, the absorption bands of Cr and Nd overlap, so there is competitive absorption.

The nonexponential Cr decay results from the sensitivity of the 3d electrons of Cr³⁺ to the exact locations of the surrounding glass ions combined with the site-to-site variations in local environment in a glass. The transfer efficiency was determined

Fig. 2-229. Decay of Cr³⁺ excitation in the presence of varying amounts of Nd in phosphate laser glass. The upper curves are linear plots of the decays showing the increased chromium decay rate due to energy transfer to neodymium. The lower curves are logarithmic plots of the same data showing the highly nonexponential nature of the decays.

from the decay functions of Cr in the presence of varying amounts of Nd (from 0 to 3 wt%). An increase in the decay rate of Cr with increasing Nd concentrations (as in Fig. 2-229) indicates Cr-to-Nd energy transfer. The Cr was excited by 100-ns, 660-nm pulses from a cooled, frequency-doubled Nd:YAG laser. Illumination at 660 nm produced very little excited Nd. The Cr³⁺ fluorescence signal from a photomultiplier was processed by a Tektronix digital processing oscilloscope and PDP 11/40 computer system.

A computer program compared Cr decays with and without Nd, calculated the transfer rate as a function of time, and integrated the product of Cr population times transfer rate to give the total transfer efficiency. The transfer efficiencies for the Owen-Illinois EV-2 phosphate glasses were $\epsilon = 0.7$ for 1 wt% Nd₂O₃ and $\epsilon = 0.8$ for 3 wt% Nd₂O₃. A simple comparison of the areas under the normalized curves for 0 wt% and 1 wt% Nd₂O₃ gives a value of 0.53, which provides a lower limit to the transfer efficiency. Thus, the Cr-to-Nd transfer efficiency was found to be greater than 0.5, even at low Nd concentrations (1 wt%).

The second complication in the Cr—Nd system is the substantial overlap of the Cr and Nd absorption bands. The ABSGEN-VODAC programs¹⁰² calculate the efficiency with which a doped glass absorbs energy from xenon flashlamps. The programs were modified and converted to the XFER

program, which takes account of competitive absorption and includes a variable transfer efficiency. XFER computes the relative absorption efficiency E (proportional to gain):

$$E = \sum_{\lambda} P_{\lambda} S_{\lambda} \quad (70)$$

where P_{λ} is the power output of the flashlamp at wavelength λ , and S is computed at each wavelength from

$$S = \lambda \left(\frac{\alpha_{Nd} + \epsilon \alpha_{Cr}}{\alpha_{Nd} + \alpha_{Cr}} \right) \times \left(1 - \exp \left\{ - (\alpha_{Nd} + \alpha_{Cr}) l \right\} \right) \quad (71)$$

The Nd absorption in cm⁻¹ is $\alpha_{Nd} = N_{Nd} \sigma_{Nd}$, where N_{Nd} is the Nd concentration and σ_{Nd} is the absorption cross section, and similarly for Cr. The transfer efficiency from Cr to Nd is ϵ , and l is the sample thickness. Transfer efficiency ϵ varies from 0 (no transfer) to 1.0 (every excited Cr ion transfers its excitation to a Nd ion). For the examples shown here, ϵ is conservatively estimated to be 0.5, independent of Nd concentration.

Fig. 2-230. Gain profiles for a 3-cm-thick disk calculated by the XFER program. The increased uniformity predicted for Cr-sensitized disk is apparent from a comparison of the two lower curves, both of which have an average gain of 0.03 cm⁻¹. The Cr-sensitized 1% Nd—0.02% Cr example has a much lower ratio of face to bulk gain coefficient. Increasing the doping to 2% Nd—0.07% Cr gives an average gain of 0.04 cm⁻¹ with ratio of face to bulk gain equal to 2.

The XFER program was used to optimize the gain through a disk by adjusting the Cr and Nd concentrations, subject to the constraint that the ratio of gain coefficient at the disk face to average gain coefficient through the disk should be less than or equal to 2.0. This is because higher face-to-bulk gain coefficients contribute to parasitic oscillation modes in the disk.

Figure 2-230 shows the relative gain coefficient as a function of distance through a 3-cm-thick disk. The 3% Nd—0% Cr case has an average gain coefficient of 0.03 cm^{-1} (relative units), with high gain at

the disk faces and low gain in the center. A much more uniform gain profile is predicted for 1% Nd—0.02% Cr, with the same average gain coefficient of 0.03 cm^{-1} . Increasing both Nd and Cr concentrations to 2% Nd—0.07% Cr gives the optimum condition for a 3-cm disk: the average gain coefficient is 0.04 cm^{-1} and the face-to-bulk gain ratio is 2.0. Other disk thicknesses or different constraints on face-to-bulk gain ratio will result in different optimum values of Cr and Nd concentrations.

To test these predictions directly, a series of A-size laser disks was obtained from Kigre, Inc. for

Fig. 2-231. Results of gain measurements on Cr-sensitized Nd-glass disks. The gain coefficient (cm^{-1}) was measured for each Nd-Cr combination at several flashlamp bank energies.

gain measurements in a disk amplifier described in § 2-4.3. A phosphate glass of slightly different composition from the EV-2 glass used in the Cr decay measurements was doped with four combinations of Cr and Nd(wt%):

Nd_2O_3	Cr_2O_3	
3	0	control sample,
2	0.07	predicted optimum for 3-cm disk,
2	0.2	near optimum for 1.5-cm disk,
3	0.07	check on Nd concentration dependence.

Figure 2-231 shows the measured gains in these samples. A 1064-nm beam passed twice through two 1.5-cm-thick disks inside a disk amplifier. The gain coefficient as a function of flashlamp pump power is displayed in Fig. 2-231. In spite of predicted improvements due to Cr sensitization of greater than 50%, the Cr-doped disks all showed decreased gain compared to Nd only.

The explanation of this discrepancy between calculation and experiment is not yet known. A test for excited-state absorption of 1.06- μm light by Cr gave a negative result. No increase in 1.06- μm absorption was observed when samples of Cr-doped glass were pumped in the disk amplifier cavity. Some phosphate laser glasses have shown degraded performance due to the presence of water. This and other possible explanations of the poor performance of Cr-sensitized Nd laser glass are being investigated.

Author
C. B. Layne

Major Contributors
M. J. Weber
G. J. Linford
S. M. Yarema

Saturation Fluence

The saturation flux of Nd:glass determines the amplification properties of glass lasers under conditions where high energy densities are propagated. At pulse durations of 1 ns or longer, the energy per unit area in an amplifier may approach saturation before the power per unit area reaches the limits imposed by beam breakup.

Previous measurements of saturation flux have involved pulse durations much longer than the 1- to 10-ns region of interest for laser fusion.¹⁰³ The difficulty in measuring saturation flux for these short pulses is that high peak powers are involved, making it difficult to propagate a well-characterized beam through enough gain medium to measure gain and gain depletion accurately.

A new technique has been devised to observe fluorescence depletion rather than gain depletion, so that a long path length through the amplifying medium is unnecessary. Figure 2-232 shows the experimental setup with which we obtained the preliminary results. A thin (~1-mm) sample of Nd:glass is pumped by a short (~1-ns) pulse of frequency-doubled Nd:YAG light. After a delay of about 60 ns, the pumped volume of the sample is saturated by an intense 1.06- μm pulse from the same Nd:YAG-glass laser. A photomultiplier monitors the fluorescent intensity at 880 nm from the excited Nd ions.

Fig. 2-232. Experimental setup for saturation flux measurements. About 10% of the incident 1064-nm beam from the ILS laser is frequency-doubled in a KDP crystal and focused onto the glass sample. A polarizer (P) and filter (F) remove the remaining 1064-nm radiation from the pump beam. The 1064-nm beam is delayed 60 ns and illuminates an aperture (AP) which is imaged onto the sample.

Fig. 2-233. Preliminary data from saturation flux experiment in ED-2 laser glass. The vertical axis is the fraction of the initial ${}^4F_{3/2}$ population removed by a saturating pulse of intensity E (horizontal axis). The curve is a best fit of the data to Eq. (72) with $\sigma = 2.7 \times 10^{-26} \text{ cm}^2$ and $E_s = 3.8 \text{ J/cm}^2$.

As shown in Fig. 2-232, the 532-nm pump pulse is focused to excite a small volume in the sample. The saturating pulse is made to illuminate uniformly the pumped volume by an imaging technique. A hard aperture is almost uniformly illuminated by the incident 1.06- μm beam. A lens in the beam path then images this aperture, with a demagnification to increase intensity, onto the sample. The saturating pulse intensity on the sample is nearly uniform except for a bright outer ring caused by coherent-light imaging with a lens of a finite aperture.¹⁰⁴

After excitation at 532 nm, the Nd ions cascade down by nonradiative decay to the ${}^4F_{3/2}$ upper laser level. This decay has a lifetime of about 10 ns,¹⁰⁵ hence the 60-ns delay to allow all the excited ions to reach the ${}^4F_{3/2}$ level. The ${}^4F_{3/2}$ decay time is several hundred microseconds or effectively infinite for the time scales of interest here. Passage of the 1.06- μm saturating pulse stimulates a portion of the ions in the ${}^4F_{3/2}$ to emit at 1.06 μm and make the transition to the ${}^4I_{11/2}$ terminal laser level. The photomultiplier monitoring the 880-nm emission thus sees a drop in emission intensity proportional to the number of ions removed from the ${}^4F_{3/2}$ level.

At low saturating intensity, the drop in ${}^4F_{3/2}$

population is proportional to the saturating pulse intensity, I , times the cross section for stimulated emission, σ . As the saturating intensity increases, however, the fully-saturated region is reached where the number of induced transitions downward from ${}^4F_{3/2}$ to ${}^4I_{11/2}$ is just equal to the number of upward transitions. Further increases in saturating intensity will not lead to further decreases in ${}^4F_{3/2}$ population.

The fractional depletion ϵ of the ${}^4F_{3/2}$ population after passage of a saturating pulse is given by

$$\epsilon = 1 - \frac{N_3}{N} \quad (72)$$

where N^* is the initial and N , the final population of the ${}^4F_{3/2}$ level. The dependence of ϵ on saturating intensity $E(\text{J/cm}^2)$ and saturation flux E_s is described by

$$\epsilon = \frac{E_s \sigma}{\hbar \omega} (1 - e^{-E/E_s}) \quad (73)$$

where $h\omega$ is the 1.06- μm photon energy. This description assumes that the $^4\text{I}_{11/2}$ level does not decay during the saturating pulse and that the Stark levels of the $^4\text{F}_{3/2}$ and of the $^4\text{I}_{11/2}$ are thermalized on a picosecond-time scale.

For an amplifier, the saturation behavior of the gain coefficient α is described by

$$\alpha = \alpha_0 e^{-E/E_s}, \quad (74)$$

where α_0 is the small signal gain coefficient.

The preliminary data for ED-2 laser glass shown in Fig. 2-233 are best fit by

$$E_s = 3.8 \pm 1.0 \text{ J/cm}^2,$$

$$\alpha = 2.7 \pm 0.3 \times 10^{-20} \text{ cm}^2. \quad (75)$$

The large error in saturation flux results from the lack of data at energies greater than about $2 E_s$. Several refinements of the experimental technique have been devised for continued experiments. The thermal population of the $^4\text{I}_{11/2}$ is sufficient (10^{-5} of the total ion density) to allow measurement of the upward saturated behavior in the absence of pumping into the $^4\text{F}_{3/2}$. This greatly simplifies the experiment. The technique of observing fluorescence depletion (or increase in the thermally-pumped case) is applicable to small samples of many Nd-doped glasses and to Nd:YAG.

Author

C. B. Layne

Major Contributor

G. A. Hayward

Fluorescence Line Narrowing

Paramagnetic ions generally enter glasses as network-modifier ions. Because of differences in the bonding to nearest-neighbor ions and in the types and statistical distribution of more distant neighbor ions in multicomponent glass compositions, the local fields at individual sites vary. This results in site-to-site differences in the energy levels and radiative and nonradiative transition probabilities of paramagnetic ions in glass. Under broadband excitation, these features are evident from the large, inhomogeneous optical absorption and emission

linewidths and the multi-exponential fluorescence decays.

By employing tunable narrowband excitation, we can excite selected subsets of ions, namely, those resonant to within the homogeneous linewidth. This effectively reduces the inhomogeneous broadening, and a line-narrowed fluorescence spectrum is obtained. In the past several years, with the availability of tunable lasers, the fluorescence line narrowing (FLN) technique has proved to be a powerful method for investigating a wide range of phenomena in glassy media.¹⁰⁶ These include energy levels and coordination models, homogeneous line broadening, site-to-site variations in radiative and nonradiative transition probabilities, and energy transfer processes. The experimental techniques used in these studies have been reviewed elsewhere; the apparatus is shown schematically in Fig. 2-234.

Energy Levels. Brecher and Riseberg,¹⁰⁷ in work supported partially by ILL, have carefully measured the $^7\text{F}_1$ and $^7\text{F}_2$ energy levels in a Eu^{3+} silicate glass as a function of laser wavelength ($^7\text{F}_0 \rightarrow ^4\text{D}_0$ transition) and fitted the spectra to obtain a set of crystal-field parameters, assuming C_{2v} site symmetry. Large variations in crystal-field parameters were observed. These changes were then correlated with a geometric model for the structure at the ion site. Beginning with eight nearest-neighbor oxygens at the vertices of an elongated Archimedean antiprism, a ninth oxygen was introduced along the z-axis of the Eu^{3+} and its distance systematically decreased until an approximately equidistant nine-fold coordination was achieved. The ratio of crystal-field parameters calculated for this geometrical arrangement gave a consistent account of the observed changes and an encouraging demonstration that FLN measurements can provide information about the local structure in amorphous media.

The energy level behavior of Eu^{3+} in other glasses — silicates, phosphates, and fluoroberyllates — has been studied to determine the effects of glass network-former and modifier ions on the internal fields and degree of inhomogeneity. Preliminary results indicate different local fields and coordination are required for the fluoride glasses.

Linewidths. Homogeneous line broadening arising from one- and two-photon transitions between nearby Stark levels can be measured by using resonant FLN techniques. Studies of Yb^{3+} have shown

that the linewidths and their temperature dependencies vary with excitation wavelength.¹⁰⁸ This arises from a combination of changes in the energy-level spacings, thereby requiring that different phonons be active, and changes in the strength of the ion-

phonon coupling with site. Selzer et al.^{4,109,110} have demonstrated further that FLN can also reveal the presence of other line-broadening mechanisms in glass. In Fig. 2-235, the temperature-dependent linewidths of the $\text{Eu}^{3+} {}^5\text{D}_0 \rightarrow {}^7\text{F}_0$ transitions are

Fig. 2-234. Apparatus for time-resolved fluorescence line-narrowing spectroscopy.

Fig. 2-235. Comparison of the temperature dependences of the ${}^5\text{D}_0 \rightarrow {}^7\text{F}_0$ fluorescence linewidth of Eu^{3+} in oxide and fluoride crystals and in glasses.

Fig. 2-233. Preliminary data from saturation flux experiment in ED-2 laser glass. The vertical axis is the fraction of the initial ${}^4F_{3/2}$ population removed by a saturating pulse of intensity E (horizontal axis). The curve is a best fit of the data to Eq. (72) with $\sigma = 2.7 \times 10^{-28} \text{ cm}^2$ and $E_s = 3.8 \text{ J/cm}^2$.

As shown in Fig. 2-232, the 532-nm pump pulse is focused to excite a small volume in the sample. The saturating pulse is made to illuminate uniformly the pumped volume by an imaging technique. A hard aperture is almost uniformly illuminated by the incident 1.06- μm beam. A lens in the beam path then images this aperture, with a demagnification to increase intensity, onto the sample. The saturating pulse intensity on the sample is nearly uniform except for a bright outer ring caused by coherent-light imaging with a lens of a finite aperture.¹⁰⁴

After excitation at 532 nm, the Nd ions cascade down by nonradiative decay to the ${}^4F_{3/2}$ upper laser level. This decay has a lifetime of about 10 ns,¹⁰⁵ hence the 60-ns delay to allow all the excited ions to reach the ${}^4F_{3/2}$ level. The ${}^4F_{3/2}$ decay time is several hundred microseconds or effectively infinite for the time scales of interest here. Passage of the 1.06- μm saturating pulse stimulates a portion of the ions in the ${}^4F_{3/2}$ to emit at 1.06 μm and make the transition to the ${}^4I_{11/2}$ terminal laser level. The photomultiplier monitoring the 880-nm emission thus sees a drop in emission intensity proportional to the number of ions removed from the ${}^4F_{3/2}$ level.

At low saturating intensity, the drop in ${}^4F_{3/2}$

population is proportional to the saturating pulse intensity, I , times the cross section for stimulated emission, σ . As the saturating intensity increases, however, the fully-saturated region is reached where the number of induced transitions downward from ${}^4F_{3/2}$ to ${}^4I_{11/2}$ is just equal to the number of upward transitions. Further increases in saturating intensity will not lead to further decreases in ${}^4F_{3/2}$ population.

The fractional depletion ϵ of the ${}^4F_{3/2}$ population after passage of a saturating pulse is given by

$$\epsilon = 1 - \frac{N_3}{N} \quad (72)$$

where N^* is the initial and N_3 the final population of the ${}^4F_{3/2}$ level. The dependence of ϵ on saturating intensity $E(\text{J/cm}^2)$ and saturation flux E_s is described by

$$\epsilon = \frac{E_s \sigma}{\hbar \omega} (1 - e^{-E/E_s}) \quad (73)$$

that the linewidths and their temperature dependencies vary with excitation wavelength.¹⁰⁸ This arises from a combination of changes in the energy-level spacings, thereby requiring that different phonons be active, and changes in the strength of the ion-

phonon coupling with site. Selzer et al.^{4,109,110} have demonstrated further that FLN can also reveal the presence of other line-broadening mechanisms in glass. In Fig. 2-235, the temperature-dependent linewidths of the $\text{Eu}^{3+} {}^5\text{D}_0 \rightarrow {}^7\text{F}_0$ transitions are

Fig. 2-234. Apparatus for time-resolved fluorescence line-narrowing spectroscopy.

Fig. 2-235. Comparison of the temperature dependences of the ${}^5\text{D}_0 \rightarrow {}^7\text{F}_0$ fluorescence linewidth of Eu^{3+} in oxide and fluoride crystals and in glasses.

shown for an oxide and a fluoride glass together with corresponding observations in an oxide and a fluoride crystal. The symmetries of the Eu^{3+} sites in these crystals are low (C_{1h} and C_2). The line broadening in the crystals is explained by phonon-induced transitions to higher-lying 7F_1 levels and is confirmed by the observed exponential temperature dependence. The linewidths in the glasses, however, are significantly larger at low temperatures (<100 K) and exhibit a different temperature dependence, $T^{1.8 \pm 0.2}$. In recent years, many experiments (see literature cited in Ref. 109) have provided rapidly expanding evidence for the existence of low-frequency excitations (tunneling or disorder modes) in amorphous materials. The increased broadening in glasses shown in Fig. 2-235 is attributed to these motions. Efforts to account for the temperature dependence of the line broadening yield a linear dependence on T . The observed higher-power law suggests the coupling constant may be temperature-dependent.

At 1.7 K, the Eu^{3+} silicate glass linewidth in Fig. 2-235 was reduced to ≈ 20 MHz. Since the inhomogeneous linewidth of the transition is ~ 200 GHz, this represents FLN by $1:10^5$. Using extreme line narrowing, we can probe the number of physically distinguishable sites in a glass. No discontinuity in fluorescence was detected when scanning the ${}^5D_0 \rightarrow {}^7F_0$ transition of Eu^{3+} with a resolution of $1/2000$ of the inhomogeneous linewidth.¹¹⁰ This indicates the existence of a quasi-continuum of different sites.

Transition Probabilities. Electric-dipole transitions between 4f states of rare-earth ions occur because of small admixing of opposite parity states by the odd harmonics in the expansion of the crystal-field potential. Since, as seen from the Stark splitting, the even-order crystal-field terms vary from site to site, the odd-order terms also vary. The observed fluorescence decay following broadband excitation or excitation into a level having a large homogeneous width is, therefore, composed of a combination of different exponential decays. The extent of multi-exponential decay character is a measure of the degree of inhomogeneity present. If we use selective laser excitation, the decay becomes more exponential with a rate that changes with the excitation wavelength. Factors of 2 to 3 differences in radiative decay rates have been observed for rare earths.¹¹¹

The rates of nonradiative decay by multiphonon emission are also site dependent. Studies of multiphonon processes in glasses have shown that for states such as the ${}^4S_{3/2}$ state of Er^{3+} , which is relaxed predominantly by multiphonon emission to ${}^4F_{9/2}$, the fluorescence decay is nonexponential.¹¹² From FLN studies of the ${}^4F_{3/2}$ state of Nd^{3+} in a silicate glass, Brecher and Riseberg¹¹³ found a small nonradiative component that varies with excitation wavelength. For high-order multiphonon processes, many details of the electronic states and phonon modes are averaged out, leaving the energy gap or number of phonons required to conserve energy as the most important rate-governing parameter. Since the energy gap will vary only slightly for dissimilar sites, the differences in nonradiative rates are attributed principally to variations in the strength of the ion-phonon interaction.

Other Ions. To date, only transitions of trivalent rare earths have been used for FLN experiments. While these ions possess the desirable properties of small homogeneous linewidths and of crystal-field effects that can be treated as small perturbations, the energy level structures are complicated. Narrow line emission from other transition and post-transition metal ions in glasses is rare, however. Ions such as Cr^{3+} , which exhibit a narrow ${}^2E \rightarrow {}^4A_2$ R-line fluorescence in ruby, have a broadband ${}^4T_2 \rightarrow {}^4A_2$ emission in most glasses. The $4d^3$ counterpart of Cr^{3+} is Mo^{3+} , and ${}^2E \rightarrow {}^4A_2$ emission is observed¹¹⁴ at $\approx 1.0 \mu\text{m}$. Because of the site variations in the strengths of the crystal-field and electrostatic interactions, the absorption and fluorescence widths of this transition are very broad, several hundred cm^{-1} . The fluorescence decay of Mo^{3+} in a phosphate glass at ambient and liquid nitrogen temperatures is also highly nonexponential; initial and final decay rates vary by almost an order of magnitude.¹¹⁵ Since the observed decay rates are all faster than the radiative decay rate predicted from the absorption strength, the nonexponential character is indicative of site variations in the nonradiative rates. Because of the large inhomogeneity of the spectral properties and the relatively simple energy level structure for the d^3 configuration, we are presently examining Mo^{3+} for FLN and energy transfer studies.

Author
M. J. Weber

Major Contributor
A. J. De Groot

Fluorescence Quenching

The lifetime and quantum efficiency of the Nd^{3+} ${}^4\text{F}_{3/2}$ fluorescence in glass decrease with increasing neodymium content because of ion-ion interactions. This self-quenching may involve one-step direct processes or multistep energy migration. These processes are important since they eventually nullify, by nonradiative losses, attempts to improve laser gain by increasing the Nd absorption. The fluorescence-decay rates vs Nd content are also required in the computer simulations of optimum gain coefficients, as discussed elsewhere in this report.

The rate of Nd-fluorescence quenching depends upon the host material. For numerous and complicated reasons, this rate must be determined for each material. The ion-ion interactions are multipolar in nature. However, for the ${}^4\text{F}_{3/2}$ excited state of Nd^{3+} , only dipole-dipole processes are allowed by ΔJ selection rules. The probability for dipole-dipole transitions of two ions A and B separated by distance R_{AB} is

$$P_{dd} \propto \frac{f_A f_B}{R_{AB}^6} \int g_A(\nu) g_B(\nu) d\nu, \quad (76)$$

where f is the oscillator strength and g the normalized lineshape function of the transitions. The host dependence arises because of (1) the range and distribution of ion-ion separations R_{AB} , (2) the oscillator strengths, as evident from the dependence of Judd-Ofelt intensity parameters on glass network-

former and network-modifier ions, and (3) the different frequencies and linewidths of the ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{15/2}$, ${}^4\text{I}_{9/2} \rightarrow {}^4\text{I}_{15/2}$ transitions.

Because of the range of interaction distances, the observed fluorescence decay represents an ensemble average and is nonexponential when ion-ion processes are active. However, even in the absence of ion-ion coupling, the decays are nonexponential under broadband excitation because of the site-to-site variation of the probabilities for both radiative and nonradiative transitions, as discussed elsewhere. Thus, the question arises of how to measure and quantify the quenching. All approaches involve assumptions and some arbitrariness. For the surveys, the first three e-foldings of the decay are routinely determined. These indicate semi-quantitatively the deviation from a single exponential. We have also defined and calculated a mean lifetime of the fluorescence decay signal $\phi(t)$ given by

$$\tau_m = \int_0^\infty \phi(t)t dt / \int_0^\infty \phi(t) dt. \quad (77)$$

The decay can also be fitted to a linear combination of three exponential terms. This form is convenient for input to a computer but has no physical significance. For the decay data presented below, we use the second e-folding time. This lifetime is free of uncertainties arising from the finite excitation-pulse duration and the response time of the detection system, which can affect the initial

Fig. 2-236. Comparison of fluorescence self-quenching in silicate and phosphate laser glasses.

Fig. 2-237. Fluorescence self-quenching in fluoride glasses (295 K).

decay time, and it is not plagued by the small signal-to-noise ratio and baseline uncertainties associated with the long-term decay times.

The differences in concentration quenching for various glass types are shown in Figs. 2-236 and 2-237. The fluorescence lifetime (second e-folding time) is plotted as a function of neodymium ion density rather than weight percent (the conversion varies with host). The large difference in the behavior for the two silicate glasses in Fig. 2-236 is due in part to the smaller oscillator strengths of LG-650. The concentration quenching in the phosphate glass is less severe than in ED-2 glass. In phosphate glasses, the presence of water can cause an additional nonradiative loss that reduces the apparent effectiveness of ion-ion self-quenching.

In Fig. 2-237, results are presented for three fluoride glasses, and further differences in behavior

are observed. We are currently studying the effects on fluorescence quenching of changing network-modifier ions within a given glass network. These results will be correlated with variations in the Judd-Ofelt parameters, the absorption and fluorescence linewidths, and spectral overlaps.

Authors

M. J. Weber

A. J. DeGroot

Major Contributor

R. A. Saroyan

Multiphonon Relaxation

We recently studied the relaxation of excited electronic states of trivalent rare earths by multiphonon emission in a series of oxide glasses.¹¹⁶ Measurements of the temperature dependences of multiphonon-emission rates, combined with vibrational frequencies determined from Raman

Fig. 2-238. Comparison of the rates of multiphonon emission from rare-earth ions in silicate and fluoroberyllate glasses plotted as a function of energy gap to the next-lower level. Data recorded at 295 K.

spectra, demonstrated that the highest frequency vibrations in each glass were the dominant cause of relaxation. We have extended these studies to rare earths in a beryllium-fluoride-based glass to compare the relaxation behavior in oxide vs that in halide glasses.

Rare-earth ions studied were Nd^{3+} and Er^{3+} . The host-glass composition was (mole %): 49 BeF_2 , 27 KF , 14 CaF_2 , 10 AlF_3 ; the rare-earth fluoride dopant concentrations were 0.2 mole %. Measurements of multiphonon emission rates were made at 295 K by monitoring the transient fluorescence following pulsed optical excitation into selected J states. For Nd^{3+} , the risetime of the $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{9/2} + ^4\text{I}_{11/2}$ fluorescence was measured following excitation (1) at 532 nm using the second harmonic and (2) at 355 nm using the third harmonic of a Nd:YAG laser. The risetime is a measure of the rate-limiting step in the cascade from the initial excited state to $^4\text{F}_{3/2}$. For Er^{3+} , the $^2\text{H}_{11/2}$ state was excited using the 532-nm second-harmonic Nd:YAG laser output; we observed subsequent fluorescence from the $^4\text{S}_{3/2}$, $^4\text{F}_{9/2}$, and $^4\text{I}_{11/2}$ lower states. The article cited in Ref. 116 gives additional details of the apparatus and experimental techniques. In all cases, the laser pulse duration was very short compared to the multiphonon emission times. In addition, the rates of multiphonon emission were very much greater than the rates of radiative decay.

The latter were estimated by using the Judd-Ofelt intensity parameters.

The rates of multiphonon emission for rare earths in crystals and oxide glasses have been found to exhibit an approximately exponential dependence on energy gap ΔE to the next-lower level of the form

$$W_{\text{MP}} = W_0 \exp(-\alpha \Delta E), \quad (78)$$

where W_0 and α are phenomenological parameters. Data for five different rare-earth electronic states in fluoroberyllate glass are plotted as a function of energy gap in Fig. 2-238 and are seen to exhibit a similar dependence. (The measured rates are an effective average over the different sites.) The dashed straight line in Fig. 2-238 corresponds to Eq. (78) with $W_0 = 9 \times 10^{11} \text{ s}^{-1}$ and $\alpha = 6.3 \times 10^{-3} \text{ cm}^{-1}$. As observed previously, for excited states where the energy ΔE can be conserved by only ≈ 2 phonons (e.g., the $^4\text{G}_{7/2}$ state of Nd^{3+}), the data deviate from the simple exponential dependence that results from the averaging effects of higher-order processes.

For comparison, data on multiphonon relaxation for rare earths in a silicate glass (composition [mole %] = 67 SiO_2 , 15 Na_2O , 18 BaO) are also included in Fig. 2-238. The energy gaps between rare-earth J states in the silicate and fluoroberyllate glasses are

Fig. 2-239. Polarized Raman spectra at 295 K of a silicate and a fluoroberyllate glass.

approximately equal. The difference in multiphonon emission rates is therefore attributed to different vibrational spectra and/or crystal field strengths. The ranges of the vibrational frequencies for the two glasses are evident from the Raman spectra shown in Fig. 2-239. The highest frequency vibrations are associated with Si-O and Be-F bond-stretching modes of the glass-former groups: SiO_4^{4-} and BeF_4^{2-} . (Note that there is a reversal of the cation/anion mass ratio for these glasses.) Since these frequencies are higher for the silicate glass, a given amount of transitional energy can be conserved in a lower-order process. The local field at the rare-earth sites in the oxide glass is also larger because of the larger charge and more covalent bonding of the ligand ions.

For laser action from the $^4F_{3/2}$ level of Nd^{3+} , the energy gap to the next-lower state is $\approx 4700 \text{ cm}^{-1}$. Extrapolating the results of Fig. 2-238 to this gap yields a multiphonon-emission rate of $\sim 50 \text{ s}^{-1}$ at 300 K. The calculated average radiative decay rate is $1.6 \times 10^3 \text{ s}^{-1}$. Therefore, nonradiative losses by multiphonon emission are very small, and the radiative quantum efficiency of the $^4F_{3/2}$ level of Nd^{3+} at low Nd concentrations is approximately unity. This is consistent with other measurements that show the relative radiative quantum efficiency from the $^4F_{3/2}$ state of Nd^{3+} in a fluoroberyllate glass to be constant, independent of site.¹¹⁷

References

99. R. R. Jacobs, C. B. Layne, M. J. Weber, and C. F. Rapp, *J. Appl. Phys.* **47**, 2020 (1976).
100. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-5002-75 (1976), p. 201.
101. *Ibid.*, p. 204.
102. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), p. 269.
103. P. C. Magnante, *IEEE J. Quant. Electron.* **QE-8**, 440 (1972).
104. G. B. Parrent and B. J. Thompson, *Physical Optics Notebook* (Society of Photo-Optical Instrumentation Engineers, Redondo Beach, Ca., 1971), p. 53.
105. C. B. Layne, W. H. Lowdermilk, and M. J. Weber, *Multiphonon Relaxation of Rare-Earth Ions in Glasses*, Lawrence Livermore Laboratory, Rept. UCRL-78876. Preprint (to be published in *Phys. Rev. B*).
106. For a brief review, see M. J. Weber, *Proc. Colloque Lyon, 1977* (in press).
107. C. Brecher and L. A. Riseberg, *Phys. Rev.* **B13**, 81 (1976).
108. J. A. Paisner, S. S. Sussman, W. M. Yen, and M. J. Weber, *Bull. Amer. Phys. Soc.* **20**, 447 (1975) and *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976).
109. P. M. Selzer, D. L. Huber, D. S. Hamilton, W. M. Yen, and M. J. Weber, *Phys. Rev. Lett.* **36**, 813 (1976).

110. P. M. Selzer, D. L. Huber, D. S. Hamilton, W. M. Yen, and M. J. Weber, *Structure and Excitations of Amorphous Solids*, Williamsburg, Virginia, March 1976 (AIP Conf. Proc.), No. 31, p. 328.
111. M. J. Weber, J. A. Paisner, S. S. Sussman, W. M. Yen, L. A. Riseberg, and C. Brecher, *J. Luminescence* **12**, 729 (1976).
112. C. B. Layne and M. J. Weber, *Phys. Rev. B* (in press).
113. C. Brecher, L. A. Riseberg, and M. J. Weber, *Appl. Phys. Lett.* (in press).
114. S. Parke, S. Gomolka, and J. N. Sandoe, *J. Non-Cryst. Solids* **20**, 1 (1976).
115. M. J. Weber and A. J. DeGroot, *Bull. Amer. Phys. Soc.* **22**, 466 (1977).
116. C. B. Layne, W. H. Lowdermilk, and M. J. Weber, *Phys. Rev. B* (in press).
117. C. Brecher, L. A. Riseberg, and M. J. Weber, *Appl. Phys. Letters* (in press).

Authors

C. B. Layne
M. J. Weber

2-4.7 Faraday Rotator Materials

Lasers for fusion experiments must be protected from back-scattered light and, in the case of multibeam experiments, from scattered and transmitted light. Optical isolation, obtained by using the Faraday effect, can provide this protection. The requirements for a good Faraday rotator material include low absorption at the laser wavelength, low birefringence, high homogeneity, and high threshold of damage. The angle of rotation of the polarization is given by $\theta = V\ell H$, where V is the Verdet constant, ℓ the optical path length, and H the component of the magnetic field in the direction of light propagation. For a 45° rotation in a given H field, the Verdet constant of the material should be as large as possible to reduce ℓ and the beam-breakup integral B . A figure-of-merit for a Faraday rotator material to maximize the power per unit B integral is

$$\frac{P_{\text{out}}}{B} \propto \frac{\lambda n}{n_2} \frac{D^2}{\ell} \rightarrow \frac{nV}{n_2} \quad (79)$$

where λ is the laser wavelength. Absorption and scattering losses at the laser wavelength are assumed negligibly small.

Faraday isolators have been built using diamagnetic and paramagnetic materials.

Classically, the Verdet constant for a diamagnetic material is proportional to the dispersion $dn/d\lambda$. But materials having large dispersion (low Abbe number) also have large n_2 values. This, combined with the fact that larger Verdet constants are possible with paramagnetic materials, favors the latter for use in fusion lasers. The total Verdet constant for a material is generally composed of a positive diamagnetic contribution and a negative paramagnetic contribution. Since one selects low-dispersion host materials to minimize n_2 , the diamagnetic contribution is also reduced.

The paramagnetic Verdet constant is approximated by

$$V(\lambda) = - \frac{(n^2 + 2)^2}{9n} \frac{N}{T} \frac{A}{\lambda^2 - \lambda_t^2} \quad (80)$$

where N is the number of active paramagnetic ions per unit volume, T is the temperature, and A and λ_t (the effective transition wavelength) are constants characteristic of the ion and host material. Rare earths have been used extensively as the paramagnetic ion. Of these, Tb^{3+} , Ce^{3+} , and Eu^{2+} are particularly useful for the visible and near-infrared spectral region since they have large Verdet constants per ion but no absorption bands in this region. The rotation occurs by means of virtual $4f^n - 4f^{n-1}5d$ transitions. Since the location and transition matrix elements of the $5d$ bands exhibit only

small variations with host, the specific Verdet constant of a given rare earth is about the same for all materials in the long-wavelength limit (λ much longer than λ_t). Therefore, to increase V , the concentration N should be made as large as possible. Increasing the rare-earth content in a glass will concurrently increase the linear and nonlinear refractive indices; however, this is generally a smaller effect. As evident from Eq. (80), the paramagnetic V can also be increased by reducing the temperature.

Glasses having small n_2 values are obvious choices as hosts for paramagnetic rotator ions. Relative figures-of-merit (normalized to FR-5) of some commercial and prospective Faraday rotator glasses are listed in Table 2-62.

Whereas the specific V for Ce^{3+} is approximately 80% of that for Tb^{3+} at $1.06 \mu m$, the larger V for FR-5 is due mainly to the larger amount of terbium that can be incorporated into this glass while still preserving good glass-forming properties. The maximum Tb concentrations for the fluorophosphate and fluoroberyllate glasses are not known and are currently under investigation. The entries for these glasses in Table 2-62 are based on an assumption that a Tb content about 70% of that in FR-5 may be obtained. The actual figure-of-merit achievable may be higher or lower than this estimate.

The rare-earth density in crystals can be significantly higher than that in most glasses. By combining this feature with a fluoride host, superior rotator materials are possible. Data for two examples, $LiTbF_4$ and CeF_3 , are included in Table 2-62.

Table 2-62. Verdet constants V , linear and nonlinear refractive indices, and relative figures-of-merit of Faraday rotator materials at 1064 nm and 295 K

Glasses	V (min/Oe-cm)	n	n_2 (10^{-13} esu)	Vn/n_2
FR-4 (Ce-phosphate)	0.031	1.556	1.9	0.45
FR-5 (Tb-silicate)	0.071	1.678	2.1	1.00
Tb-fluorophosphate	~0.05	1.51	~0.9	~1.5
Tb-fluoroberyllate	~0.05	~1.38	~0.5	~2.4
Crystals				
$LiTbF_4$ (tetragonal)	0.13	1.49	~0.7	4.9
CeF_3 (hexagonal)	0.11	1.60	1.5	2.1

Fig. 2-240. Wavelength dependence of the Verdet constant for Faraday rotator materials. FR-4 is a Ce^{3+} -doped phosphate glass; FR-5 is a Tb^{3+} -doped borosilicate glass. Measurements were made at 295 K.

The projected figures-of-merit are higher (based upon estimated n_2 values) than for glasses. These crystals have been grown with good optical quality but only in diameters of a few centimeters.

The paramagnetic rotator materials in Table 2-62 are also useful throughout the visible (except for the region of the ${}^7\text{F}_6 \rightarrow {}^5\text{D}_4$ absorption of Tb^{3+} at ≈ 490 nm). From Eq. (80), the Verdet constant increases with decreasing wavelength. This is shown in Fig. 2-240. Measurements were taken at ambient temperatures in magnetic fields to 10^4 Oe using the following lasers and wavelengths:

Material	$D(\text{min-nm}^2/\text{Oe-cm})$	λ_t (nm)
FR-4	3.34×10^4	280
FR-5	8.70	219
CeF_3	1.41	242

The results for CeF_3 are for light propagating along the crystallographic c-axis.

Author	Major Contributor
M. J. Weber	W. Moss

Laser	Wavelength (nm)
He-Cd	325
He-Cd	441
Nd:YAG (second harmonic)	532
He-Ne	633
Nd:YAG	1064

Similar data were recorded using a tungsten light source and a monochromator equipped with a vidicon readout (Tektronix rapid scan spectrometer). Fitting the measured wavelength dependence of V to an expression of the form $V = D/\lambda^2 - \lambda_1^2$ yielded* the following values for the constant D (which included the temperature and the local field correction) and λ_1 :

*Measurements were made by W. Moss and R. Morgret; W. Moss did the analysis and data reduction.

2-4.8 Lens/Substrate Materials

Because of their low predicted n_2 values, fluoride glasses are the most promising candidates for passive components such as lenses, windows, and substrates. Fluoride crystals such as CaF_2 , LiF , NaF , and MgF_2 might also be suitable for passive components since they can be prepared in large sizes, either as single crystals or in polycrystalline forms (hot pressed, hot forged, or fusion cast). The optical quality of the polycrystalline forms is frequently inadequate for high-power fusion laser applications because of excessive scattering or birefringence.

Improvements in the optical quality of polycrystalline materials may be possible with better processing techniques. These materials are attractive since the production costs should be lower

Table 2-63. Refractive indices and relative figures-of-merit for lens materials at 1064 nm

Glasses	n_D	$n_2 (10^{-13} \text{ esu})$	$n(n-1)/n_2$
Borosilicate (BK-7)	1.517	1.24	1.0
Fused silica (SiO_2)	1.458	0.95	1.1
Fluorosilicate (FK-5)	1.487	1.0	1.1
Fluorophosphate (FK-51)	1.487	0.69	1.7
Fluoroberyllate	$\sim 1.35 - 1.40$	0.4 (est.)	2.0
Crystals			
CaF_2 (cubic)	1.434	0.57	1.8
LiF (cubic)	1.392	0.35	2.5

than for large single crystals. Studies to improve optical quality are needed for hot-forged and fusion-cast fluoride crystals. The Raytheon Company is presently exploring the quality and sizes of CaF_2 obtainable with fusion casting under ERDA contract EY-76-C-02-4029*000.

The figure-of-merit of a lens material is given by $n(n-1)/n_2$. Values of the B integral and relative to the BK-7 presently used, are given in Table 2-63. Improvements by a factor of $\lesssim 2$ are possible with pure fluoride materials.

In addition to their low n_2 , fluoride materials generally have large band gaps and, hence, transmit over a large spectral range. This makes them potentially useful for high-power lasers operating at other wavelengths.

2-4.9 Oscillator Crystals

The wavelength of the peak fluorescence and gain associated with the $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{11/2}$ transition of Nd^{3+} changes significantly with the glass network former. This is illustrated in Fig. 2-241. Therefore, the presently used Nd:YAG oscillator, which operates at 1.064 μm and is a good spectral match for silicate amplifier glasses, will not be appropriate for new glasses such as phosphates and fluorides. Optimum use of these glasses will require the development of new oscillator materials and/or the use of other transitions. For mode-locked os-

cillators with good TEM₀₀ mode output, materials with large stimulated-emission cross sections and low n_2 values are desired.

Phosphate and fluorophosphate glasses both have Nd^{3+} fluorescence band peaks at about 1.054 μm . For mixed (nonberyllium) fluoride glasses with a very small phosphate content, the fluorescence peak can occur at shorter wavelengths (around 1.050 μm). Three approaches can be taken to developing oscillators for the shorter wavelengths:

- Operate a Nd:YAG oscillator on the 1.052- μm transition by suppressing the other wavelengths.
- Use a different neodymium-doped crystal that oscillates naturally near 1.050 to 1.054 μm .
- Make an oscillator from the same neodymium glass used for the amplifier chain.

The first approach works and has been described recently.¹¹⁸ It makes use of existing materials and pump cavities. Exploration of various frequency-selection techniques, characterization of the resulting performance, and engineering design of a final configuration are needed to implement this approach.

There are several fluoride crystals with Nd^{3+} fluorescence peaks in the wavelength region of interest. Of these, neodymium-doped LiYF_4 is a promising candidate because (a) oscillation occurs at 1.053 μm , providing a good spectral match with phosphate glasses, (b) large single crystals doped with certain rare earths¹¹⁹ have been grown and used for lasers, and (c) the material has a very low n value and reasonable gain— $\sigma = 23 \times 10^{-20} \text{ cm}^2$, according to a recent study.¹²⁰ Crystals of Nd:LiYF₄

Fig. 2-141. ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ fluorescence spectra of Nd^{3+} in different glasses show shift in wavelength of peak fluorescence by network former. Variations for different network-modifier ions are generally much smaller (less than ± 2 nm).

oriented for 1.053- μm operation are being grown for LLL by Sanders Associates. Test and evaluation of laser rods in various sizes are scheduled for early 1977.

Nd:LiYF_4 is also of interest because, in another polarization, oscillation occurs at 1.047 μm ($\sigma = 61 \times 10^{-20} \text{ cm}^2$). This is an exact match with the peak wavelength of neodymium fluoroberyllate glasses and, thus, might be a suitable oscillator material for these glasses, too. Research on crystals for this orientation is being supported by ERDA.

Compared with crystals, neodymium glasses have small stimulated-emission cross sections, and problems have been encountered in making good mode-locked glass oscillators. New phosphate laser glasses offer higher cross sections and gain coefficients. A recent report describes a mode-locked neodymium-phosphate glass oscillator producing 3- to 10-ps pulses.¹²¹

References

118. J. M. McMahon, *Opt. Commun.* 18, 170 (1976). Presented at IQEC, Amsterdam, June 1976.
119. These rare earths have generally been the smaller ones in the latter half of the $4f^n$ series, which are easier to incorporate into Y^{3+} sites than into Nd^{3+} .

120. Cross sections measured by H. Janssen, Massachusetts Institute of Technology (private communication).
121. H. Kuroda, H. Masuko, and S. Muekawa, *Opt. Commun.* 18, 169 (1976). Presented at IQEC, Amsterdam, June 1976.

Author

M. J. Weber

2-4.10 Laser-Induced Damage

Before 1976, laser-damage experiments at LLL were mainly for establishing a general data base, qualifying vendors, and determining the acceptability of specific optical elements. These tests, conducted with linearly polarized 1064-nm, 125-ps pulses, indicated that the average damage threshold for antireflective coatings and thin-film polymers was $\approx 4 \text{ J/cm}^2$. Typical thin-film structures with high reflectivity evidenced damage at 5 to 6 J/cm^2 and bare polished surfaces at 9 to 12 J/cm^2 . The general data base was summarized in a recent paper.¹²²

While we continued to watch the performance of routine optical fabrication during 1976, we also commenced general research aimed at understanding the damage mechanisms and improving the laser damage thresholds. The major experiments are described below.

Antireflective Coatings for Shiva Amplifier Rods

The Shiva laser will employ glass rod amplifiers with small-signal gains in excess of 100. Owens-Illinois and Spectra Physics, Inc., jointly developed a coating process that achieved high-quality, damage-resistant antireflective films without introducing stress birefringence in the rods. We ran damage tests of these films, deposited both on witness samples of ED-2 glass and on actual amplifier rods. Table 2-64 shows the data. Each row in the table gives the damage thresholds for the rod end and two witnesses coated in a single run. The experiments not only indicated that the coating thresholds exceeded a minimum acceptable value of 2 J/cm^2 but also produced two interesting results: that testing witness samples may not be equivalent to testing optics themselves, and that antireflective films can exhibit high damage thresholds.

To eliminate the complications of self-focusing in the rods, we tested the samples on rod ends with the

films facing toward the incident light beam. One witness from each run was damage-tested with the film facing the laser; the other witness was tested in reverse orientation, with the film on the exit surface. The average damage threshold for the films on the witness samples, 6.4 J/cm^2 , is significantly greater than either the average value for films on rod ends, 4.5 J/cm^2 , or the typical value of $\approx 4.0 \text{ J/cm}^2$ observed during our normal damage tests on antireflective films. The results of tests on the witness samples indicate that damage thresholds of antireflective films depend on either substrate quality or placement of substrates during the coating run. Therefore, testing witness samples may not be equivalent to testing the optical components that were simultaneously coated. The latter result, that damage thresholds for antireflective films can be significantly greater than typical, is encouraging, but not yet understood.

Finally, we saw no systematic difference in whether a film was used as an exit or an entrance surface.

Pulse-Duration Dependence on Surface Damage

Since operation over a range of pulse durations between 0.04 and 3.0 ns is contemplated for fusion lasers, we have measured the $1.06\text{-}\mu\text{m}$ damage

Table 2-64. Laser damage thresholds of antireflective coatings on ED-2 amplifier rods and associated witness samples (1064 nm, 125 ps)¹²²

Rod end tested	Damage threshold	Thresholds for witnesses ^a	
		Film forward	Film reversed
1,end A	4.4 ± 0.7	5.7 ± 1.0	—
1,end B	—	6.3 ± 1.5	6.0 ± 1.0
2,end A	3.3 ± 0.5	6.7 ± 1.5	6.0 ± 1.0
2,end B	3.5 ± 0.5	8.0 ± 1.5	6.0 ± 1.0
3,end A	5.4 ± 0.8	4.8 ± 0.8	8.0 ± 1.5
3,end B	6.0 ± 1.0	5.3 ± 1.0	8.1 ± 2.0
Column averages	4.5	6.1	6.8

^aTwo witness samples of ED-2 were simultaneously coated with each rod end.

threshold of five surfaces at three pulse lengths: 0.125, 0.60, and 1.1 ns. The nanosecond-duration pulses were generated by gating a portion of the 20-ns pulse emitted by a Nd:YAG laser operating in a single-cavity mode. The pulses at 0.125 ns were obtained from a passively mode-locked oscillator, and those at 0.60 ns were generated by active mode locking. All pulses were amplified in the system designed for 125-ps pulses, but start-pulse energy was less for both the 0.60-ns and 1.1-ns pulses. This resulted in reduced output energy for these longer pulses. Because of this limitation, damage tests were performed at 1.1 ns by using a beam diameter of 0.2 mm instead of the larger beams of 2.0 to 6.0 mm diameter that are normally used. Since the density of defects responsible for laser damage¹²³ varies

from 10^6 to 10^7 cm^{-2} at 100 ps to about 10^5 cm^{-2} at 1.4 ns, the reduced spot size for the 1.1-ns measurements is not expected to produce anomalous results. Diagnostics on the smaller beams, however, are more difficult.

For tests with the longer pulses, we chose samples at random from those recently tested at 0.125 ns. All tests were conducted using linearly polarized pulses at nearly-normal incidence. Surface-damaged threshold as a function of pulse duration is shown in Fig. 2-242 for a polished quartz sample and a highly reflective thin film. Table 2-65 gives results for three additional samples.

These tests generally confirm that damage thresholds increase as the square root of pulse duration τ , as reported in previous studies on the bulk of

Fig. 2-242. Laser-damage threshold of a bare, polished, fused-silica surface and a $\text{TiO}_2/\text{SiO}_2$ thin-film reflector as a function of pulse duration. The box surrounding each point indicates measurement error for pulse duration and damage threshold. Curves of slope 1/2 illustrate dependence of the damage threshold on the square root of pulse duration.

Table 2-65. Measured and predicted damage thresholds at three laser pulse durations

Sample	0.125-ns pulse, 2.0-mm beam ^a	0.60-ns pulse, 0.50-mm beam ^{a,b}		1.10-ns pulse, 0.25-mm beam ^{a,b}	
	Threshold (J/cm ²)	Threshold (J/cm ²)		Threshold (J/cm ²)	
		Measured	Predicted	Measured	Predicted
1. Fused silica ^c	10.0 ± 1.0	23.0 ± 3.0	21.8 ± 2.2	27.0 ± 4.0	29.7 ± 3.0
2. BK-7 ^c	9.2 ± 1.5	19.5 ± 3.5	20.2 ± 3.3	25.0 ± 3.0	27.3 ± 4.5
3. FK-51 ^c	10.0 ± 1.1	17.0 ± 3.0	21.8 ± 2.4	21.0 ± 3.0	29.7 ± 3.0
4. 99% reflector	5.1 ± 1.0	9.5 ± 2.0	11.7 ± 2.2	11.5 ± 2.5	15.1 ± 3.0
5. Antireflective coat	5.5 ± 1.0	11.0 ± 2.0	12.0 ± 3.3	9.5 ± 2.0	16.3 ± 3.0
6. 7051 substrate ^{c,d}	9.0 ± 1.5	—	—	>38.0	26.7 ± 4.5

^aBeam size is $\approx e^{-1}$ diam in intensity.

^bPredicted thresholds at 0.60 and 1.10 ns were calculated from the 0.125-ns data assuming that the threshold goes as the square root of the pulse duration.

^cSilica, BK-7, and FK-51 glass samples had been subjected to normal polishing. The 7051 substrate was a commercially available flame-finished material. Both thin films were of TiO₂/SiO₂.

^dSample 6 was not tested at the intermediate pulse duration.

NaCl¹²⁴ and dielectric films.¹²⁵ However, the behavior of thin films was less systematic than that of polished surfaces, and use of a slower growth function, $\tau^{0.4}$, is recommended for extrapolation of data obtained at $\tau = 0.125$ ns.

Pulse-duration dependence will be investigated in more depth during the coming year, since damage thresholds appear to be the limiting aspect for fusion lasers at $1.0 < \tau < 3.0$ ns.

Other Studies

Two additional studies were begun during the year: a study of sputter-deposited titania and a study of damage vs thin-film design, both in cooperation with Optical Coating Laboratory.

Sputter-deposited titania films were recently reported to have extremely good damage resistance.¹²⁶ Indeed, the values reported there were

above those observed on most bare polished glass surfaces. We have measured the damage threshold of four sputtered $\lambda/4$ titania single layers on quartz substrates. Thresholds ranged from 3.5 to 5.0 J/cm², values comparable to those found for titania deposited by e-beam evaporation. Although films can be prepared by sputtering that have very low scatter and refractive indices approaching that of crystalline materials,¹²⁷ we cannot yet satisfactorily demonstrate that sputtering offers an increase in damage threshold.

We began a second study to investigate the correlation between laser damage and a variety of thin-film variables, such as the electric field of standing waves in these devices,¹²⁸ absorption in film material, and problems associated with the interfaces. The first results from this study will be available in time to affect Shiva coating specifications.

References

122. D. Milam, *Applied Optics* (to be published).
123. D. Milam, R. A. Bradbury, and M. Bass, *Appl. Phys. Lett.* **23**, 654 (1973).
124. D. W. Fradin, N. Bloembergen, and J. P. Letellier, *Appl. Phys. Lett.* **22**, 635 (1973).
125. D. Milam and R. A. Bradburn, *Laser Focus* **9**, 41 (1973).
126. B. E. Newman and D. H. Gill, "Super-High Damage Thresholds for RF-Sputtered TiO_2 Films," *O.S.A. Fall Meeting, Boston (October 21-24, 1975)*.
127. A. Shimkunas, OCLI (private communication).
128. J. H. Apfel, J. S. Matteucci, B. E. Newman, and D. H. Gill, "Role of Electric-Field Strength in Laser Damage to Dielectric Multilayers," *Boulder Damage Conference, Boulder, Colorado (July 14, 1976)*.

2-4.11 Nonlinear Optics

Our measurements of the nonlinear refractive-index coefficient n_2 have been expanded to investigate third-order nonlinear susceptibility of a wider class of materials including fluoride crystals. Work is under way on a substantial upgrading of our laser-damage/nonlinear optics facility.

Refractive Index Nonlinearity

The index of refraction of a material is given by

$$n = n_0 + \Delta n \quad (81)$$

where n_0 is the refractive index normally measured with low-intensity light of given polarization and propagation directions, and Δn is the change in index induced by an intense optical beam. The quantity Δn is expressed in terms of the time-averaged optical electric-field amplitude E as $n_2 \langle E^2 \rangle$, where the nonlinear refractive-index coefficient n_2 is in electrostatic units. The dominant contribution to n_2 for short (≈ 1 ns) optical pulses is electronic in origin. Expressions have been derived relating n_2 and the linear refractive indices in the long-wavelength limit.¹²⁹

By using dispersion data and a single adjustable parameter, we were able to fit satisfactorily measured n_2 values for silicate glasses spanning a range of about 10. By means of time-resolved

interferometry,¹³⁰⁻¹³² we made n_2 measurements for a wider class of materials including several low-index, low-dispersion glasses and crystals. Figure 2-243 shows the experimental arrangement. The results, obtained with linearly polarized 100-ps, 1064-nm laser pulses, are shown in Fig. 2-244 together with predicted values. Within experimental error, all the data is accounted for by using a single fixed parameter. Since low n_2 values are characteristic of materials having low index and low dispersion, these properties provide guidance in the search for improved optical materials.

We are presently measuring n_2 in order to investigate the third-order nonlinear susceptibility of a wider class of materials. These materials are indicated in Table 2-66. Measurements of n_2 for a number of different fluoride crystals have been completed and are summarized in Table 2-67. For the cubic alkali and alkaline earth fluorides, measurements were made with the laser pulse propagating along a 100 axis; for the axial crystals, the propagation direction was along the crystallographic c-axis.

Table 2-66. Materials for nonlinear refractive index studies

Crystals:

Alkali halides		Fluorides		Oxides
LiF	KCl	MgF ₂	CdF ₂	SiO ₂
NaF	KBr	CaF ₂	PbF ₂	TiO ₂
NaCl	KI	SrF ₂	LaF ₃	TeO ₂
		BaF ₂	LiYF ₄	Al ₂ O ₃
				Y ₃ Al ₅ O ₁₂

Glasses:

Simple		Multicomponent	
SiO ₂	B ₂ O ₃	Silicate	Fluorosilicate
GeO ₂	As ₂ O ₃	Borosilicate	Fluorophosphate
BeF ₂	As ₂ S ₃	Phosphate	Fluoroberyllate

Polymers:

Acrylic (PMMA) Polystyrene

Liquids: Organic solvents

Table 2-67. Linear and nonlinear refractive indices of fluoride crystals

Material	Structure type	n_D	ν	$n_2(10^{-13} \text{ esu})$
LiF	Cubic (NaCl)	1.392	99	0.35 ± 0.10
NaF	Cubic (NaCl)	1.326	85	0.43 ± 0.10
CaF ₂	Cubic (fluorite)	1.434	95	0.65 ± 0.09
SrF ₂	Cubic (fluorite)	1.438	92	0.60 ± 0.10
BaF ₂	Cubic (fluorite)	1.475	82	1.0 ± 0.2
CdF ₂	Cubic (fluorite)	1.576	61	1.44 ± 0.20
PbF ₂	Cubic (fluorite)	1.769	34	4.8 ± 1.2
MgF ₂	Tetragonal (rutile)	1.378	108	0.30 ± 0.10
LaF ₃	Hexagonal (tysonite)	1.603	57	1.49 ± 0.27
CeF ₃	Hexagonal (tysonite)			1.53 ± 0.35
LiYF ₄	Tetragonal (Scheelite)	1.457	93	0.59 ± 0.07

Fig. 2-243. Experimental arrangement and diagnostics used in the measurements of nonlinear refractive index. Beam diameter is ≈ 5 mm; sample lengths for low-index materials are ~ 10 cm.

Other studies are under way that include (a) the dependence of n_2 on polarization and propagation direction (for crystalline materials), which provides information about the relative magnitudes of the electronic and nuclear contributions to n_2 , (b) the frequency dispersion of n_2 , and (c) the dependence of n_2 on pulse duration, for cases where electrostrictive and thermal self-focusing are significant.

Expanded experimental capabilities to measure temporal, spatial, and frequency effects are

described below. These studies are supported in part by the materials sciences program of ERDA's Division of Physical Research.

Facilities

In 1976, LLL began a substantial upgrading of the laser damage/nonlinear optics facility. Figure 2-245 shows the additions to the facility.

Fig. 2-244. Calculated vs measured nonlinear indices n_2 . Good correlation is obtained for a wide class of materials including silicate (ED-2) and phosphate (EV-1, LHG-5) neodymium laser glasses; borosilicate glass (BK-7); fluorosilicate (FK-5), fluorophosphate (FK-51), and Faraday rotator (EY-1, FR-4, FR-5) glasses; and three fluoride crystals (LiF, MgF_2 , CaF_2).

Fig. 2-245. Expansion of the nonlinear optics/laser damage facility. Units outlined with dashed lines are new additions and include (1) a new amplifier chain with variable pulse duration, (2) nonlinear crystals for generating second, third, and fourth harmonics of the Nd:YAG oscillator wavelength, and (3) PDP-11 computer and data acquisition and processing system.

A new laser chain was designed to provide the important characteristic of an adjustable pulse duration. This laser system is shown in Fig. 2-245 as the dotted oscillator-amplifier chain. The oscillator itself is a well-stabilized Nd:YAG, single-longitudinal-mode, electro-optically Q-switched device producing ~ 20 ns FWHM, TEM₀₀ pulses. A fast (≥ 0.5 ns risetime) Pockels cell shutter will be used to excise an essentially square temporal waveform of length ~ 1 to ~ 10 ns. Five subsequent amplifier stages will boost the pulse energy to several joules, allowing 5 GW to be produced at any pulse duration within the above range.

In addition to adjustable pulse duration, this laser will have adjacent harmonic generation cells allowing the production of intense 532-, 355-, and 266-nm pulses. The frequency dispersive processes that will be interrogated with these ir, visible, and uv pulses were outlined in the earlier discussions of oscillator crystals and laser-induced damage.

In 1976, a computer-controlled data acquisition and analysis system (DAAS) was designed, and component procurement was begun. This equipment will rectify the present severe restriction to the throughput of the ILS laboratory caused by the fractional time spent in data reduction. A silicon vidicon TV camera will monitor the pulse spatial profile. A silicon SIT vidicon will read the output of a streak camera tube. These two TV frames will be simultaneously recorded on a video disk recorder and monitored on TV. A video digitizer will then digitize the TV frames and make the data available to other components of the DAAS through parallel registers. A CAMAC dataway interface will be used for flexibility to provide transmission between the various components.

Precision LLL calorimeters will provide $\pm 3\%$ energy measurements, and a CAMAC calorimeter module will perform analog to digital conversion and storage of the calorimeter signals. A Tektronix

R7912 transient digitizer will monitor temporal waveforms real-time with less than 0.5-ns resolution, well-matched to the laser pulse duration capability. These several components will communicate by way of the CAMAC dataway under the instruction of a PDP-11/05 computer. Long-term data and program storage is provided by a dual floppy disk unit. Floppy disk format data may be transferred to magnetic tape and the LLL Octopus computer system by way of a translator in our laboratory. These components will be received and used in 1977.

A small, separate, microscopy laboratory is planned to support the laser-damage facility. A Zeiss research microscope that will allow bright- or dark-field microscopy in reflected light, bright-field microscopy in transmitted light, or phase-contrast

microscopy, at up to 500X, has been received. Accessories were purchased to allow photography under all conditions.

References

129. *Laser Program Annual Report--1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74.
130. E. S. Bliss, D. R. Speck, and W. W. Simmons, *Appl. Phys. Lett.* **25**, 728 (1974).
131. D. Milam and M. J. Weber, *J. Appl. Phys.* **47**, 2497 (1976).
132. D. Milam and M. J. Weber, *IEEE J. Quant. Electron.* **QE-12**, 512 (1976).

Authors

W. L. Smith
D. Milam
M. J. Weber

2-5 PULSE GENERATION AND SHAPING

2-5.1 Overview

Current experiments on laser-driven fusion place severe demands on the laser pulse source. First, the oscillator must deliver a pulse on command with complete reliability. The basic pulse for simple experiments should have an approximately Gaussian time dependence, its duration should be variable through the range of 100 ps to 2 ns, its energy should be about 1 mJ, and its amplitude and duration must not vary from specified values by more than $\pm 5\%$. Also needed are pulses whose time dependence is considerably more complicated than Gaussian. An example is a composite pulse that consists of a series of rectangular pulses of varying amplitude, duration, and separation. Finally, diagnostic laser pulses of very short duration (less than 30 ps) are needed for experimental observations. These diagnostic laser pulses must be synchronized with the target-irradiating laser pulse to a tolerance less than the diagnostic pulse's duration.

Laser-fusion experiments at LLL have been conducted using a Nd:YAG oscillator mode-locked by a saturable absorber. This oscillator has not proved to be sufficiently reliable. Experimental and theoretical studies¹³³ have confirmed our own

experience¹³⁴ that the passively mode-locked oscillator's reliability is limited by fluctuation statistics of the initial fluorescence noise from which the short pulse is formed. These results led us to conclude that further development of passively mode-locked oscillators would not be productive.

It became clear after considering alternate methods of short-pulse generation that active mode-locking was the only technique capable of reliably generating a pulse with the needed stability and flexibility. In addition, since the energy of pulses from actively mode-locked oscillators is only about 10 nJ, the required energy of 1 mJ would have to be developed by multipass amplification. Two paths of development were followed which used this general scheme of pulse generation.

The first approach was to Q-switch an actively mode-locked oscillator. An acousto-optic Q-switch reduces the cavity Q during a several-millisecond period while a nearly steady-state short pulse is formed in the cavity by an acousto-optic modulator. The Q-switch loss is then reduced and the pulse is amplified. This work was begun at Stanford University in 1974 under LLL sponsorship¹³⁵ and continued at Stanford Research Institute (SRI) through 1974¹³⁶; the principal investigator was Dr.

D. J. Kuizenga. During 1976, a prototype oscillator was constructed which met all stability and reliability requirements. This type of oscillator, with some engineering design improvements, was chosen to be built at LLL for use on Shiva. A second prototype with a longer resonator cavity was built at SRI and is in use on Argus. The Argus oscillator required a reliable single-pulse switchout. For this purpose, a new type of switchout that uses avalanche transistors to switch voltage onto the Pockels cells was designed, built, and tested at LLL.

The second approach to reliable short-pulse generation was to amplify the pulse from a continuous-wave actively mode-locked oscillator in a separate "regenerative amplifier" resonator cavity. A regenerative amplifier was built and experimented with at LLL. Circuits were designed to control pulse amplitude fluctuations well within the required tolerance of $\pm 5\%$. The effects of saturation, dispersion, and coherence phenomena on short-pulse amplification were studied by numerical modeling. These studies showed, and the results were confirmed by experiment, that the pulse shape was unaffected by an energy gain of 10^6 . Controlled increase or decrease of the pulse's duration by an intracavity etalon or saturable absorber was also demonstrated. This important result showed that well-synchronized, short-duration diagnostic pulses can be produced by a regenerative amplifier. Table 2-68 gives performance and reliability comparisons of the original passively mode-locked oscillator with the new actively mode-locked oscillator and regenerative amplifier.

To create complex pulse shapes, one may use

passive optical elements such as etalons and mirrors or an active element such as a Pockels cell. At this time, only the passive shaper, which coherently adds short optical pulses, can provide shaped pulses with the required risetime of about 100 ps. The theory of both the two- and four-surface coherent pulse stacker has been investigated. In addition, both types of stackers have been built, successfully demonstrated, and used for target experiments.

The major disadvantages of the passive pulse shaper are its lack of flexibility and its high loss. Both these problems can be overcome by an active pulse shaper, whose basic limitation for present target experiments is its risetime. During this year, careful risetime measurements were made for Pockels cells in a variety of electrical configurations.

The following articles in this section contain a full account of the progress made in each area: actively mode-locked Q-switched oscillator, regenerative amplifier, and passive and active pulse-shaping.

The successful development of pulse sources to meet the requirements of complex laser-fusion experiments is summarized in Fig. 2-246. The use of long pulses and "subtractive" shaping was studied. A single-mode Q-switched Nd:YAG oscillator that reliably produced 20-ns pulses was built and used to demonstrate electro-optic pulse-shaping to create pulses with risetimes greater than 300 ps. However, because of the risetime limitations, this area of research has been temporarily put aside. Instead a general philosophy has been developed which favors creating the pulses required for most laser-fusion experiments from a "master pulse" whose duration is on the order of 100 ps. The master pulse

Table 2-68. Comparative performance of three oscillator methods for producing short pulses for laser amplification

	Pulse energy (mJ)	Variation in pulse duration	Proportion of misfires	Synchronization precision
Passively mode-locked oscillator	$1 \begin{pmatrix} +40\% \\ -100\% \end{pmatrix}$	$\pm 20\%$	3/10	$\sim 5 \mu\text{s}$
Actively mode-locked oscillator	0.4 ($\pm 2\%$)	$\pm 2\%^a$	None	<50 ps
Regenerative amplifier	0.5 ($\pm 1.5\%$)	$\pm 2\%^{a,b}$	None	<10 ps

^aWithout switchout.

^bWith gain control.

will be modified by active and passive techniques to provide both the complex shaped pulses that irradiate the target and the short synchronized diagnostic pulses. The actively mode-locked, Q-switched oscillator provides the master pulse with exceptional stability in amplitude, duration, and frequency. Research has further shown that the regenerative amplifier can both compress and expand the master pulse's duration by as much as a factor of 10, and coherent pulse stackers can expand a pulse by a factor of 10 and compress it by a factor of 2. Thus, one has great flexibility in adding pulses together which have different amplitudes and durations, and also in generating a synchronized short diagnostic pulse. While these techniques will meet

near-term needs, additional experiments indicate that it may soon be possible to synchronize two separate master oscillators to within 30 ps. This achievement would be most desirable since it would make possible the creation of synchronized pulses having a wide variety of durations and frequencies.

References

133. Numerous papers have been published on this subject. The fluctuation model was first proposed by V. S. Letokhov [*JETP* 28, 562 (1969) and *JETP* 28, 1026 (1969)] and further developed by P. G. Kryukov and V. S. Letokhov [*IEEE J. Quant. Electron.* QE-8, 766 (1972)], T. J. Kuznetsova [*JETP* 30, 904 (1972)], J. A. Fleck [*Phys. Rev.* B1, 84

Fig. 2-246: Summary of developments in pulse generation and shaping in 1976.

(1970) and *Appl. Phys. Lett.* **13**, 365 (1968)], and B. Hausherr, E. Mathieu, and H. Weber [*IEEE J. Quant. Electron.* **QE-9**, 455 (1973)]. The most recent works are by W. H. Glenn [*IEEE J. Quant. Electron.* **QE-11**, 8 (1975)] and A. M. Zherikhin, V. A. Kovalenko, P. A. Kryukov, Yu. A. Matveets, S. V. Chekalin, and O. B. Shatberashvili [*Sov. J. Quant. Electron.* **4**, 210 (1974)].

134. We wish to acknowledge helpful discussions on this subject with W. D. Fountain.
135. LLL Subcontract 1547503; also see the report by D. J. Kuizenga, *Generation of Short Optical Pulses for Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-13651 (1975).
136. LLL Subcontract 5241805.

Author

W. H. Lowdermilk

2-5.2 Actively Mode-Locked and Q-Switched Oscillator

In recent years, the stability and reliability requirements of an oscillator for laser-fusion systems such as Argus and Shiva have exceeded the reasonable expectations for a passively mode-locked Nd:YAG laser. It was realized that the most promising approach to satisfy the short-pulse requirements of these systems was an actively mode-locked oscillator.¹³⁷

One approach to develop a suitable oscillator was initiated at Stanford University in 1974 (LLL subcontract 1547503) and was continued at Stanford Research Institute (SRI) through 1976 (LLL subcontract 5241805). From earlier work at Stanford University,¹³⁸ we knew that a cw mode-locked Nd:YAG laser could provide the necessary range of short pulses required for laser fusion; however, pulse energies were too low. Further work with a simultaneously mode-locked and Q-switched Nd:YAG laser¹³⁹ revealed that considerably more energy was available with this approach and that, under certain operating conditions, short transform-limited pulses could be obtained. During the development program at Stanford University and SRI we fully investigated this approach.

In September 1976 we completed a prototype laser. Measurements at SRI and LLL showed that the oscillator was very stable and reliable. This

precipitated the decision to construct this type of oscillator for the Shiva laser system. We also decided to assemble one of these oscillators at SRI for the Argus system. This oscillator was installed on Argus in January 1977 and was producing successful target shots at the writing of this report.

Theory

We have investigated the active-mode locking of the Nd:YAG laser in detail. Under steady-state condition, the pulse width, τ_p , is given by¹³⁹:

$$\tau_p = \frac{(2\ell n 2)^{1/2}}{\pi} \frac{g^{1/4}}{\theta_m^{1/2}} \left(\frac{1}{f_m \cdot \Delta f} \right)^{1/2} \quad (82)$$

where f_m is the external modulation frequency, Δf is the linewidth, g is the roundtrip amplitude gain, and θ_m is the depth of modulation. The steady-state pulse width is determined by two processes. On each roundtrip in the cavity, when the pulse passes through the amplitude modulator, it is shortened a little; this contributes the factor $(1/\theta_m f_m)^{1/2}$ to Eq. (82). As a result of the linewidth of the active medium, the pulse is lengthened a bit on each pass through the crystal; this contributes the factor $(g^{1/4}/\Delta f^{1/2})$ to Eq. (82). For typical operating conditions in a Nd:YAG laser, the shortest pulses available range from 50 to 100 ps, depending mainly on the modulation frequency and hence on the cavity length.

For longer pulses, the effective bandwidth of the laser can be narrowed with an etalon. The pulse width is then given by

$$\tau_p = \frac{(2\ell n 2)^{1/2}}{\pi} \frac{1}{\theta_m^{1/2}} \left(\frac{1}{f_m \Delta f_e} \right)^{1/2} \quad (83)$$

where Δf_e is the effective bandwidth of the laser. In terms of the reflectivity R , thickness h , and index of refraction n of the etalon, this bandwidth is given by

$$\Delta f_e = \left(\frac{c}{2\pi n h} \right) \frac{1 - R}{\sqrt{R}} \quad (84)$$

For an uncoated etalon, this becomes

$$\Delta f_g = \left(\frac{2C}{\pi h} \right) \frac{1}{n^2 - 1} \quad (85)$$

The above equations completely predict the width of the pulses in a mode-locked cw Nd:YAG laser under steady-state conditions. In such a laser, the energy for single short pulses ranges from 1 to 10 nJ, insufficient for direct injection into a typical laser fusion Nd:glass amplifier.

It is well known that a Nd:YAG laser can easily be Q-switched, allowing a peak power 10^4 times the typical cw power. However, if one considers the simultaneous mode-locking and Q-switching of a Nd:YAG laser, it appears under almost all operating conditions of the laser that steady-state, mode-locking conditions are *not* achieved. Rather, the resulting pulses are long, containing substructure.¹³⁹ The buildup time of the Q-switched laser is always too short for the mode-locking process to reach steady state. Therefore, we must devise some method to allow the mode-locking process to reach steady state before the laser is Q-switched.

Figure 2-247 shows such a method. Here, the laser is pulsed in a quasi-cw way for several milliseconds, then the loss in the Q-switch is adjusted so that the laser just exceeds threshold. During this prelude period, the modulator is on continuously, allowing the mode-locking process to reach steady state. When the laser is Q-switched at the end of the quasi-cw period, a transform-limited, stable short pulse exists in the cavity. Hence we obtain a stable Q-switched train of short pulses.

To determine the necessary duration of the prelude period, we must consider the transient buildup of the short pulses. When the laser gain exceeds threshold, two processes occur in the laser. First, the initial noisy field in the cavity passes through the modulator, which begins to shape the envelope of the short pulse. On repeated passes through the modulator, the pulse becomes shorter. At first, the gain linewidth has no effect on the pulse duration. Then, as the pulse width approaches its steady-state value, the linewidth becomes important, limiting the pulse width to the steady-state value given by Eq. (82).

The pulse width is within 5% of steady-state value after a number of roundtrips, M , where M is given by

$$M = \frac{0.38}{\sqrt{g} \theta_m} \left(\frac{\Delta f}{f_m} \right) \quad (86)$$

Fig. 2-247. Principle of operation of the mode-locked and Q-switched laser with prelude period. The long prelude period of several milliseconds allows the mode-locking process to reach steady state and hence, the initial conditions when the laser is Q-switched are stable, short, transform-limited pulses.

The ratio of the linewidth to the modulation frequency, $\Delta f/f_m$, is typically 10^{-3} : approximately the number of roundtrips required to reach steady-state mode-locking. This condition is easily satisfied during the prelude period.

The second process that occurs when the laser gain exceeds threshold is a narrowing of the spectral field width in the laser cavity with each pass through the active medium (or etalon). It is difficult to precisely analyze the narrowing process in the presence of the modulator, but two approximate conditions can be obtained. The bandwidth of the laser field is within twofold of that for a perfect, transform-limited pulse after a number of roundtrips:

$$M > \frac{0.5}{\sqrt{g} \theta_m} \left(\frac{\Delta f}{f_m} \right) \quad (87)$$

This is essentially the same as the condition in Eq. (86) above. Thus, when the pulse envelope is within 5% of the steady-state value, the spectral width of the pulse is within a factor of two of the transform limit of the steady state pulse.

An upper limit on the number of roundtrips required for perfect transform-limited pulses is essentially the same as that required by single-axial mode operation with the modulator off. This condition is given by

$$M > \frac{\ln 2}{2g} \left(\frac{\Delta f}{f_{ax}} \right)^2 \quad (88)$$

where f_{ax} is the axial-mode spacing of the cavity. For most operating conditions in a typical Nd:YAG laser, it takes a few milliseconds to satisfy this condition.

Finally, the prelude period must be long enough to let the relaxation oscillations die away after the laser exceeds threshold. This usually takes a few upper-level lifetimes of the active medium and, hence, the prelude period should be at least 0.5 to 1.0 ms for Nd:YAG. Experimentally, we find that a prelude period of 3 to 5 ms is very convenient and satisfies all the above conditions. In addition, we find that single pulse energies from 0.1 to 1.0 mJ can reasonably be expected from this type of laser, with Nd:YAG as the active medium.

Experimental Development

The major goal of this research program was to develop the necessary hardware for the Nd:YAG laser and to demonstrate the range of available pulsewidths, as well as the single-pulse energy range and amplitude and pulse-width stability of these pulses.

Early in the program, we decided to make *all* surfaces in the cavity at Brewster's angle, allowing us the following advantages:

- There could be no spurious etalon effects (such effects are probably responsible for most of the poor and anomalous behavior of mode-locked lasers).

- There would be no coatings inside the cavity, reducing the risk of optical damage to components.

- Insertion loss of all components would be very low.

- By reducing back-scatter and multiple reflection between components, the noise level between pulses would be as low as possible.

A double-ellipse pump cavity was developed for a Brewster-angle crystal. To obtain uniform cooling, the crystal and lamps were cooled with separate flow tubes and the pump cavity was flooded. We decided to use an acousto-optic modulator and Q-switch. It is well known that this modulator is acoustically resonant and can be very unstable under high rf drive conditions as a result of substrate heating from the transducer. This problem was solved by cooling the transducer directly with water.

The main advantage of acousto-optic devices was that fused quartz could be used as the substrate material. Quartz has very good optical quality and very low insertion loss and can easily be made at Brewster's angle. A typical arrangement of such a mode-locked and Q-switch laser is shown in Fig. 2-248.

During the prelude period, the laser is typically about 5% above threshold. Thus, to obtain a stable prelude, it is extremely important that all the laser parameters be very stable during this period. In particular, the signals to the Q-switch and to the modulator must be very stable; the pump power must also remain stable.

The latter requirement developed into a major problem. CW pumping was initially planned for this oscillator but because of astigmatism introduced by the Brewster's ends of the rod, thermal focusing in the rod became a severe problem. As a result of this

Fig. 2-248. Diagram of a typical mode-locked and Q-switched Nd:YAG laser with the essential diagnostics. The modulator and Q-switch are acousto-optic devices; all components in the cavity are at Brewster's angle.

astigmatism, the effective thermal focal length in the plane of the Brewster ends was decreased by n^2 , rendering cw pumping of this laser impossible. However, since the maximum repetition rate of this laser must be about 20 pps, the thermal problem can be solved by pulsing the laser. The conventional L-C discharge-type pulsed pumping was rejected for this laser because it would be difficult to obtain the required constant pump power during the prelude period. At best, it could probably only be obtained at one particular pump level. Because the required lamp currents were well within the range of available power transistors, a transistor-regulated pulser was constructed.

Several new problems were encountered. We found that the risetime of the high-pressure krypton arc lamps used in these lasers was very slow, usually a few milliseconds and was probably the result of the slow arc expansion in the lamps. Instabilities of the lamps and of the available power supply also caused problems and, eventually, a lamp driver was developed that had transistor-regulating circuits for proportional control of both the voltage and the lamp current. A schematic diagram of this lamp controller is shown in Fig. 2-249(a), where (b) presents a multiple exposure of various lamp currents. With this circuit, the short- and long-term pump-power fluctuations were less than 1%.

The first mode-locked and Q-switched laser, assembled at Stanford Research Institute, had an approximate 4.5-ns cavity roundtrip time, corresponding to a modulation frequency of 111.17

Hz. The Q-switch was driven at about 50 MHz. The modulator depth θ_m was obtained by measuring single-pass transmission at 1.06 μm . It was assumed that the modulator operated in the Bragg-diffraction region.

We also measured the threshold pump power for a range of output couplers from 0 to 50% transmission. From this measurement, we obtained the laser gain as a function of the pump power and cavity roundtrip loss. The loss was found to be 2.7%, excluding the output coupling. This indicated that very low insertion losses could be achieved with all the components at Brewster's angle. The laser was usually operated at 20 pps, and we experienced no problems due to thermal focusing in the Nd:YAG crystal.

The pulse widths obtained from this first laser were measured with an optical correlator, using type II SHG. This type of correlator has been used before,¹³⁹ but was considerably improved and automated for our latest model. A typical set of pulse-width measurements are shown in Fig. 2-250. These measurements were taken when the lamp current was 20 A. With no etalon in the resonator cavity, pulses from about 55 to 350 ps were obtained as the rf drive power to the modulator was varied.

When a 1-cm uncoated quartz etalon was placed in the cavity, 250-ps to 1-ns pulses were obtained. The range of pulses that can be obtained as a function of the rf drive for a particular setup is well defined. With strong rf drive, where the depth of modulation θ_m equals or exceeds 1, the output

Fig. 2-249. Diagram of the transistor-regulated lamp controller. Both voltage and current regulation were required to obtain stable, quasi-cw pump power. The multiple exposure of the lamp-current characteristics in (b) shows that quasi-cw operation can be achieved over a wide range of currents. Pulse width could also be adjusted from 1 to 10 ms.

Fig. 2-250. Range of short pulses available from the Nd:YAG laser for typical operating conditions. Pulses as short as 60 ps can be obtained in this short laser cavity. The entire range of short pulses can be obtained with only one uncoated quartz etalon. For this experiment, lamp current = 20 A, $g = 0.47$, $f_m = 111.17$ MHz, and output coupler = 33.5% T.

power from the laser decreases very significantly. The laser can easily drop below threshold for very strong modulation. For weak modulation, we found that at a certain level, the mode-locking becomes unstable. Also, there was a very significant noise level between the pulses and the operation of the laser deteriorated very rapidly. We determined that these two limits are about the same with or without an etalon in the cavity. Between these limits, the mode-locking was always very stable and reliable.

The experimental results in Fig. 2-250 were compared with the theoretical predictions of Eqs. (82-85). If we assume a linewidth of 175 GHz for Nd:YAG (which is somewhat larger than the more widely accepted value of 120 GHz), the theoretical prediction agrees with the experimental results. For the 1-cm etalon, the predictions of Eqs. (83) and (85) agree very well with the measured pulse widths.

Very good performance of the laser was obtained using a 33% transmitting output coupler. In this case, the optimum lamp current was about 24 A and we found about 10 short pulses in the Q-switched pulse envelope. This quantity of pulses permitted a selection of a single pulse near the center of the pulse train with nearly constant amplitude.

We measured the average power from the laser at 20 pps and recorded the pulse train with a fast detector. From these measurements, we calculated the energy of a single pulse at the peak of the pulse train. The results for various lamp currents are shown in Fig. 2-251. Pulse energies up to 400 μ J were obtained. However, we have found a rapid decrease in output energy for strong modulation which, presently, we do not understand.

Further diagnostic measurements were made. We recorded the output pulse train with a Tektronix R7912 transient digitizer; the amplitude of the largest pulse in the train was stored in a computer. Figure 2-252(a) shows a typical pulse train recording. In each data run, we recorded 500 pulse trains and a typical histogram for 500 pulses is given in Fig. 2-252(b). The width (FWHM) of the histogram is less than 3%, with no spurious pulses outside the $\pm 3\%$ range. Similar results were obtained for all pump levels well above threshold and for all modulation depths that produced good mode-locking. Streak camera measurements were also made. These measurements revealed that the pulse shape was always smooth and symmetrical and free from fine structure and double pulses.

Fig. 2-251. Energy in a single pulse at the peak of the pulse train for various lamp currents. At strong depths of modulation, there is a considerable drop in pulse energy. Pulse energies with the uncoated 1-cm etalon are approximately the same as without the etalon. Here, $f_m = 111.17$ MHz and output coupler = 33.5% T.

We also discovered that because laser operates nearly in the steady-state regime where gain equals loss during the prelude period, any pump-power fluctuation will cause an output power fluctuation; however, the gain and hence the stored energy remains constant. Thus, when the laser is Q-switched, the pulse-train envelope is very stable. This effect contributes considerably to the overall

stability of this laser. In addition, during the prelude period, the excess gain in the laser is very low (~ 5 to 10%) so transverse-mode selection is very easy. To obtain TEM₀₀ mode output, an iris is needed only for high lamp currents.

The prelude signal is also an excellent indication of how well the laser is working. Some typical prelude signals for various conditions in the laser are presented in Fig. 2-253. These levels were recorded with a slow PIN 10 diode at the high-reflector end of the laser (see Fig. 2-247). With the modulator off, as shown in Fig. 2-253(a), the relaxation oscillations are irregular as the laser exceeds threshold.

However, with good mode-locking, these oscillations do become very regular. When the cavity length is slightly longer or shorter than the optimum, the laser goes into driven-relaxation oscillations as shown in Fig. 2-253(c). For good mode-locking, the cavity length must be adjusted to within about 25 μm and, in practice, this is done by observing the characteristic prelude levels shown in Fig. 2-253.

All other measurements have shown that this alignment method gives the best performance of the laser. It is rather remarkable and extremely convenient that this laser can be set up correctly with only a slow diode and oscilloscope. Other laser conditions, such as higher-order transverse modes which occur later, above threshold, are shown in Fig. 2-253.

Fig. 2-252. Laser-stability measurements. A pulse train is recorded with a transient digitizer, as shown in (a) where the lamp current = 22 A and $\theta_m = 0.63$. The computer then records the relative amplitude of a pulse at the peak of the pulse train. The typical energy fluctuations are shown in a histogram for 500 pulses in (b). Typically, there are no pulses outside the $\pm 3\%$ range.

Fig. 2-253. Laser-prepulse conditions. The prepulse signal is a very accurate indication of the operation of the mode-locked and Q-switched laser. The prepulse signal with no modulation is shown in (a). With modulation, the relaxation oscillations become very stable, (b). A slight cavity length change ($\pm 25 \mu\text{m}$) cause driven-relaxation oscillations, (c). Other conditions such as higher-order transverse modes, (d) and cavity misalignment (e) can be identified. The relative energy in the Q-switched pulse is shown in (f). It is possible in this laser not to Q-switch at the end of the prepulse period as shown in some recordings above.

Fig. 2-254. Argus oscillator.

Fig. 2-255. Range of measured and predicted pulse widths (a) and the single-pulse energies (b) for the Argus oscillator. For this long cavity ($f_m \approx 50$ MHz), the shortest pulses available are about 110 ps. Here, lamp current = 22 A, $f_m = 49.8$ MHz, and output coupler = 33% T. The quartz etalons are uncoated.

The prelude signal also indicates other problems in the laser. Small instabilities in the Q-switch driver, that can hardly be observed on an oscilloscope, produce a very strong ringing in the prelude level. A signal generator for the modulator with short-term phase fluctuations also produces a ringing. However, when a regular stable-prelude level is obtained [Fig. 2-253(b)], we can be certain that the laser is running very well.

We decided to assemble an oscillator of this type for the Argus system. The cavity length was extended to a 10-ns roundtrip time to allow adequate time for reliable single pulse selection. The laser was mounted in an Invar-stabilized resonator, used previously at LLL. In this longer cavity, the Gaussian-beam waist was larger; thus, the laser was much more sensitive to thermal focusing in the rod. To decrease thermal loading, the repetition rate was reduced to 5 pps. In addition, the control electronics and lamp driver were further improved. The modulator and Q-switch were both driven at about 50 MHz; the Q-switch could be driven by the same rf source as the modulator. The Q-switch also opened at the same phase of the rf signal. Thus, the short pulses were synchronized with the opening of the Q-switch and hence, to the envelope of the Q-switched pulse train.

Subsequent tests on the laser showed that the laser was now stable enough so that a single pulse could be selected by counting a predetermined number of cycles of the rf drive to the modulator from the time the Q-switch was opened. We plan to use this pulse-selection method on the Shiva oscillator, allowing very good synchronization of this oscillator with other fast instrumentation on Shiva.

Figure 2-254 is a photograph of the Argus oscillator. The range of measured pulse widths as a function of the rf level setting on the signal generator is shown in Fig. 2-255(a). The shortest pulses (~ 110 ps) available from this oscillator are longer than those of the prototype because of the longer cavity. Pulse widths were measured without an etalon as well as with a 1-cm uncoated etalon. To cover the available pulse-width range (~ 110 ps to 3 ns) we needed three etalons. The predicted pulse-width range covered by each etalon is also shown in Fig. 2-255(a).

The range of good mode-locking for this laser is considerably narrower than for the prototype laser; the reason for this behavior is presently not known. We see from Fig. 2-255(b) that single short pulses of

600 μ J are available with this laser. However, the decrease of energy for strong modulator drive is more severe than for the shorter prototype laser. However, this oscillator presently is operating successfully in the high electromagnetic-noise environment of Argus and has produced successful target shots.

References

137. D. J. Kuizenga and A. E. Siegman, *IEEE, J. Quantum Electronics* QE-6, 694 (1970).
138. D. J. Kuizenga, D. W. Phillion, T. Lund, and A. E. Siegman, *Optics Comm.* 9, 221 (1973).
139. D. J. Kuizenga, *Generation of Short Optical Pulses for Laser Fusion*, Final report under P.O. 5241805 (UCLLL); Rept. 2451 (Microwave Laboratory, Stanford University); Lawrence Livermore Laboratory, Rept. UCRL-13651.

Authors

D. J. Kuizenga
W. H. Lowdermilk
J. E. Murray
S. J. Davis

Electronic Switchout

We have designed and built an electronic switchout for the new Argus oscillator. Avalanche transistor drivers are used to generate the fast-rising, high-voltage waveform for the Pockels cells. We adopted these drivers as a result of the success experienced with this type of circuit to provide the various optical-switching functions for the regenerative amplifier work. The advantages offered by the avalanche transistor drivers include synchronization, long lifetime, relatively low electromagnetic interference generation (compared to spark gaps), and simplicity of design.

A diagram of the optical components in the switchout is presented in Fig. 2-256. The multiplicity of components was required to realize adequate prepulse isolation with the minimum specifications for the Pockels cells and thin-film polarizers. Two photodiodes on the rejected pulse train provide the synchronization for the switchout as well as a monitor of the rejected train. Each Pockels cell is dual-crystal, reducing the voltage required from the drivers. Two avalanche-transistor strings (fifteen 2N5551 transistors each) are used

Fig. 2-256. Diagram of the optical components in the switchout for the new Argus oscillator.

Fig. 2-257. Flow diagram of the discriminator circuit for the Argus oscillator switchout.

with each Pockels cell. One string applies the fast-rising high-voltage and the second string cancels it.

The trigger for the avalanche-transistor drivers is synchronized by a signal derived from the rejected pulse train. When this signal reaches a preset level before the peak of the train, a comparator triggers the drivers (through the appropriate delay) and switches the peak pulse in the train. Figure 2-257 diagrams this discriminator circuitry. The pair of flip-flops is used to ensure that the timing signal is obtained from the second pulse exceeding the reference-voltage level. This eliminates jitter that could result from the slowly varying peak of the photodiode pulse if it just barely reaches the

reference level. The second pulse is at least 10% larger and thus its leading edge at the reference voltage level is well defined in time. The AND circuit allows the switchout to operate whenever an optical pulse train arrives (internal enable) or alternatively, only if an external enabling signal is also present.

We tested prototypes of the discriminator circuit and of the avalanche transistor drivers for lifetime and trigger jitter. The driver survived a 10^7 -shot lifetime test with no measurable effect on its switching characteristics. A switchout assembled from these prototypes exhibited a triggering jitter of less than ± 1 ns. In each test, the switchout selected

Fig. 2-258. Switchout assembly for the new Argus oscillator, with (a) and without (b) dust covers.

a single pulse from each of 500 consecutive shots with no switching errors; in addition, it introduced no measurable amplitude variation into the switched-out pulse.

The switchout installed on Argus (see Fig. 2-258) has measured prepulse and postpulse rejection ratios of 10^7 and 10^3 , respectively — well within our design goals. The Pockels cells each switch more than 95% of the pulse. Although loss in the cells and in the thin-film polarizers reduces transmission through the switchout assembly to about 70%, this is substantially better than our minimum design goal of 50%.

Authors

J. E. Murray

S. J. Davis

D. C. Downs

W. H. Lowdermilk

2-5.3 Regenerative Amplifier

A regenerative amplifier is a multipass amplifier in which the pulse to be amplified is injected into a resonant cavity containing the gain medium, amplified and subsequently switched out. Figure 2-259 shows a schematic of the regenerative amplifier used in the work described here. It is a simple YAG os-

cillator with two Pockels cells added which switch an external pulse into and out of the resonator.

We have demonstrated four important applications for the regenerative amplifier. First, we studied its use as a low-noise, high-gain pulse amplifier. We demonstrated that the amplified pulse energy can be held constant within 3% while the initial pulse energy varies over eleven orders of magnitude. Second, the regenerative amplifier can store an optical pulse for milliseconds with no significant pulse-shape distortion. Third, the pulse

Fig. 2-259. Schematic of regenerative amplifier showing the Q-switch Pockels cell used to trap the injected pulse and to Q-switch the cavity and the cavity-dump Pockels cell used to extract the amplified pulse from the cavity.

duration can be lengthened during amplification using an etalon in the resonator. Fourth, addition of a saturable absorber to the amplifier resonator permits pulse compression to a limit determined by the gain bandwidth. This versatility makes the regenerative amplifier a very useful and important building block for the pulse-generating systems of Shiva and Shiva Nova fusion lasers.

Theoretical Considerations

We performed detailed modeling of the regenerative amplifier to identify possible sources of pulse-shape distortion which might result from the large amplifications available. In particular, the effects of dispersion, gain narrowing, coherent interactions of the pulse and gain medium, and amplification off line center were studied. To model these effects, the regenerative amplifier was treated as a traveling-wave amplifier through which the injected pulse made many passes. The amplitude and shape of the optical pulse were calculated during its amplification by solving the equations of coherent resonant propagation.¹⁴⁰ These equations describe response of the material polarization, the population inversion, and the electric-field amplitude. These equations were solved numerically¹⁴¹ for each pass through the amplifier. The results showed that a YAG regenerative amplifier does not distort the pulse shape for the range of operating parameters and for injected pulse durations of interest. This is an important property of the cw oscillator-regenerative amplifier system; namely, that without additional cavity components, the temporal properties of the output pulse are determined by the injected pulse and are independent of the regenerative amplifier.

With this result, the waveform characteristics of the regenerative amplifier output could be determined by simplifying these equations to those for a Q-switched oscillator. The following analytic solution gives the peak energy of the regenerative amplifier output¹⁴²:

$$\phi_p - \phi_i = \gamma[\eta - 1 - \ln \eta] , \tag{89}$$

where ϕ_p and ϕ_i are, respectively, the normalized energies in the pulse at its maximum and at injection, γ is the single-pass cavity loss, and η is the

ratio of initial population inversion to that required for threshold.

Equation (89) was differentiated to obtain the stability of the output energy to fluctuations in gain and loss. Defining ΔJ as the percentage change in output energy resulting from a percentage change Δg in gain or $\Delta \gamma$ in loss,

$$\begin{aligned} \frac{\Delta J}{\Delta g} &= \frac{\eta - 1}{\eta - 1 - \ln \eta} , \\ \frac{\Delta J}{\Delta \gamma} &= \frac{\ln \eta}{\eta - 1 - \ln \eta} . \end{aligned} \tag{90}$$

These relationships are plotted in Fig. 2-260. Also shown is the dependence from Eq. (89) of the peak energy density in the regenerative amplifier on η , where

$$J = \int_{\text{pulse}} I \, dt = (\hbar \omega / \sigma) \phi_p ,$$

Fig. 2-260. Rate-equation solutions for the peak pulse energy in the regenerative amplifier and its output energy stability to gain and loss variations: J is the peak energy density in the amplified pulse; γ is the single-pass exponential cavity loss; ΔJ is the percent energy change for a percentage gain change of Δg or loss change of $\Delta \gamma$; and η is the ratio of the population inversion at Q-switch opening to that required for threshold.

σ = transition cross section, and it is assumed that $\phi_i \ll \phi_p$.

Since ϕ_i/ϕ_p is on the order of 10^{-3} for conditions of interest, Eq. (89) indicates a second important characteristic of the cw oscillator-regenerative amplifier system: the output pulse energy and, therefore, the energy stability are determined entirely by the regenerative amplifier and are independent of the cw oscillator. Thus, this type of pulse-generation system separates the amplitude and temporal formation of the pulse, allowing separate optimization.

Experimental Apparatus

A cw mode-locked YAG oscillator from Quantronix Corporation provided the injection pulse for the regenerative amplifier. The oscillator delivered pulses at a repetition rate of 100 MHz and easily achieved 1 W of average output power. The pulse width was adjustable from about 100 ps to greater than 1 ns by varying the rf drive level to the modulator and by the use of various intracavity etalons.

A single pulse was selected from the output of the cw oscillator by use of an optically synchronized switchout which we designed and built. Two avalanche transistor chains applied, and removed, 3 kV to a single crystal, KD*P (potassium dideuterium phosphate) Pockels cell mounted between crossed polarizers. The total on-to-off time was less than 15 ns. A photodiode, monitoring the beam rejected by the polarizers, provided the synchronizing signal. This switchout reliably selected about half of one mode-locked pulse and had a pre- and post-pulse rejection ratio of about 10^3 which was limited by the quality of the polarizers and Pockels cell.

The fraction of selected pulse energy coupled into the resonator of the regenerative amplifier was determined by alignment and by mode-matching of the injected pulse to the resonator's eigenmodes. The alignment and mode-matching accuracy required to achieve a given coupling efficiency was calculated for TEM₀₀-mode beams with the following results:

$$A_{\omega,\delta} = 4 \left[\frac{\omega_1 \omega_2}{\omega_1^2 + \omega_2^2} \right]^2 \frac{1}{1 + \left[\frac{\lambda \delta}{\pi(\omega_1^2 + \omega_2^2)} \right]^2}, \quad (91)$$

$$A_\epsilon = \exp \left[- \frac{2\epsilon^2}{\omega^2} \right], \quad (92)$$

$$A_\phi = \exp \left[- \phi^2 (\pi\omega/\lambda)^2 \right], \quad (93)$$

where

$A_{\omega,\delta}$ = fraction of injected pulse energy coupled into the regenerative amplifier with perfect alignment but a mismatch of beam properties ω and δ ;
 A_ϵ = fraction coupled with perfect mode-matching, perfect angular alignment, but a translational misalignment of ϵ between the injected beam axis and that of the resonator;

A_ϕ = fraction coupled with perfect mode-matching, perfect translational alignment, but an angular misalignment of ϕ ;

ω = beam radius at a waist;

δ = position error of the two beam waists measured along the beam direction;

ϵ = position error in overlapping the two beam axes in the transverse direction;

ϕ = angular error in overlapping the two beam axes.

For a typical TEM₀₀ beam radius of 1 mm in the regenerative amplifier, we obtained [Eqs. (91-93)] the following tolerances for mode-matching and alignment of the injected TEM₀₀ pulse required to couple at least 90% of its energy into the TEM₀₀ mode of the regenerative amplifier cavity:

$$0.72 \leq \omega \leq 1.39 \text{ mm},$$

$$\delta \leq 65 \text{ cm},$$

$$\epsilon \leq 0.3 \text{ mm},$$

$$\phi \leq 0.1 \text{ mrad}.$$

Matching of the beam radii and waist locations to these tolerances was done with lenses by use of the standard transformation formula for Gaussian beams.¹⁴³ Overlapping the axes to these tolerances was a relatively easy alignment task.

A schematic of the experimental regenerative amplifier is shown in Fig. 2-259. The optical resonator consisted of a spherical mirror, with an effective 2.5-m radius and coated for maximum reflectivity at $1.06\text{ }\mu\text{m}$, and a flat mirror. Initial alignment of the cavity mirrors was easily performed using the cw mode-locked laser pulses. The Nd:YAG rod ($1/4 \times 3\text{ in.}$) was mounted at Brewster's angle and pumped by two linear flashlamps in a dual-ellipse cavity. The flashlamps were simmered with a current of 150 mA to reduce shot-to-shot fluctuations in the pump energy. The oscillator was prevented from lasing prior to pulse injection by applying the quarter-wave voltage to the Q-switch Pockels cells. The cavity-dump Pockels cell was used to switch the amplified pulse out of the oscillator cavity. Both were single-crystal KD*P units driven by avalanche transistor circuits similar in design to those for the single pulse selector mentioned in Sec. G. The Q-switch was triggered directly from the single pulse selector. The cavity dump was triggered by a threshold circuit which monitored the pulse buildup in the regenerative amplifier. Thin-film polarizers were used to inject and extract the pulse from the regenerative amplifier resonator.

Considerable care was taken to ensure that light reflected from the various surfaces of the Pockels cells would not remain in the oscillator cavity. Without this care, the amplified pulse became modulated and distorted even by extremely weak etalon effects. For example, with a KD*P crystal ($n = 1.48$), polished parallel and in an index-matching fluid with $n = 1.28$, the first echo pulse trailing the main pulse was down in energy by a factor of about 3×10^{-5} . Experimentally, we found that etalon effects of this strength resulted in total pulse breakup for 100-ps injected pulses after a few roundtrips. For pulse shortening where the maximum gain bandwidth was needed, a much weaker effect than the above would dominate the final pulse width.¹⁴⁴

To avoid this effect, the cell windows and crystal surfaces were wedged so that no two surface normals were aligned with each other or with the beam path to within $1/2^\circ$. The outside window surfaces were AR (antireflection) coated and the cells were filled with a Cargille fluid with $n = 1.48$. In this fluid, absorption at $1.06\text{ }\mu\text{m}$ required chopping the cw mode-locked YAG beam to prevent thermal blooming when the full cw beam was used for alignment without pulse selection.

System Operation

Amplification. A typical set of operating characteristics for the regenerative amplifier was as follows: (1) single pass cavity loss $= \gamma = 0.25$, (2) TEM_{00} beam area in YAG $= 2.0\text{ mm}^2$, and (3) number of times over threshold $= \eta = 2.0$. This gave about 0.5 mJ in the switched-out pulse and a FWHM pulse envelope of about 200 ns.

Amplitude Stability. To demonstrate that the output pulse energy from the regenerative amplifier was independent of the input, the peak energy in the regenerative amplifier was monitored while the input was varied from 10^{-4} to 10^{-17} J . The results, shown in Fig. 2-261, confirm this independence over almost eleven orders of magnitude of input pulse energy. This variation of injected energy was obtained with Nd filters calibrated at $1.06\text{ }\mu\text{m}$ with the cw mode-locked laser. The energy range below 10^{-9} was obtained using the cw mode-locked oscillator. To obtain the higher injected pulse energies, we used a single pulse from a passively mode-locked oscillator. The high-energy end of the range was limited by the available energy storage in the YAG: when the input pulse energy was comparable to the stored energy in the YAG, the output was no longer independent of the input. The lower end of the range was limited by competition with spontaneous

Fig. 2-261. Experimental data for peak pulse energy in the regenerative amplifier as a function of injected pulse energy.

emission noise energy from the YAG amplifier. Injection locking was detectable with injected energies as low as 10^{-17} J, but the final energy in the locked pulse decreased for values below 10^{-15} J, because the available stored energy was shared between the pulse and the amplified spontaneous noise power.

The interpulse noise level at the time of maximum output energy was calculated by assuming uniform distribution of spontaneous emission noise over the gain bandwidth of the YAG amplifier. The frequency filtering effects of the resonator and the effects of gain narrowing were considered with the following result:

$$E_N = \frac{h\lambda L}{\sigma\tau\pi} \sqrt{\frac{g}{N\pi}} \frac{1}{\sqrt{1 + (2\mathcal{F}/\pi)^2}} \quad (94)$$

where

h = Planck's constant

λ = laser wavelength

σ = stimulated emission cross section

τ = radiative lifetime

L = optical length of resonator

g = single-pass exponential gain of YAG rod

N = number of passes through rod

$\mathcal{F}$ = finesse of resonator at time of maximum output energy.

This predicts a noise energy of about 7×10^{-18} J for the conditions of Fig. 2-261, which is in reasonable agreement with the value deduced from the data, i.e., $E_N = 2 \times 10^{-18}$ J.

The energy of the amplified pulse was measured for 500 consecutive shots. We found the maximum variation from the average to be 5%. Since the output pulse energy is independent of the initial pulse energy, these fluctuations resulted from gain and loss variations in the regenerative amplifier. To determine the importance of gain fluctuations, we monitored the YAG amplifier fluorescence at $1.064 \mu\text{m}$ to obtain a direct indication of flashlamp output and rod gain. With a digital processing system, the output pulse energy and the fluorescence intensity just prior to Q-switching were recorded for a large number of shots. The results indicated that most of the observed variations in output energy were caused by variations in the flashlamp output. The magnitude of the flashlamp variation was of the order of 2% peak to peak for new lamps (approx-

Fig. 2-282. Histograms showing peak energy in the regenerative amplifier: (a) without stabilization, and (b) with stabilization. Both cases are for 500 consecutive shot samples at the same average output energy. The data of (a) were obtained by triggering the Q-switch, after a fixed delay, from the lamp fire trigger. For the data of (b), the Q-switch was triggered by the gain stabilization circuit. The standard deviations for the "without" and "with" samples are 1.265 and 0.434, respectively. There were no pulses outside the range of the histograms in either case.

imately 10 J per lamp with a 150-mA simmer current), and it increased to 5% or more as the lamp aged.

We circumvented this problem by triggering the Q switch (and pulse injection) when the gain in the regenerative amplifier reached a fixed reference level. This was done by monitoring the fluorescence at 1.06 μm from the YAG and comparing it to a constant but adjustable reference level. When the fluorescence signal crossed the reference level with decreasing slope, the Q-switch was triggered. This technique allowed us to bypass the lamp stabilization problem. Under normal operating conditions when the fluorescence amplitude fluctuations are a few per cent, our gain stabilization circuit will adjust the Q-switch time so that the gain, just prior to Q-switching, fluctuates by less than 0.25%. This gain stability limit results from noise on the fluorescence signal input to the level sensing circuit.

Figure 2-262 shows histograms of peak energy in the regenerative amplifier with and without this gain stabilization circuit. The "without" data were obtained by Q-switching, after a fixed time delay, from the trigger which fired the lamps. Each sampling consisted of 500 consecutive shots with the same average pulse energy and without switchout. These data show a three-fold improvement with the circuit, both in total fluctuations, 7.9% to 2.7 %, and in standard deviation, 1.265% to 0.434%.

Pulse Width Stability. The pulse width stability of the amplified output pulse is determined by the stability of the injected pulse and the stability of any temporal effect caused by the amplification process in the regenerative amplifier. The theoretical studies discussed above indicated that the regenerative amplifier would introduce no temporal changes for input pulse widths down to about 100 ps. This result was confirmed experimentally by using a sampling scope to measure the input pulse width and a streak camera to measure the amplified pulse width. No change was detected ($\pm 5\%$) between input and output down to a pulse width of 100 ps, the shortest pulse generated by our cw mode-locked oscillator.

Pulse Storage. In addition to pulse amplification, the regenerative amplifier could be used to store pulses. Storage times of several microseconds were demonstrated with no attempt made to optimize the system for storage. By increasing cavity length and operating closer to threshold, we could easily achieve storage times in excess of 10 μs . This storage capability is potentially useful for construction of complex pulse shapes and for generating synchronized diagnostic pulses.

Pulse Lengthening. The amplified pulse width was

Fig. 2-263. Amplifier gain line of the regenerative amplifier showing the effect of an intracavity etalon. Also shown is the spectrum of an injected pulse which is centered on a transmission maximum of the etalon for optimal lengthening of its pulse width in time.

increased over that of the injected pulse by decreasing the gain bandwidth of the regenerative amplifier. This was accomplished experimentally by introducing an etalon into the regenerative amplifier resonator.¹⁴⁵ The effect of this etalon is illustrated in Fig. 2-263. Its periodic resonances modulate the net gain in the cavity as shown. By tuning the angle of the etalon to shift this modulation in frequency, one of the maxima was centered on the injected pulse spectrum. This was done experimentally by tuning for maximum energy out. As long as the full spectrum of the injected pulse fell within one modulation period of the etalon, the pulse was amplified with an effective gain bandwidth determined by one cycle of the modulation. The depth and frequency of this modulation was adjusted by varying etalon thickness and reflectivity. With this technique, pulse stretching by as much as a factor of seven was demonstrated.

This method of pulse lengthening was treated analytically, assuming Gaussian input and output pulses and ignoring gain saturation. The following relationship was obtained

$$\tau_f^2 = \tau_i^2 + (16 \ln 2) N \left[\frac{g}{(\Delta\omega_a)^2} + \left(\frac{\mathcal{F}d}{\pi c} \right)^2 \right] \quad (95)$$

where τ_i and τ_f are the input and final pulse widths (FWHM) after N passes through the amplifier which had an exponential gain of g and a radian frequency bandwidth of $\Delta\omega_a$, $\mathcal{F}$ is the finesse of the etalon, and d is its optical thickness.

Pulse Shortening. The output pulse width was shortened by the action of a bleachable dye in the regenerative amplifier cavity. As the pulse is amplified through the nonlinear transmission region of the dye, the dye attenuates its leading and trailing edges more than its peak, resulting in a shortened pulse. Since the shortening occurred only when the pulse amplitude is in the nonlinear region of the dye, the greatest shortening occurs when the pulse amplitude is held in this range as long as possible. However, in this nonlinear range of the dye, the cavity loss is continually decreasing, thereby increasing the net gain and accelerating the rate of growth of the pulse. Thus, the nonlinearity of the dye also makes the final pulse width very sensitive to the initial conditions of the regenerative amplifier.

For calculations, a dye model was added to the single-pass amplifier model mentioned above. The model assumed a four-level dye with an unsaturable excited-state absorption as well as the usual saturable absorption. Ignoring the finite relaxation times of the dye transitions, the dye cell transmission assumes the form¹⁴⁶

$$T(t) = T_0 \left[\frac{1 + J(t)}{1 + J(t)T(t)} \right]^{\gamma-1}, \quad (96)$$

Fig. 2-264. Theoretical results showing pulse shortening with a bleachable dye in the regenerative amplifier cavity. This example is for a small-signal dye transmission of 40%, a single-pass cavity loss of 60% excluding the dye, and an initial net gain of 4.7% per pass.

Fig. 2-265. Theoretical results for pulse shortening showing the variation of final pulse width and peak pulse energy with initial net gain in the regenerative-amplifier. This example is for a single-pass cavity loss of 60% and three values of T_0 , the small-signal dye transmission.

where

$T(t)$ = transmission ratio = ratio of output to input intensities,

T_0 = small-signal transmission,

$J(t) = I(t)/\gamma I_s$,

$I(t)$ = input intensity.

I_s = saturation flux,

γ = ratio of the unsaturated absorption coefficient from the ground state to the absorption coefficient from excited state.

For Kodak 9860 dye, $I_s = 56 \text{ MW/cm}^2$ ¹⁴⁷ and $\gamma = 8.8$. With this dye model, numerical integration of the amplifier equations indicated that pulse shortening from 200 ps to about 30 ps should be possible. However, the process of shortening to this degree was extremely sensitive to gain, cavity loss, and small-signal dye transmission.

To understand these dependencies without excessive use of this very detailed code, we wrote a simpler code which treated the amplifier in the rate-equation approximation, ignoring its finite gain

Fig. 2-266. Streak-camera records showing the pulse lengthening and shortening that has been achieved experimentally starting with a 200-ps pulse. The series of images is created by a mirror pair for calibration purposes. Successive echo pulses are reduced in intensity by a factor of two.

bandwidth. Also, the dye was treated as a two-level system. Figure 2-264 shows an example of these calculations. The energy flux (log scale) and the pulse width are plotted against the number of round trips in the cavity. At first the energy grew exponentially. Then its rate slowed because of gain saturation prior to bleaching of the dye. Finally, the pulse saturated the dye and grew at a faster exponential rate until it had used all the available amplifier energy. This calculation (Fig. 2-264) showed a final pulse width of less than 20 ps for a 200-ps input pulse. A surprising prediction of this code was that substantial pulse shortening occurs at fluxes well below the saturation flux of the dye. In this example, the first factor-of-two shortening has already occurred when the pulse amplitude reaches $I^*/10$.

Figure 2-265 shows the code predictions for final pulse width and energy as functions of initial net cavity gain. Results are shown for three values of small-signal dye transmission and a single-pass cavity loss of 60%, excluding loss in the dye. There is a definite threshold value of the small-signal dye transmission above which substantial shortening does not occur for any value of initial gain. This threshold level was found to be a function of the cavity loss. For the example of Fig. 2-265, with

cavity loss = 60%, the threshold value of small-signal dye transmission was between 60% and 70%.

Experimental shortening from 200 to 30 ps has been demonstrated with the same qualitative behavior shown in Fig. 2-265. Figure 2-266 shows streak camera records of the maximum and minimum pulse widths achieved, starting with a 200-ps injection pulse. Thus, one cw oscillator providing injection pulses at 200 ps could be used to feed two regenerative amplifiers: one, for shortening the pulse to obtain a diagnostic pulse, and the second, for lengthening to the desired pulse width for target illumination.

References

140. R. H. Pantell and H. E. Puthoff, *Fundamentals of Quantum Electronics* (John Wiley & Sons, Inc., New York, 1969), p. 40.
141. The analysis was performed by A. J. Glass, and the computer code was written by P. A. Renard.
142. W. G. Wagner and B. A. Lengyel, *J. Appl. Phys.* **34**, 2040 (1963).
143. H. Kogelnik and T. Li, *Proc. IEEE* **54**, 1312 (1966).
144. D. J. Kuizenga and A. E. Siegman, *IEEE J. Quantum Electron.* **QE-6**, 709 (1970).
145. D. J. Kuizenga and A. E. Siegman, *IEEE J. Quantum Electron.* **QE-6**, 694 (1970).

146. M. Herscher, *Appl. Opt.* 6, 947 (1967).
 147. Eastman Kodak Co. Data Release, *Eastman Products for Laser Systems*. (Eastman Kodak Co., Rochester, New York), Minor Revisions E (1970).

Authors

W. H. Lowdermilk
 J. E. Murray
 D. C. Downs

2-5.4 Passive Pulse Shaping by Coherent Pulse Addition

The passive pulse-shaping program in 1976 tested and implemented devices capable of generating pulse shapes significant for target implosion experiments. These devices have been developed for the first shaped-pulse experiments that will be performed on the Argus laser system early in 1977 and on the Shiva laser system in 1978. For advanced systems such as Shiva and its upgrades, very com-

Fig. 2-267. Example of a proposed pulse shape for Shiva target experiments. The individual rectangular steps may be separated from adjacent steps.

plex and yet undefined pulse shapes will be required. Figure 2-267 shows an example of a pulse shape that could be used on Shiva. The super-exponentially rising pulse of Nuckolls and Wood¹⁴⁸ has been approximated by a series of impulsive rectangular steps to circumvent instabilities in the plasma compression due to surface finish variations in target shells.¹⁴⁹

The basic technique for achieving such complex pulse shapes is the coherent superposition of many replicated Gaussian laser pulses; the original pulse is generated by the mode-locked, Q-switched master oscillator. The basic principles are generation of single transform-limited Gaussian laser pulse, amplitude division of this pulse into many replicas, time delay and attenuation of each individual pulse, and coherent recombination into the final shaped pulse. This technique is a variation of more familiar multiple-beam interferometry.

Pulse Stretching with a Fabry-Perot Interferometer

The simplest possible pulse stacker is the Fabry-Perot interferometer. Two partially transmitting mirrors are separated by a distance d . The delay time between two successive pulses formed by multiple reflections is then $\Delta\tau = 2d/c$. The ratio in intensity between two successive pulses is given by the product of the mirror reflectivities R_1 and R_2 . For the general case of a time-dependent input pulse given by $a(t) = e^{-i\omega_0 t} f(t)$, the output intensity is given by

$$I(t) = (1 - R)^2 \left[\sum_{m=0}^{\infty} R^m e^{-i\omega_0 m \Delta\tau} f(t - m \Delta\tau) \right] \times [\dots]^* \quad (97)$$

where $R = R_1 = R_2$ is the mirror reflectivity. $I(t)$ is a superposition of delayed, attenuated pulses, and only an output pulse of decaying intensity in time can be produced. Using a Gaussian input pulse,

$$f(t) = e^{-2\ln 2(t/w)^2} \quad (98)$$

with w equal to the intensity FWHM we require $\omega_0 \Delta\tau = 2n\pi$ so that the transmitted pulses are in phase. Figure 2-268 shows the predicted output pulse shapes for $R = 0.95$. In this figure, the curves are normalized to the peak intensity and the time to t/w . Figure 2-269 shows the output pulse FWHM for various mirror reflectivities, and Fig. 2-270 shows the peak intensity expected for values of the stretching parameter $\Delta\tau/w$.

This technique is particularly useful for generating a long, bell-shaped pulse from a short-duration Gaussian pulse. Figure 2-271 shows reticon streak camera traces of the input and output pulses derived from a passively mode-locked oscillator. Before development of an actively mode-locked oscillator, Fabry-Perot pulse stretching was the only practical way to generate fairly long (500-1000 ns) pulses using the available passively mode-locked oscillator. By adjusting the Fabry-Perot mirrors for destructive interference [$\omega_0 \Delta\tau = (2n + 1)\pi$ in Eq. (97)], pulse shortening or differentiation of up to 30% can occur.¹⁵⁰ This has been observed experimentally.¹⁵¹ A feature of this technique more important for general use is that the output pulse is determined by the spectral characteristics of the input pulse. A transformation-limited pulse will obey the following relation:

$$\Delta\lambda\Delta t = (\lambda^2/c) \frac{2\ell n^2}{\pi} = 0.441 (\lambda^2/c), \quad (99)$$

where $\Delta\lambda$ and Δt are the spectral and temporal half-widths. It can be shown¹⁵⁰ that in a Fabry-Perot interferometer with 0.95 reflectivity mirrors, $\Delta\lambda\Delta t \approx 0.50 (\lambda^2/c)$, and for 0.99 reflectivity mirrors, $\Delta\lambda\Delta t \approx 0.46 (\lambda^2/c)$. Thus, a smoothly varying output pulse with the correct duration from a Fabry-Perot interferometer implies that the input pulse is nearly band-width limited and "stackable."¹⁵¹ This technique is now being used to determine oscillator pulse characteristics.

Double-Etalon Pulse Shaper

The pulse shaper developed to produce rectangular shapes required for future target experiments is shown schematically in Fig. 2-272. This device was designed after studying four-mirror¹⁵² and double solid etalons.¹⁵¹ The two tilted etalons are formed between the two outside 100% reflectivity mirrors and the wedge. This configuration has several advantages: (1) minimum material in the optical path; (2) maximum pulse-shape flexibility with

Fig. 2-268. Pulse shapes from a Fabry-Perot interferometer used to stretch a Gaussian input pulse of FWHM w . The round trip time between the mirrors is $\Delta\tau$. For these calculations, $R = 0.95$.

Fig. 2-269. Output pulse FWHM/w vs normalized delay time $\Delta\tau/w$ for various mirror reflectivities. Note that a given stretch (FWHM/w) can be achieved a number of ways.

Fig. 2-270. Output-pulse peak intensity vs delay time $\Delta\tau/w$ for different mirror reflectivities.

(a) | ← 525 ps

(b) | ← 525 ps

Fig. 2-271. Input (a) and output (b) for a Fabry-Perot pulse stretcher using a Reticon array streak camera. The input pulse FWHM is 325 ps, the output pulse is 760 ps. The noise on the pulses is due to electronic processing.

minimum adjustments; (3) fairly inexpensive construction compared with four-mirror or double-etalon devices. This technique has been reported previously^{151,152}, and a brief review of its operation is given here.

For the device of Fig. 2-271, the time delay between successive pulses is

$$\Delta\tau = \frac{2d_1}{c} \left[\frac{1}{\cos\theta_1} - \frac{\tan\theta_1 \sqrt{n^2 - \sin^2\theta_1}}{n^2 \sin\theta_2 \cos\theta_2} + \tan\theta_1 \left(\tan\theta_2 \sqrt{n^2 - \sin^2\theta_1} - \sin\theta_1 \right) \right] \quad (100)$$

The relative intensity between adjacent pulses is given by $\alpha = R_1/R_2$, so that rising output pulses can also be produced. For rectangular pulses, $R_1 = R_2 = R$. For maximum transmission, $R = (N-1)/(N+1)$, where N is the number of output pulses. The output amplitude for a time-dependent input pulse is

$$B(t) = t_1 t_2 e^{+i\omega_0 t} \frac{r_2^N}{r_1} \sum_{m=1}^N \left(\frac{r_1}{r_2} \right) n_e^{-i\omega_0 m \Delta\tau} f(t - m\Delta\tau), \quad (101)$$

Fig. 2-272. Wedge dual-mirror double-etalon pulse stacker. For the device under consideration, $n_4 = n_3 = n = 1.451$, $n_1 = 1.000$, $R_1^* = R_2^* = 1.00$.

Fig. 2-273. Calculated output pulse shape for a 10-beam pulse stacker with $R_1 = R_2$ and a Gaussian input pulse.

Fig. 2-274. Stacker output-pulse peak intensity normalized to the input pulse versus delay time and the number of beams.

where r_1, r_2, t_1, t_2 are the reflectances and transmittances of the surfaces of the wedge. The intensity transmission for coherent pulse addition ($\omega_0 \Delta \tau = 2n\pi$) is

$$I(t) = (1 - R_1) (1 - R_2) \left(\frac{R_2}{R_1} \right)^N \left[\sum_{m=1}^N \left(\frac{R_1}{R_2} \right)^{m/2} f(t - m\Delta\tau) \right]^2 \quad (102)$$

Figure 2-273 shows the output pulse normalized to the input for $N = 10$ for the Gaussian input pulse of the last section, as a function of t/w and $\Delta\tau/w$. Figures 2-274 and 2-275 show the peak intensity and energy output for rectangular pulses composed of up to 20 separate pulses. The points labeled with values of α (an exponentially rising pulse) are for a 10-beam pulse stacker. Although the energy transmission (efficiency) is greater than 12% for a 10-beam stacker, the intensity transmission is only about 1.2% for an output pulse whose length is 10 times the input pulse length.

Figure 2-276 shows the present pulse stacker. The device is a modified commercial Fabry-Perot interferometer. Figure 2-277 shows the input and output pulse for this nine-beam device using a mode-locked cw laser as an input. The Gaussian input pulse width (FWHM) is 350 ps, and the output pulse width is 1.49 ns. The theoretical output pulse width is calculated to be 1.55 ns for the spacings, angles, and number of beams used.

The complex pulse shapes of Fig. 2-267 can be generated by a sequence of passive pulse stackers, as in Fig. 2-278. Quarter wave plates and polarizing beam splitters provide lossless amplitude variations among the component pulses. A very simple version of this scheme will be used for the first controlled shaped-pulse experiments on Argus early in 1977. This pulse will consist of a 1- to 2-ns rectangular pulse followed by a 300- to 400-ps Gaussian pulse with as much as a 1:100 difference in intensity.

Polarizing Beam-Splitter Stacker

A very promising alternative to the double-etalon pulse stacker is a technique proposed by H. E. Bates of Florida Technological University.¹⁵³ The original

Fig. 2-275. Stacker output-pulse energy normalized to the input pulse versus delay time and the number of beams.

Fig. 2-276. Prototype wedge dual-mirror pulse stacker.

device consisted of a series of birefringent optical elements that delayed orthogonal polarizations of light by different amounts due to large differences in the refractive indices. By placing several elements of various thicknesses in series separated by rotation plates and/or polarizers, a large variety of pulse shapes including rectangular pulses could be produced. A disadvantage of using birefringent material is the relatively small delays achievable with birefringent materials of suitable optical quality. Calcite, for example, will delay two orthogonally polarized pulses at the rate of only 5.4 ps/cm, so a very long path of calcite is necessary for the interpulse delays contemplated for Shiva pulse shapes (100 to 300 ps).

The optical equivalent of birefringent crystal is a

version of the Michelson polarizing interferometer, such as that shown in Fig. 2-279. By placing the two mirrors at varying distances from the polarizing beam splitter, we can generate a very large delay time per stage. By arranging several of these devices in series separated by variable rotators (or folding the optical paths so that many passes can be made using a single beam splitter), we can produce a large number of possible pulse shapes. With partial funding from LLL, Bates has developed computer codes that can predictably generate pulses of more or less arbitrary shape from these birefringent pulse stackers.

The biggest single advantage of this technique over that of the double etalon stacker is the potentially higher efficiency. Multiple polarizing beam

(a)

(b)

Fig. 2-277. Input pulse (a) 350 ps FWHM and output pulse (b) 1.49 ns FWHM from the nine beam device in Fig. 2-276.

splitters offer energy transmissions of slightly less than 50%, regardless of the number of stages. The maximum number of beams in a practical double-etalon stacker is about 10, which gives an energy

transmission of 12%. This increase in efficiency would allow smaller system impact and encourages further development of polarizing beam-splitter pulse stackers.

Fig. 2-278. Multiple-pulse stacker configuration for generating a four-level pulse. S1, S2, S3 are pulse stackers; B1, B2, B3 are polarizing beam splitters. Intrapulse levels are set by rotating the wave plates.

Fig. 2-279. One stage of a proposed multiple polarizing interferometer pulse stacker.

References

148. J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, *Nature* (London) **239**, 139 (1972).
149. J. D. Lindl and W. C. Mead, *Phys. Rev. Lett.* **34**, 1273 (1975).
150. W. E. Martin, *Pulse Stretching and Spectroscopy of Sub-nanosecond Optical Pulses Using a Fabry-Perot Interferometer*, Lawrence Livermore Laboratory, Rept. UCRL-78936, Preprint (1976); (to be published in *Optics Communications*).
151. W. E. Martin and D. Milam, *Appl. Opt.* **15**, 3054 (1976).
152. C. E. Thomas and L. D. Siebert, *Appl. Opt.* **15**, 462 (1976).
153. H. E. Bates, Final Report on P. O. 3940803 from LLL (Nov. 26, 1976).

Authors

W. E. Martin
D. Milam

2-5.5 Active Pulse Shaping

As an alternative to passive pulse-shaping techniques (§ 2-5.4), we considered Pockels cell active pulse shaping. This approach is based on the fact that optical transmission of a linear electro-optic (EO) material when placed between crossed

polarizers, is a function of applied voltage through the relationship

$$T(\vec{r}, t) = T_0 \sin^2 \frac{\pi V(\vec{r}, t)}{2V_\pi}$$

where T_0 ($0 \leq T_0 \leq 1$) accounts for optical insertion loss (typically a few percent), and V_π is the voltage that must be applied to change the plane of polarization by 90° . V_π is a function of wavelength and material and has a value of about 7 kV for $1.06\text{-}\mu\text{m}$ light in the EO crystal KD_2PO_4 (KD*P). The extent to which active pulse shaping is successful depends on the ability to apply the appropriate voltage waveform, $V(\vec{r}, t)$, to the Pockels cell optical switch.

Active pulse shaping with Pockels cells potentially offers the advantages of high optical transmission and flexibility in tailoring pulse shapes. As an example, the calculated peak-pulse transmission for a Pockels cell shaper producing the pulse of Fig. 2-280 is 0.52. A passive pulse shaper producing the same pulse would have a peak-pulse transmission of 0.04. This potential advantage is largely lost if the individual steps of the pulse are separated in time. In this case, the passive shaper remains at 0.04 transmission, but the Pockels cell shaper drops to

0.09 transmission for the configuration we will discuss. Flexibility and transmission thus depend on the details of the desired pulse shape.

The basic idea behind active pulse shaping is to use the Pockels cell as a voltage-controlled, variable-transmission optical shutter. Since $I_{out}(t) = I_{in}(t) \cdot T(r,t)$, an output pulse of virtually any shape can, in principal, be gated out of a longer input pulse. At present, use of this technique is limited by lack of a reliable means for generating the required shaped voltage pulses and by the optical risetimes of available Pockels cells.

Example of Pockels Cell Active Pulse Shaping

An example of a two-element Pockels cell pulse

shaper is shown in Fig. 2-280(a). The device consists of two stages of optical switching and operates as follows. An incident optical pulse of about constant intensity passes through stage 1, which consists of a Pockels cell (PC1) between crossed polarizers. Initially, no voltage is applied to PC1 or PC2, so P2 rejects all of the light input. At a predetermined time, PC1 is switched to its half-wave voltage; it then transmits nearly all the incident light intensity into stage 2. This stage consists of a quarter-wave ($\lambda/4$) plate, a second Pockels cell (PC2), and an output polarizer (P3) that is crossed with P2. By applying a single, time-delayed rectangular voltage pulse to both Pockels cells, as shown in Fig. 2-280(b), it is possible to generate a "stairstep" pulse of the general form of I_5 in Fig. 2-280(b) at the output of polarizer P₃. The total duration and relative time

Fig. 2-280. A two-element Pockels cell active pulse shaper: (a) long laser pulse incident from left passes through sequence of polarizers (P1-3), Pockels cells (PC 1-2), and a quarterwave retardation plate ($\lambda/4$); (b) pulse time history. V_{PC1} and V_{PC2} are the voltages applied to PC1 and PC2 respectively. $I_1 - I_5$ represent the optical intensities at the respective locations in the shaper. Dashed and solid lines represent orthogonal polarization directions. I_5 is the time-shaped output pulse.

Fig. 2-281. Experimental two-step time-shaped pulse generated by KD*P active pulse shaper, traced from 519 oscillogram.

delay of each of the two steps may be varied by changing the length of the applied voltage pulse and by adjusting optical (propagation) and electrical (e.g., cable) delays to achieve the desired pulse. Relative intensities of the two steps are varied by rotating the $\lambda/4$ plate. The peak intensity of the second step can be made approximately equal to the input intensity (minus optical insertion losses). Intensity ratios of 100:1 between steps, with a total isolation from background of greater than 1000:1, can be achieved with high-quality pockels cells and precise control over applied voltage.

A tailored optical pulse of the form I, in Fig. 2-280 has been generated and is shown in Fig. 2-281. This pulse was produced using two KD*P Pockels cells driven by a laser-triggered spark gap to carve the about 2.5-ns-shaped output pulse from the center of a 20-ns Q-switched input pulse.

System Requirements for Active Pulse Shaping

Before active-pulse-shaping schemes (e.g., the example in Fig. 2-280) can be used in laser-plasma experiments on large-scale systems, such as Argus and Shiva, a number of important requirements must be met. The most demanding requirements are reliability and short risetimes. Timing accuracies of 100 ps with optical transmission risetimes of less than 200 ps are reasonable system objectives for all near-term pulse-shaping approaches.¹⁵⁴ To satisfy these requirements, three elements must be developed before active pulse shaping can be applied: (1) a reliable single-mode, 1.06- μm Q-

switched laser oscillator, (2) a high-voltage pulse generator capable of producing the voltages (about 7 kV) and rise and fall times (less than 200 ps) necessary for driving KD*P cells, and (3) a PC whose risetime is less than or equal to 200 ps.

A satisfactory system-compatible oscillator for active pulse shaping may be developed from either the Kuizenga Nd:YAG oscillator¹⁵⁵ or from a hardened version of the single-mode oscillator used in this study. Solutions to the other problems are likely to be more difficult to achieve. A Pockels cell and pulse generator combination with the required risetime and reliability is a significant technical challenge.

Contacts were made with industry to explore the feasibility of developing suitable high-voltage pulse generators and Pockels cells. Indications from several companies were that high-voltage pulse technology could possibly be extended into the range of interest, although potential solutions would require 6 to 12 months and at least \$100,000 to explore adequately. Some of the Pockels cells developed by industry showed promise of achieving required risetimes. Thus, a significant portion of the active-pulse-shaping effort was devoted to measuring the optical risetimes of these state-of-the-art Pockels cells.

Optical Risetime Measurements of KD*P Pockels Cells

Among the many crystalline materials exhibiting an electro-optic effect, KD*P has the important advantages for high-peak-power pulsed applications at 1.06 μm of high damage threshold and extremely good optical quality. When used in the CRE geometry,¹⁵⁶ in which the KD*P crystal is cut in the form of a right circular cylinder whose axis is coincident with the optical axis of the crystal. A longitudinally directed electric field is applied to the crystal by means of two electrode bands placed peripherally on the crystal surface. By appropriate choice of crystal aspect (length/diameter) ratio, and electrode dimensions and placement on the crystal, it is possible to obtain high field uniformity while minimizing crystal capacitance. ("CRE" is an acronym for "cylindrical, ring electrode.") The excellent transmission uniformity, high contrast ratios and small capacitance combine to maximize performance in fast switching applications.

In all of the devices tested, the small-aperture (less than 1 cm) crystal was mounted into a parallel plate stripline that was approximately impedance-matched to the external 50-ohm coaxial circuitry and connectors. Six different types of cells were tested in the experiments.

The first experiment performed on the Pockels cells was a small-signal voltage-response measurement. The response of each Pockels Cell to a small (about 200-mV) but fast-rising (about 30-ps) pulse was observed with a sampling oscilloscope to obtain the voltage response of each device.

The second experiment consisted of placing the test device between crossed polarizers and driving it with a high-voltage, high-pressure (about 15 atm N_2) laser-triggered spark gap and recording the optical transmission risetime on a high-speed image converter streak camera.¹⁵⁷ Since the streak camera record is on photographic film, extreme care must be taken to ensure that the conversion from film density to input intensity is accurate.

The optical risetime data was processed on a computer-controlled microdensitometer, which performed a digitized raster scan of the film. A calibrated step tablet generated the curve of density/intensity (D vs $\log E$). The data conversion was

performed on the CDC-7600 computer using a specially developed subroutine (PDSVECTOR) that operated in conjunction with MATHSY,¹⁵⁸ an interactive mathematics and graphics software system. As a further check on the tablet-generated $D/\log E$ curve, the data was taken in the form of multiple images, with known intensity steps between each image. This data was then correlated with the step-tablet information to verify the conversion curve for the pulsed data.

Table 2-69 summarizes the results of the small signal and optical transmission risetime measurements. Measured optical risetimes ranged from about 250 to 400 ps, and in all except devices (4) and (6) the ratio of optical-to-electrical risetimes was 0.7 to 0.9, the approximate value expected from the $\sin^2$ transmission dependence. We attribute the deviations to variations in the risetime of the high-voltage pulse in the spark gap driver. The longer risetimes observed for cells (4) and (6) may be due to electrical breakdown problems in the electrical connections to the Pockels cell stripline or its KD*P crystal.

These results show that transmission risetimes in the 250 to 400-ps range can be obtained. An analytical treatment of the interaction between

Table 2-69. Measurements of small signal and optical transmission risetimes

Device	Aperture (mm)	Electrical risetime (ps)	Optical risetime (ps)
(1) Lasermetrics Model 1081	10	495	350 $\pm$ 40
(2) Lasermetrics Model 1080	7	280	255 $\pm$ 15
(3) Lasermetrics Model 1080 RTX (resistor-terminated)	7	280	255 $\pm$ 10
(4) Lasermetrics Model "FTX"	3.5	360	415 $\pm$ 20
(5) Lasermetrics Model "STX"	3.5	360	260 $\pm$ 25
(6) Inrad, Model 632	3.0	180	380 $\pm$ 50

propagating electrical and optical waves in a longitudinal-field electro-optic crystal¹⁵⁹ indicates the transit-time-limited response for these cells with 1-mm size beams would be about 30 ps. The observed risetimes are much longer than this value because of imperfect impedance matching onto the stripline and crystal, which causes high frequency components of the input voltage waveform to be reflected. The finite risetime and imperfect impedance matching of the spark gap driver also contributes to risetime degradation. It may be possible to improve the observed responses with better impedance matching and new high-voltage driver sources, but these developments present significant technical challenges. With the current technology, an active pulse-shaping system using KD*P stripline Pockels cells would be limited to risetimes greater than about 300 ps.

Stripline Optical Modulators and Other Techniques

There are a large number of alternatives to con-

ventional CRE KD*P longitudinal-field Pockels cells. Transverse-field traveling-wave devices have been demonstrated with bandwidths in excess of 15 GHz. The stripline geometries and electrical characteristics of these devices are quite well known, and a number of design papers are available.^{160,161}

The principal difficulty in designing a fast optical modulator or switch is the difference in the propagation velocities of the electrical and optical signals in most good EO materials. Typically, the tradeoffs for a Pockels cell design are evaluated on the basis of voltage requirements, speed or risetime, transmission wavelength range, material properties and availability, and optical quality. Power dissipation requirements are not considered for optical pulse shaping since repetition rates are only a few pulses per second.

Figure 2-282 shows risetime calculations based on electrical and optical transit times in traveling-wave Pockels cells with transverse fields.¹⁶⁰ The risetime divided by the electrooptic coefficient gives a measure that trades off low operating voltages (high

Fig. 2-282. Optical risetimes vs l_{mod} for transverse-field traveling-wave optical modulators. Made from various materials normalized to unity applied field (t_R / t_{EFF}). In the transverse-field configuration, greater lengths mean smaller applied fields for a given extinction ratio but at the expense of risetime.

Table 2-70. Transverse-field optical traveling-wave modulators

Material	Bandwidth/length (GHz/cm)	Impedance (Ω)	Aspect ratio (W/d)	V _{peak}
ADP ₄₁	12	14.3	10.2	1620
	6	21.5	5.0	1620
LiTaO ₃	12	26.0	4.6	489
	6	35.0	2.6	489
LiNbO ₃	12	43.0	2.7	659
	6	56.5	1.6	659

electrooptic coefficients, r , but generally high dielectric coefficients, ϵ) with short risetimes (small ϵ). Gallium arsenide has appreciable absorption losses (about 4 dB/cm) at 1.06 μm , and ZnTe is not available in large quantities with good optical quality. Table 2-70 summarizes traveling-wave modulator design calculations for several materials.¹⁶¹ These calculations were based on a 2 mm $\times$ 2 mm $\times$ 1 cm modulator size. The characteristic impedance of the stripline excited Pockels Cell modulator is shown in the table as well as the aspect ratio that is the stripline electrode width, W, divided by the crystal width, d (in this case, d = 2 mm). The calculations show that lithium niobate or tantalate would be optimum choices to minimize drive voltage, V_{peak}.

Stripline devices in lithium niobate and tantalate are well known. The optical quality of these materials is not as good as KD*P, and devices made with them will have relatively poor extinction (50 to 100:1). These materials are not as resistant to optical damage and, in the transverse-field orientation, will require careful temperature control to avoid birefringence effects, but reduced voltage levels may allow operation with planar triode or avalanche transistor drivers.

Summary

Active pulse shaping with conventional CRE Pockels cells cannot meet the present system re-

quirements on pulse risetime. In addition, use of this technique requires an as-yet undeveloped driver. Although considerable success was achieved in laboratory demonstrations of the general active pulse shaping technique, the lack of an adequate driver hampers further development. Less stringent driver characteristics may be required with a stripline technology, but much of the desired pulse envelope flexibility may be lost because of microwave matching problems. Tradeoff studies will be made to explore the limits of present techniques and new methods such as the light activated silicon switch¹⁶² when operated with large laser systems.

References

154. J. D. Lindl and W. C. Mead, *Phys. Rev. Lett.* **34**, 1273 (1975).
155. D. J. Kuizenga, "Generation of Short Optical Pulses for Laser Fusion," Lawrence Livermore Laboratory, Rept. UCRL-13651 (1975).
156. L. L. Steinmetz, T. W. Poulriot, and B. C. Johnson, *Appl. Opt.* **12**, 1468 (1973).
157. S. W. Thomas, J. W. Houghton, G. R. Tripp, and L. W. Coleman, "The LLL Compact 10-psec Stream Camera—1974 Update," in *Proc. 11th Intern. Cong. High-Speed Photography*, London, 1974 p. 101.
158. G. Peterson, Lawrence Livermore Laboratory, private communication (1976).
159. B. C. Johnson and W. D. Fountain, "Transient Field Effects in Ultra-fast Electro-optic Modulators," presented at *IX Intern. Quantum Electronics Conf.*, Amsterdam, June 1976.
160. G. White and G. M. Chin, *Opt. Commun.* **5**, 374 (1972).

161. M. Bracale and A. Lombardi, *Radio and Electr. Engr.* 39, 185 (1970).
162. P. LeFur and D. H. Auston, *Appl. Phys. Lett.* 28, 21 (1976).

Authors

B. C. Johnson
W. E. Martin
R. R. Guinn

2-5.6 Metallic-Coated Apodizing Apertures

In previous annual reports,^{163,164} we have discussed the requirements for spatial beam shaping in large laser systems. We have also described a fabrication technique developed at LLL for producing metallic-coated "apodizing" (beam-shaping) apertures (MCAA).

The basic idea behind this fabrication technique is a "rotating mask," process illustrated in Fig. 2-283. The key element is an opaque, heart-shaped mask with an angular opening, θ , that varies with the distance from mask center (Fig. 2-283 insert). This mask controls the amount of material deposited on a rotating optical substrate. The sub-

strate axis is centered at $r = 0$, in close proximity to the mask. This rotating transparent substrate eventually serves as the beam-shaping element. During the exposure cycle, the substrate receives an amount of metal (Inconel #604) coating that varies as a function of the radius and opening angle of the mask.

Processing the MCAAs is actually a multistep cycle (Fig. 2-284). By maintaining tight quality control over all phases of processing and by carefully calibrating the total metal-vapor deposition cycle, we can specify the mask-angle function, $\theta(r)$, that is required to produce virtually any desired transmission characteristic on the final aperture. In this manner, we have been able to fabricate MCAAs with accurately reproducible, arbitrarily predetermined radial transmission characteristics within a tolerance of $\pm 5\%$ in transmission.

Detailed transmission and optical microdensitometer measurements indicate that the spatial transmission characteristics required for our laser systems can be produced by these apertures. Figure 2-285 is an example of the close agreement to the desired transmission profile that can be achieved by MCAAs. Data points for measured transmission and optical density vs radius are plotted, together with the predetermined theoretical transmission and density values.

The optical-damage threshold for the Inconel #604 apertures is approximately 20 mJ/cm^2 (150 ps,

Fig. 2-283. Rotating mask technique for fabricating apodizing (beam-shaping) apertures. Opaque mask (insert) is centered over the rotating optical substrate and exposed to a metal-vapor illumination source. The variable mask opening, $\theta(r)$, produces a density gradient on the substrate surface; metal deposition is a function of the mask-opening angle, θ .

Fig. 2-284. Fabrication of metallic-coated apodizing apertures is a multistep cycle.

$1.06 \mu\text{m}$),¹⁶⁵ a relatively low value, but much greater than the approximate $1 \text{ mJ}/\text{cm}^2$ to which they are exposed under typical system operating conditions. We were not able to detect any wavefront distortion when the apertures were tested on a Fizeau interferometer, indicating that the MCAAs are also of excellent optical quality.

During 1976, a series of MCAAs was fabricated for testing and use on the Argus laser system. The apertures were designed to provide incremental increases in whole-beam fill factor* values ranging from about 0.35 to approximately 0.77. Because fill factor is roughly proportional to energy extraction for beams of equal area, this increase (0.35 to 0.77) was made in an attempt to extract more focusable power from the Argus system. In fact, the experiments conducted on Argus obtained roughly a twofold increase in power output from the original output of about 1.3 to about 2.5 TW per arm ($\text{ff} \approx 0.37$ and 0.7 , respectively). This type of experiment dramatically illustrates the value of flexibility in the choice of whole beam *spatial* profile.

Fig. 2-285. Measured transmission and optical density of MCAAs (data points) closely match previously specified (solid curves) function. The edge density ($-\log_{10} T$) of 5 means that residual diffraction ripples are reduced to less than 1% by this aperture.

References

163. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), pp. 135-138.
164. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), pp. 138-140.
165. *Ibid.*, pp. 217.

*Fill factor, $\text{ff} = 2/R^2 \int_0^R rT(r)dr$, where r = radial coordinate, R = 10^{-3} transmission radius of MCAA, and $0 \leq T(r) \leq 1$.

Author
B. C. Johnson

Major Contributors
W. E. Alston
F. M. Cutter
C. H. Dittmore
W. C. Herrmann
G. E. Loomis
R. A. McWilliams
G. F. Stone

2-6 THEORY AND DESIGN ANALYSIS

2-6.1 Overview

The hallmark of laser design in the Laser Fusion Program at Lawrence Livermore Laboratory has been the progressive development of detailed computer codes to guide the development of the laser systems themselves. This design code development has been the major responsibility of the Theory and Design Analysis group, consisting of five physicists and five applications programmers. Although the TDA group is a staff group reporting directly to the Associate Director for Lasers, its main effort to date has been in the area of solid-state laser design. Close cooperation between the analysts in the TDA group and the experimental groups has led to the development of an arsenal of user-oriented system design codes that incorporate our best understanding of the phenomena of laser physics and light propagation. A number of significant advances in laser system design have resulted from the continuing dialogue between hardware and software development and the use of computer codes for detailed system simulation. One example of the direct application of computational and analytical results to system improvement is the recognition, by John Hunt, of the use of the imaging property of spatial filters as a means of increasing the output power of the Argus laser.

There are essentially three levels of analysis embodied in this activity, represented by design codes, physics codes, and simulation codes. The end objective is the *design* code, one which can be used to survey a number of design options rapidly and economically in order to determine which of them will lead to the best performance. A design code must make use of simple descriptions of the elements of a laser system. These, in turn, require simplifications and approximations that are valid over the parameter range in which the system operates. To verify these approximate, lumped-parameter descriptions, the physics of light propagation must be accurately modeled in a detailed *physics* code. The situation is somewhat analogous to the development of circuit theory. The design code employs lumped-parameter descriptions, analogous to Ohm's law, while the physics code solves the basic equations, the optical parallel of Maxwell's equations.

To test the validity of the lumped-parameter

descriptions, and to aid in the improvement of ongoing laser systems, it is necessary to develop *simulation* codes. In such a code, the elements of the computation stand in one-to-one correspondence with the physical elements of the laser system. Where the physics code may employ an idealized model of a laser system, to emphasize one particular physical phenomenon, the simulation code must remain faithful to the real laser system. In actual fact, each of our codes has evolved into a simulation capability, so we no longer maintain the distinction among the functions of the various codes. Of the codes described below, MALAPROP and BT Gain are physics codes, ARTEMIS is both a physics code and simulation code, and VORPAL is a design code. The propagation aspects treated by each of these codes are shown in Table 2-71.

Prior to 1976, the main concern in solid-state laser design was the nonlinear phase distortion resulting from the interaction of the intense electric field of the light wave with the laser host material — i.e., the B-integral. In the presence of this nonlinearity, small fluctuations of phase and amplitude grow on the beam, reducing the focusable power. The analysis of this growth, and its remedy by spatial filtering, was the main thrust of our propagation studies during this period. Associated studies led to the relation of the index nonlinearity to the compositional parameters of the host material, and to the identification of promising materials for future development.

In 1976, our attention turned to the effect of low-frequency fluctuations of phase and amplitude on system performance, to the detailed performance of multiply filtered systems, to the modeling of the onset of fluctuations due to noise sources in the beam, and to the analysis and design of saturated systems operating at longer pulse durations and therefore not necessarily B-limited. These advances are documented in the descriptive articles which follow.

In addition to the laser design activity, the Theory and Design Analysis Group has been active in the support of the Experimental Physics program. Computer code development carried out in conjunction with the program for finding new solid-state laser materials is described below. Three other programming developments of general utility are also described below. One is MCHARTSC, a tool

Table 2-71. Laser propagation aspects treated by four computer codes used by the LLL Theory and Design Analysis Group in designing solid-state lasers (X indicates the aspect is treated by the code, dash indicates it is not)

Propagation aspects	Computer codes			
	BT Gain	VORPAL	ARTEMIS	MALAPROP
Ray optics	x	x	—	—
Diffraction:				
1-D finite difference	—	—	—	x
2-D finite difference	—	—	—	x
Radial modes	—	—	x	—
Nonlinear index:				
Bespalov-Talanov	x	—	—	—
Nonlinear phase	—	x	x	—
Differential equation	—	—	—	x
Gain:				
Saturation	x	x	x	x
Recovery	—	x	—	x
Time history	—	x	x	x
Spatial filtering:				
Focal aperture	x	—	x	x
Transfer function	x	x	—	—
Noise:				
Rippled input	—	—	x	—
Lumped noise	—	x ^a	—	—
Spectral noise	—	—	—	x ^b

^aBetween filters.

^bAt surfaces.

designed to provide a manager with a technique for creating, editing, and displaying milestone charts. Another is MATHSY, a high-level language designed to facilitate mathematical operations in the computer, which allows the user to manipulate vector functions mathematically without programming, while providing continuous two- and three-dimensional graphic displays of the functions involved. Finally, a procedure for the analysis of densitometer records has been devised and is described

under the heading DLOGE. The development of each of these codes has been carried out in close cooperation with the eventual user. Applications of the codes are described elsewhere in the report, with appropriate references to this section for details of the code design and capability.

Author
A. J. Glass

2-6.2 ARTEMIS: A Diffraction Model for Laser Light Propagation

Diffraction theory provides a convenient method for studying both the propagation and focusing properties of intense laser light as it passes through a chain of optical elements. Large-scale phenomena such as gain amplification and whole-beam aberrations are often addressed by conventional geometric ray-tracing methods.¹⁶⁶ However, when optical path lengths become large or intensity profiles display severe gradients, the geometric approach quickly breaks down. This is especially true within the focal region of a lens where it is desirable to understand the detailed aspects of the light-intensity profile.

The development, optimization, and understanding of large laser systems, such as those constructed and used by the Laser Program at Lawrence Livermore Laboratory, depend on a diffraction analysis of light propagation. Because of the high power yields associated with the LLL laser systems, the analysis of these systems is dominated by the nonlinear effects on the light, the result of passing intense fields through largely glass optical elements. Efforts to understand and combat these effects have resulted in the development of a computer-based simulation, employing diffraction theory, to model the current and proposed glass-laser systems.

The computer program, ARTEMIS, developed for the LLL CDC-7600 computers, simulates the nonlinear propagation and focusing of laser light through a simplified chain of optical elements. Its specific capabilities include:

- Diffraction.
- Spatial filter transmission.
- Nonuniform gain.
- Gain saturation.
- Whole beam self-focusing.
- Nonlinear propagation in both rod- and disk-type amplifiers.
- Focusing.
- Thin lens combinations.
- Nonlinear ripple growth.
- "Soft" apertures.
- Seidel aberrations.

Currently, only radially symmetric beams are allowed, thus limiting the types of distortions. Of the basic Seidel aberrations, only spherical aberration is considered. The effects of astigmatism and coma have previously been studied¹⁶⁷ and are, for the purposes of the ARTEMIS simulation, assumed to be correctable. In addition to the radial (spatial) profile of the laser pulse, it is possible to model the temporal dependence, the basis for encountering gain saturation.

Program Description

The wave function for the initial beam that is injected into a laser system of optical components may be approximated by a generalized Fourier decomposition in which the basis functions are the familiar Laguerre-Gauss mode functions. The propagation of the beam in terms of its decomposition coefficients and modal phase is well understood¹⁶⁸; it is defined in terms of one complex propagation parameter, q , and an optical element-transformation matrix, T . The temporal dependence of the wave function is accomplished by considering the radial-wave function at a number of discrete planes of fixed t value in a time frame that is moving along with the wave form. Typically, for short pulses, only the zero position of the time envelope is modeled. For long pulses, the effect of gain saturation may be important and a time history is essential. A set of decomposition coefficients is obtained for each time slice and each is propagated accordingly.

The amplitude envelope of the initial wave function typically is Gaussian temporally and super-Gaussian ("top hat") spatially. Phase distortions may be present initially as may a uniform intensity ripple. Once the initial profile is characterized by a set of decomposition coefficients, free-space (vacuum-passage) propagation is effected by a simple diffraction-phase accumulation that is only dependent on propagation distance. The wave function may be reconstructed in any downstream position from its original coefficients and distance-dependent phase.

Optical elements placed in the path of the propagating beam are characterized by a transformation matrix.¹⁶⁸ Passive elements are those which only serve to alter the phase of the associated wave function, or specifically, the modal phases of each

Laguerre-Gauss basis function used in decomposition. Typical passive elements are thin-lens and free-space propagation (treated here as an "optical element"). Active elements combine a phase change with an amplitude change and, to account for non-uniform spatial amplification and the subsequent remixing of the Laguerre-Gauss modal functions, the decomposition coefficients are actually altered. Both passive and active elements may have associated with them an incremental static distortion (Seidel aberration) or an intensity-dependent nonlinear distortion. The wave function is then reconstructed from its current decomposition, the additional distortions are folded in, and a new set of modal coefficients is obtained. In terms of program logic, beam propagation starts afresh at each decomposition and only the relative diffraction-propagated phase between such decompositions is necessary to reconstruct the wave function at intermediary planes.

Generalized Fitting Scheme ¹⁶⁷

The most crucial aspect to a successful propagation simulation is the ability of ARTEMIS to decompose a given wave function into a finite number of modal functions. Given a wave function, $\psi(r, z, t)$, it is necessary to form the approximation

$$\bar{\psi}_i(r, z) \cong \psi(r, z, t_i).$$

It is assumed that the time variable, t , is fixed at suitably placed coordinate positions, thus forming a vector of approximations. For purposes of discussion, only one component of this vector is expanded. The form chosen for $\bar{\psi}$ is

$$\bar{\psi}(r, z) = \sum_{m=1}^N \gamma_m \Lambda_m e^{-i\phi_m}, \quad (103)$$

where the basis functions are

$$\Lambda_m = \frac{\sqrt{2}}{w(z)} L_m \left\{ \left(\frac{r}{w(z)} \right)^2 \right\} \exp \left\{ -\frac{1}{2} \left[\frac{r}{w(z)} \right]^2 \right\},$$

and the modal phase is separated as

$$\phi_m = (2m + 1) \phi \quad ; \quad \phi = \tan^{-1} \left(\frac{-R(z)}{kw^2(z)} \right) \quad (104)$$

Here, L_m is the m^{th} order Laguerre polynomial, k is the wave number, and $R(z)$, the curvature radius and $w(z)$, the Gaussian waist parameter, are obtained from the complex propagation parameter, q (Ref. 168):

$$\frac{1}{q} = \frac{1}{R(z)} - \frac{i}{kw^2(z)} \quad (105)$$

Elementary analysis provides the decomposition coefficients as

$$\gamma_m = e^{i\phi_m} \int_0^a \psi(r, z) \Lambda_m r dr, \quad (106)$$

where a defines the aperture radius in a given decomposition plane. Initially, $\psi(r, z)$ arises from an analytic expression of the general form

$$\psi(r, z) = A(r) e^{-i\phi_0},$$

where $A(r)$ is some radial-amplitude profile (e.g., Gaussian, quadratic, super-Gaussian) and ϕ_0 is an initial phase to be specified. At other decomposition planes, $\psi(r, z)$ itself arises from an expression like Eq. (103).

To accommodate gain amplification, incremental nonlinear distortion, and incremental static (Seidel) aberrations, it is convenient to treat ϕ_m as providing only the appropriate free-space phase change in the wave function as propagation proceeds; all other properties are absorbed by the γ_m coefficients. Each γ_m is actually a function of the parameter $w(z)$. In the initial fitting procedure, $w(z)$ is chosen to minimize the power residual. ¹⁶⁷ In all other decompositions, $w(z)$ is obtained from the complex propagation parameter, q .

Phase and Amplitude Changes

The following discussion provides details of the methods that ARTEMIS employs to model alterations to the wave function as it propagates through a chain of optical elements. At a fixed (r, z) position, let ψ be the wave function evaluated either analytically or from a prior decomposition. Let $\hat{\psi}$ be the wave function as it is modified to account for any amplitude or phase changes.

One attribute of laser amplifiers is that the gain they provide is typically nonuniform across the spatial dimensions of the amplifier. ARTEMIS will allow a radially varying gain profile of the form

$$G(r) = e^{[g_0 + g(r)]\ell} \quad (107)$$

where ℓ is the effective length of the gain medium, g_0 is the small signal gain coefficient, and $g(r)$ describes the radial nonuniformity. Thus, the first modification to the wave function to allow for gain amplification is simply

$$\begin{aligned} \hat{\psi}(r, z) &\approx \psi(r, z) G^{1/2}(r) \\ &= \psi(r, z) e^{1/2[g_0 + g(r)]\ell} \end{aligned}$$

If we desire to place any amount of static (Seidel) distortion on the beam, a further change in the form of a phase alteration is required. ARTEMIS will allow lumped phase alterations of the form

$$\phi_s = f_1(r) + f_2(x) + \dots$$

where, for example,

$$f_1(r) = \alpha \left(\frac{r}{a}\right)^2 \left[1 - \left(\frac{r}{a}\right)^2\right],$$

a typical form for spherical aberration. This second modification results in

$$\hat{\psi}(r, z) \approx \psi(r, z) e^{1/2[g_0 + g(r)]\ell} e^{i\phi_s}$$

Nonlinear phase distortion is similar to the static aberration, but it is intensity- (and therefore gain-) dependent. It is characteristic of a glass medium that the phase alteration may be written¹⁶ as

$$\phi_B = \frac{\nu |\hat{\psi}|^2(r, z) \{e^{[g_0 + g(r)]\ell} - 1\}}{g_0 + g(r)}, \quad (108)$$

where ν is the nonlinear refractive index for the medium. Thus, the final expression for $\hat{\psi}$ becomes

$$\hat{\psi}(r, z) \approx \psi(r, z) e^{1/2[g_0 + g(r)]\ell} \left(e^{i\phi_s}\right) \left(e^{i\phi_B}\right)$$

The phase alterations are all incremental distortions that have been accumulated since the previous decomposition and ψ , itself, contains a history of all preceding phase and amplitude modifications. New coefficients, $\hat{\gamma}_m$, can be calculated from an expression like Eq. (106), viz.,

$$\hat{\gamma}_m = e^{i\phi_m} \int_0^a \hat{\psi}(r, z) \Lambda_m r dr$$

Propagation in the region before the next decomposition plane is accomplished by keeping the $\hat{\gamma}_m$ fixed, evaluating new phase terms, ϕ_m , and calculating the new wave function as

$$\psi(r, z) = \sum_1^N \hat{\gamma}_m \Lambda_m e^{-i\phi_m}$$

The expression for gain, Eq. (107), and nonlinear distortion, Eq. (108), are valid only for *unsaturated* media. Suitable expressions are utilized for expressing the phenomenon of gain saturation.¹⁷⁰

Propagation

The propagation through space and certain passive elements can, in general, be described by a ray-transformation matrix, T , where

$$T = \begin{pmatrix} A & B \\ C & D \end{pmatrix}.$$

If q is the initial complex parameter [Eq. (105)], then, after propagation,

$$q_2 = \frac{Aq_1 + B}{Cq_1 + D}.$$

From q_2 , the quantities $R(z)$, $w(z)$, and ϕ_m can be appropriately calculated from Eqs. (104) and (105). ARTEMIS was originally intended for transformations of the more specific kind,

$$T = \begin{pmatrix} 1 & B \\ C & 1 \end{pmatrix},$$

where either B or C is zero. The case $B \neq 0$ provides an incremental free-space propagation distance and $C \neq 0$ provides a focal length for the appropriate thin-lens transformation. For passive elements, the only change effected on the wave-function decomposition is a change in the modal phases, ϕ_m . If incremental distortions are also specified for the element, a redecomposition also takes place. It has been unnecessary to associate distortions with every passive element traversed to successfully model existing systems at LLL. It is only necessary to lump distortions in strategic points along the optical chain.

Active elements are specifically gain media. The wave function is first propagated for an appropriate free-space distance (the amplifier length) to account for the correct diffraction-propagated phase change, ϕ_m . It is then decomposed to account for the gain amplifications and nonlinear effects. Both the rod- and disk-type amplifiers are the same conceptually, although care must be taken to construe the model as such to prohibit severely diverging or converging beams through an amplifier unit. Rod amplifiers may appear in segments or slices to meet this requirement and to apply the nonlinear effects in small increments. Disk amplifiers (whose individual disks are actually tilted) are always modeled as sequences of disk pairs to eliminate the need to consider steering effects. The effect of the

tilt of the disks on gain saturation and on intensity-dependent phase is modeled by decreasing the intensity-dependent index of refraction and increasing the saturation-flux parameters according to the degree of tilt of the disks.

All lengths specified for modeling purposes are not true physical lengths, but are lengths modified to provide effective path lengths of the propagating beam. Components such as turning mirrors, Pockels cells, and rotators, are relatively unimportant for simulation purposes. However, ARTEMIS does provide a generalized "loss" element to account for any attenuation experienced when encountering such components.

Additional Features

ARTEMIS is able to handle some specialized operations such as examining low-frequency ripple growth. The initial wave function may be modified by a sinusoidal intensity pattern. Focal-volume sweeps similar to those described in Ref. 169 are available. Spatial-filter pinholes also may be accurately modeled. The effect of the pinhole is determined by propagating the beam to the plane in which the pinhole is located and refitting in this plane over the aperture of the pinhole.

Figures 2-286 through 2-288 are a set of sample computer output which was obtained during an Argus simulation. Other examples of output are shown in the Argus and Shiva sections of this report and a more complete description of the code, itself, can be found in Ref. 171.

Code Limitations

In a crude sense, the code handles "nearly perfect" laser-system conditions and easily provides criteria by which to determine the relative merit of alternatives to or variations of a given system. It is less useful in providing criteria to determine a "bad" system. The wave function may be decomposed several times during the propagation and a "nearly perfect" laser system is defined as one where every such decomposition is successful. That is, the power residual obtained for the difference between an existing wave function and its subsequent fit should be relatively small.

The errors tolerated are difficult to categorize, but, in general, when intensity plots are superimposed for the wave function and its fitted estimate, no discernible difference should be apparent. This customarily corresponds to a calculated relative residual of approximately 10^{-5} . This criterion is often difficult to satisfy with a finite number of basis

functions. However, since the physically real laser beam at any point is probably worse than calculations indicate in terms of small-scale structure and overall beam abnormalities, the decomposition then may be a reasonable approximation to the beam in a nearby plane, or at least may be no worse than the beam before fitting (a smoothing process).

BEAM CHARACTERISTICS AFTER A-6 B-AMP3

Z-POSITION (CM)..... 1.942417E+03
 APERTURE RADIUS (CM)..... 4.243E+00
 PEAK INTENSITY (WATTS/CM2).. 7.153E+09
 OCCURS AT (R,T) = (8.487E-02, 0.
 W(Z) (CM)..... 3.395E-01
 R(Z) (CM) CURVATURE RAD..... 1.658E+04
 XERROR IN FIT..... 4.418E-07
 ENERGY (JOULES)..... 1.142E+02

FOR RADIAL PROFILE SHOWN:

FILL FACTOR..... 5.317E-01
 POWER (WATTS)..... 2.145E+11

TOTAL ACCUMULATED DISTORTIONS (WAVES):

NON LINEAR (ON AXIS)..... 4.906E-01
 SPHERICAL..... 0.
 OTHER..... 0.

Fig. 2-286. Sample output of ARTEMIS computer code depicting the beam characteristics after it has transversed the Argus chain through the 85-mm aperture.

In any event, this lack of fit often can be minimized by increasing the number of basis functions or by choosing a more careful integration mesh. A "bad" system is defined as one in which, during the propagation, a particular decomposition

cannot be accepted as representing the beam. Relative power residuals 10^{-4} or greater can usually be suspect. Propagation properties up to the position of the poor fit may be acceptable but at subsequent positions, they are clearly incorrect, even

Fig. 2-287. Sample output of ARTEMIS computer code depicting the beam characteristics of the Argus chain after it has traversed the entire optical chain.

though the fitting may be excellent. It is quite possible that a subsequent decomposition will fit a highly distorted beam that has arisen from a bad prior decomposition.

Because numerical integration is crucial to the

Laguerre-Gauss mode-decomposition approach and to the calculation of pertinent information such as energies and fill factors, several integration schemes are incorporated for different parts of the simulation, including simple Riemann sums as well

BEAM CHARACTERISTICS AFTER E-37 FOCAL VOLUME
 Z-POSITION (CM)..... 5.584387E+03
 APERTURE RADIUS (CM)..... 1.830E-02
 PEAK INTENSITY (WATTS/CM2)..... 1.713E+16
 OCCURS AT (R,T) = (3.419E-03, 0.
 W(Z) (CM)..... 1.464E-03
 R(Z) (CM) CURVATURE RAD..... -3.829E-02
 %ERROR IN FIT..... 0.
 ENERGY (JOULES)..... 9.946E+02

FOR RADIAL PROFILE SHOWN:
 FILL FACTOR..... 1.654E-01
 POWER (WATTS)..... 1.869E+12
 TOTAL ACCUMULATED DISTORTIONS (WAVES):
 NON LINEAR (ON AXIS)..... 1.754E+00
 SPHERICAL..... 0.
 OTHER..... 0.

Fig. 2-288. Sample output of ARTEMIS computer code depicting the focused beam characteristics of the Argus chain near the plane of the fusion target.

as embellishments of Newton-Cotes formulas. Certain adaptive integration schemes have also been tried but the increase in execution time is prohibitive.

Program Verification

The basic diffraction methods of ARTEMIS have been applied and verified previously.¹⁶⁷ Recent use of the code has involved the development of spatial-filter relay chains,¹⁷² which have been experimentally tested on the LLL Argus laser system.

References

166. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), pp. 207-211.
167. J. T. Hunt, P. A. Renard, and R. G. Nelson, "Focusing Properties of an Aberrated Laser Beam," *Appl. Optics* **15**, 1458 (1976).
168. A. Maitland and M. H. Dunn, *Laser Physics*, (North Holland Publishing Co., London, 1969), pp. 154-158.
169. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), p. 205.
170. J. B. Trenholme and K. R. Manes, *A Simple Approach to Laser Amplifiers*, Lawrence Livermore Laboratory, Rept. UCRL-51413 (1972).
171. P. A. Renard and J. T. Hunt, *ARTEMIS: A Diffraction Model for Laser Light Propagation*, Lawrence Livermore Laboratory, Rept. UCID-17381 (1977).
172. J. T. Hunt, P. A. Renard, and W. W. Simmons, "Improved Performance of Fusion Lasers Using the Imaging Properties of Multiple Spatial Filters," submitted to *Appl. Optics* (1976).

Authors

P. A. Renard
J. T. Hunt

2-6.3 Fast Lumped-Element Computer Analysis of Laser Systems

Rapid simulation of laser systems requires an analysis program that is easy to use, that uses minimal computer time, and has instantly available output. Therefore, we have developed a program that allows easy, rapid data entry from a teleprinter terminal; results are printed out in a concise form

on the same terminal. The calculations are simplified enough that response is essentially instantaneous. However, the propagation model is accurate enough to simulate actual laser systems realistically.

The entry simplicity and rapid response are achieved with a lumped-element analysis method in which the propagation properties of a component in the laser chain are described solely in terms of the B integral through that component. This means that details of beam diffraction as well as the frequency-by-frequency changes of perturbations on the beam through the component are effectively obscured. This simplification corresponds to the approximation in electrical circuits in which the full details of the solutions to Maxwell's equations around a coil are lumped into a single parameter — the inductance of the coil.

Program Input

The laser system is specified by a set of six numbers for each component in the chain (Fig. 2-289). In addition, a 10-character identifier is associated with each component. The input list is compatible with the Bepalov-Talanov ripple gain program described in § 2-6.4 (except for the intercomponent distances), allowing us to conduct a more detailed though time-consuming analysis on promising systems. Extensive, easy-to-use commands are available for creating, editing, merging, and saving the laser description files (Fig. 2-290).

The laser propagation simulation is begun by setting up the initial laser pulse. The area of the beam is divided into a specified number N of equal-area zones and the pulse power is divided among these spatial zones. Because the calculation is diffractionless, the zones do not interact. Therefore, unless it is convenient for the specific application, the zones are not assumed to have any particular spatial shape or relationship. To model situations ranging from very uniform beams to those with large spatial irregularities, the zone powers are distributed as

$$P_J = P_{TOT} \frac{(2J + 1)^{Q-1}}{\sum_{K=1}^N (2K + 1)^{Q-1}}, \quad (109)$$

where P_j is the power in the j th zone, P_{TOT} is the total beam power, and Q is the (approximate) peak-to-average intensity ratio in the beam (Fig. 2-291). Temporally, the initial pulse shape in each zone is Gaussian; 31 power values start at 1.6 times the FWHM before the pulse peak and end at 1.4 times the FWHM after the peak. This temporal distribution can be easily altered to model shaped pulses.

Propagation

The beam is then propagated through the laser components. At each component, the intensity is determined by spreading the beam power over the area of the beam at that component, as found from the specified beam diameter. If the component gain is greater than 1, it is assumed to saturate and the

Fig. 2-289. Input data for the lumped-element laser analysis program. Each component is identified by a descriptive name and the values of six parameters. Special control words (SATURATION, PINHOLE, REPEAT, TWIST, TARGET) initiate appropriate action by the program.

ARGUS LASER WITH 2.8 TW GAINS AND SPATIAL FILTERS - ONE OF TWO BEAMS									
THING NUMBER	THING	DIAM CM	THICK CM	S.S. GAIN	ANGLE DEG	REFR INDEX	WONEN	INDEX	
1	SATURATION	2.800	0.000	0.000	0.000	0.000	0.000	0.000	
2	QUARTZ LENS	2.500	0.001	0.000	0.000	0.000	0.000	0.000	
3	APODIZER	2.500	2.000	0.000	0.000	0.000	0.007	1.240	
4	POLARIZER	2.500	0.000	0.000	0.000	0.000	0.007	1.240	
5	TURN WHEEL	2.500	0.000	0.000	0.000	0.000	0.007	1.240	
6	RELAY LENS	2.500	1.000	0.000	0.000	0.000	0.007	1.240	
7	PINHOLE	INITIAL NOISE	0.02500	LOW-GAIN	FRACTION	0.5000			
8	RELAY LENS	2.500	1.000	0.000	0.000	0.000	0.007	1.240	
9	RDD 25MM	2.500	25.40	5.000	0.000	0.000	0.558	1.410	
10	RDD 25MM	2.500	25.40	5.000	0.000	0.000	0.558	1.410	
11	POLARIZERS	2.500	1.400	0.000	0.000	0.000	0.507	1.240	
12	ROTATOR	2.500	1.250	0.000	0.000	0.000	0.578	2.000	
13	RDD 25MM	2.500	25.40	5.000	0.000	0.000	0.558	1.410	
14	POLARIZERS	2.500	1.400	0.000	0.000	0.000	0.507	1.240	
15	ROTATOR	2.500	1.250	0.000	0.000	0.000	0.578	2.000	
16	POCKELS	2.500	6.500	0.000	0.000	0.000	0.470	1.000	
17	POLARIZERS	2.500	1.400	0.000	0.000	0.000	0.507	1.240	
18	DIVER LENS	2.500	0.500	0.000	0.000	0.000	0.507	1.240	
19	RDD 40MM	3.900	25.40	5.300	0.000	0.000	0.559	1.410	
20	SP 40MM	4.300	0.000	0.000	0.000	0.000	0.507	1.240	
21	PINHOLE	INITIAL NOISE	0.02500	LOW-GAIN	FRACTION	0.5000			
22	SP 65MM	8.600	0.000	0.000	0.000	0.000	0.507	1.240	
23	POLARIZERS	8.600	2.000	0.000	0.000	0.000	0.507	1.240	
24	ROTATOR	8.600	2.500	0.000	0.000	0.000	0.578	2.000	
25	DISK 95MM	8.600	14.10	3.650	57.27	1.356	1.356	1.410	
26	DISK 95MM	8.600	14.10	3.650	57.27	1.356	1.356	1.410	
27	POLARIZERS	8.600	2.100	0.000	0.000	0.000	0.507	1.240	
28	ROTATOR	8.600	2.500	0.000	0.000	0.000	0.578	2.000	
29	SP 65MM	8.600	0.000	0.000	0.000	0.000	0.507	1.240	
30	PINHOLE	INITIAL NOISE	0.02500	LOW-GAIN	FRACTION	0.5000			
31	SP 65MM	8.600	0.000	0.000	0.000	0.000	0.507	1.240	
32	BEAM SPLIT	8.600	2.200	0.000	0.000	0.000	0.507	1.240	
33	ASTIG LENS	8.600	1.260	0.000	0.000	0.000	0.507	1.240	
34	DISK 95MM	8.600	14.10	3.650	57.27	1.356	1.356	1.410	
35	SP 65MM	8.600	0.000	0.000	0.000	0.000	0.507	1.240	
36	PINHOLE	INITIAL NOISE	0.02500	LOW-GAIN	FRACTION	0.5000			
37	SP 65MM	8.600	0.000	0.000	0.000	0.000	0.507	1.240	
38	RECOL LENS	19.50	2.000	0.000	0.000	0.000	0.507	1.240	
39	POLARIZER	19.50	2.400	0.000	0.000	0.000	0.507	1.240	
40	ROTATOR	19.50	3.100	0.000	0.000	0.000	0.578	2.000	
41	POLARIZER	19.50	2.400	0.000	0.000	0.000	0.507	1.240	
42	DISK 195MM	19.50	7.950	1.960	57.27	1.356	1.356	1.410	
43	DISK 195MM	19.50	7.950	1.960	57.27	1.356	1.356	1.410	
44	ROTATOR	19.50	7.000	0.000	0.000	0.000	0.510	1.700	
45	DISK 195MM	19.50	7.950	1.960	57.27	1.356	1.356	1.410	
46	SP 195MM	19.50	2.000	0.000	0.000	0.000	0.507	1.240	
47	PINHOLE	INITIAL NOISE	0.02500	LOW-GAIN	FRACTION	0.5000			
48	SP 195MM	19.50	2.000	0.000	0.000	0.000	0.507	1.240	
49	DISK 195MM	19.50	7.950	1.960	57.27	1.356	1.356	1.410	
50	SP 195MM	19.50	2.000	0.000	0.000	0.000	0.507	1.240	
51	PINHOLE	INITIAL NOISE	0.02500	LOW-GAIN	FRACTION	0.5000			
52	SP 195MM	19.50	2.000	0.000	0.000	0.000	0.507	1.240	
53	FOCUS LENS	19.50	0.000	0.000	0.000	0.000	0.507	1.240	
54	TARGET	INITIAL NOISE	0.000	LOW-GAIN	FRACTION	0.5000			
SMALL SIGNAL GAIN FOR ABOVE COMPONENTS IS 5.145E+02									

TASK		DESCRIPTION
A	ADD	ADD COMPONENT(S) BEFORE B
B	BUILD	BUILD ENTIRE LASER SYSTEM
C	CHANGE	CHANGE ALL PINHOLES TO NEW VALUES
D	DELETE	DELETE COMPONENT(S) # (THRU #)
E	END	END
F	FIRE	FIRE PULSE(S); GET B-INTEGRAL AND FLUX
G	GRAPH	FIRE & PLOT IN VS PLOTOUT GRAPHED ON OUTPUT
H	ITERATE	ITERATES (TWIST) COMMAND LIST
I	LOAD	LOAD A SYSTEM FROM DISK "FILENAME"
J	MERGE	MERGE DISK "FILENAME" BEFORE COMPONENT #
K	OUTPUT	OUTPUT TO DISK "FILENAME" OR "TTY"
L	PRINT	PRINT COMPONENT(S) # (THRU #)
M	PRINT	PRINT PINHOLES AND/OR TARGETS
N	REPLACE	REPLACE COMPONENT(S) # (THRU #)
O	STORE	STORE SYSTEM ON DISK "FILENAME"
P	TWIST	TWIST VARIABLE(S) AT ZONE # (OR SUN OR GRAPH)
Q	ZONES	ZONAL PRINT (SPACE) OF PWR, ENRGY AND S-S
R	ZONAL	ZONAL PRINT (SPACE AND TIME) OF PWR, ENRGY AND S-S

Fig. 2-290. The code has extensive facilities for specifying, modifying, and storing descriptions of laser systems.

Fig. 2-291. Distribution of power and energy among the spatial zones for various values of the initial peak-to-average ratio. This initial distribution is changed by the effects of saturation and stripping at the spatial filters.

gain for the power in each time slice is found from the Frantz-Nodvik equation:

$$G(t) = \frac{1}{1 - e^{-R[1 - (1/G_{ss})]}} \quad (110)$$

where G_{ss} is the small-signal gain before the arrival of the pulse and R is the ratio of energy density to saturation flux inside the material. Thus,

$$R(t) = \frac{E(t)}{\Phi} \frac{n \cos \theta}{\sqrt{n^2 - \sin^2 \theta}} \quad (111)$$

where Φ is the saturation flux, n is the refractive index, and θ is the tilt angle of the component.

Because of possible pulse distortion at the spatial filter pinholes, the energy is found by numerically integrating the power. The first energy starts at the

small-signal value,

$$E(t_1) = \left(\frac{P_{\max} W}{2} \right) \sqrt{\frac{\pi}{\ln 2}} \left\{ \frac{1 + \operatorname{erf} \left[\frac{(2 \sqrt{\ln 2/W}) t_1}{2} \right]}{2} \right\} G_{sc} \quad (112)$$

where $P_{\max}$ is the peak power in the zone, W is the FWHM of the initial pulse, t_1 is the time of the first time slice in the pulse, and G_{sc} is the chain small-signal gain up to this point.

Successive values of $E(t)$ are then obtained by running cubic polynomials through four adjacent points and finding the integral of the cubic between the two center points (or the end points, in the case of the first and last time intervals).

$$E_2 = E_1 + \frac{\Delta t}{24} (9P_1 + 19P_2 - 5P_3 + P_4) ;$$

$$E_{J+1} = E_J + \frac{\Delta t}{24} (-P_{J-1} + 13P_J + 13P_{J+1} - P_{J+2}), \quad 2 \leq J \leq N-2 ;$$

$$E_N = E_{N-1} + \frac{\Delta t}{24} (P_{N-3} - 5P_{N-2} + 19P_{N-1} + 9P_N) .$$

If the pulse moves forward in time as a result of saturation effects, the temporal grid may no longer be symmetrically placed. When this occurs, a new point is added in front and the last point is dropped. The new pulse power and B integral values are obtained from the small signal formulas.

At each time and spatial position, the B integral is then found. If we assume that the gain is uniform along the path of the laser beam (not true for disks, but the error is small), then the previous expression for the instantaneous gain can be used to find the intensity as a function of distance through the component. Next, the B integral can be obtained.¹⁷³ We find that

$$B = \left[\frac{0.0263372 \, n n_2 \, I_{IN} \, t \, \cos \theta}{\lambda (n^2 - \sin^2 \theta)} \right] \times \left\{ \frac{\ln [1 + G_{ss}(e^R - 1)] - R}{(1 - e^{-R}) \ln G_{ss}} \right\} \quad (113)$$

Here, the thickness, t , is in centimeters, the input intensity, I_{IN} , is in watts per square centimeter, λ is the laser wavelength in micrometers, n_2 is the nonlinear index in units of 10^{-13} esu, and the numeric factor is $8\pi^2/c$. This B integral is then added to a running sum in each zone.

Fig. 2-292. Spatial filter transmission curves for one spatial and one temporal zone. Actual results for the entire beam will differ because of spatial and temporal averaging.

Fig. 2-293. The result of simulating the propagation of a pulse through a laser. Characteristics of the pulse at each component are printed out on the teleprinter.

1 ARGON LASER WITH 2.8 TW GAINS AND SPATIAL FILTERS - ONE OF TWO BEAMS									
INPUT: 30.00 15.97 SATURATED CHAIN ENERGY GAIN 8.305E+01 SATURATED CHAIN ENERGY GAIN 9.703E+01 MAX FRACTIONAL TAIL POWER 4.614E-03									
THING NUMBER	THING I.D.	POWER (GW)	EN/3Y	POWER GAIN	ADDED B-INT	TOTAL B-INT	PEAK/AVG	INTEN FLUX	FLUX CM2
1	INPUT	30.00	15.97						
2	DUMMY ATTEN	.030	.016	.001	0	0	1.638	10.01	5.327
3	APODIZER	.024	.013	.800	4E-04	4E-04	1.638	.010	.005
4	POLARIZER	.024	.013	.980	9E-05	9E-05	1.638	.004	.004
5	TURN PRISM	.023	.012	.980	9E-04	.001	1.638	.008	.004
6	RELAY LENS	.023	.012	.990	2E-04	.002	1.638	.008	.004
7	PINHOLE	.023	.012	LOSS (J)	4E-05	DELTA-B	.002	SF	XSMN
8	RELAY LENS	.023	.012	.990	2E-04	.002	1.638	.008	.004
9	ROD 25MM	.112	.060	.992	.011	.012	1.638	.038	.020
10	ROD 25MM	1.052	.860	3.349	.080	.082	1.617	.349	.188
11	POLARIZERS	1.010	.337	.960	.008	.100	.617	.349	.188
12	ROD 25MM	.869	.316	.960	.012	.112	.617	.305	.178
13	ROD 25MM	6.892	4.334	6.343	.633	.745	.495	2.562	1.380
14	POLARIZERS	7.769	4.160	.960	.057	.802	.495	2.552	1.380
15	ROD 25MM	7.456	3.994	.950	.090	.891	.495	2.478	1.325
16	POCKELS	6.339	3.365	.850	.240	1.130	.405	2.379	1.272
17	POLARIZERS	6.086	3.258	.960	.045	1.174	.495	2.022	1.081
18	DIVER LENS	6.025	3.227	.990	.020	1.194	.405	2.411	1.268
19	ROD 40MM	27.64	14.72	4.588	.044	2.242	.371	3.483	1.842
20	SF 86MM	27.37	14.67	.990	.046	2.289	.371	2.848	1.515
21	PINHOLE	26.07	14.29	LOSS (J)	2.79	DELTA-B	2.287	SF	XSMN
22	SF 86MM	26.11	14.15	.990	.013	2.301	.371	.652	.381
23	POLARIZERS	25.07	13.68	.980	.025	2.326	.371	.646	.358
24	ROD 40MM	24.08	13.04	.980	.045	2.370	.371	.620	.344
25	DISK 88MM	83.35	45.13	3.464	.205	2.605	.310	2.047	1.124
26	DISK 88MM	258.8	140.3	3.118	.921	3.590	.212	6.205	3.361
27	POLARIZERS	245.8	134.7	.960	.217	3.776	.236	6.205	3.361
28	ROD 40MM	239.5	129.3	.960	.100	4.188	.232	5.950	3.225
29	SF 86MM	239.5	129.3	.990	.110	4.293	.232	5.718	3.087
30	PINHOLE	230.1	125.9	LOSS (J)	2.091	DELTA-B	2.065	SF	XSMN
31	SF 86MM	227.8	124.6	.990	.103	4.393	.232	5.373	2.988
32	BEAM SPLIT	220.9	121.5	.990	.213	4.599	.232	5.312	2.958
33	ASTIG LENS	218.7	119.7	.990	.132	4.724	.232	5.160	2.867
34	DISK 86MM	577	312.8	2.638	2.086	6.723	.102	11.00	6.981
35	SF 86MM	571.3	309.8	.990	.250	6.973	.102	10.85	6.854
36	PINHOLE	518.1	295.4	LOSS (J)	14.27	DELTA-B	2.764	SF	XSMN
37	SF 86MM	505.8	292.4	.990	.205	7.157	.102	10.85	6.854
38	RECOL LENS	505.8	292.4	.990	.105	7.262	.102	10.85	6.854
39	POLARIZER	490.7	280.8	.970	.079	7.305	.102	10.088	1.571
40	POLARIZER	485.2	278.8	.950	.170	7.475	.102	10.00	1.175
41	POLARIZER	485.2	278.8	.970	.073	7.570	.102	9.900	1.175
42	DISK 195MM	895.8	474.5	1.848	.350	7.861	.077	3.445	1.985
43	DISK 195MM	1478	831.1	1.768	.640	8.501	.077	3.445	1.985
44	ROD 40MM	1404	789.6	.950	.425	8.777	.047	8.177	3.367
45	DISK 195MM	2387	1309	1.700	1.057	9.632	.039	9.908	5.225
46	SF 195MM	2363	1298	.990	.402	9.941	.039	9.908	5.225
47	PINHOLE	1874	1071	LOSS (J)	224.7	DELTA-B	3.499	SF	XSMN
48	SF 195MM	1857	1060	.990	.229	10.17	.039	6.639	3.945
49	DISK 195MM	2776	1634	1.661	1.12	11.12	.022	11.62	6.167
50	SF 195MM	2728	1677	.990	.471	11.46	.022	11.62	6.167
51	PINHOLE	2650	1647	LOSS (J)	23.87	DELTA-B	1.976	SF	XSMN
52	SF 195MM	2623	1631	.990	.448	11.80	.022	11.01	6.042
53	FOCUS LENS	2492	1549	.950	1.730	13.10	.022	10.89	5.923
54	TARGET	2492	1549	LOSS (J)	.002	DELTA-B	2.176	SF	XSMN

Spatial Filtering

The laser pulse proceeds through the laser, being amplified, temporally distorted, and accumulating B until it reaches a spatial filter. The filter strips off the amplified intensity perturbations on the beam. This cleans up the beam; it also reduces the beam power. The filter model we use assumes that power grows and is stripped independently in each spatial and temporal zone. Thus, the power reduction depends on the B integral accumulation since the last spatial filter or the beginning of the chain. A two-frequency model of the noise growth has been adopted where the phase-averaged ripple gain is

$$G_{H1} = \cosh 2B$$

for the fastest growing perturbations. An initial total noise power fraction ϵ , is therefore specified for each between-filter section of the laser. This is the fraction of the beam power that will not go through the spatial filter pinhole. It is split into a fraction f at low frequencies; $1 - f$ remains for the faster-growing high frequencies. The amplified noise fraction at the spatial filter that ends the section is

$$\eta = \epsilon f (1 + 2B^2) + \epsilon (1 - f) \cosh 2B \quad (114)$$

$$G_{LO} = 1 + 2B^2$$

for low spatial frequencies¹⁷⁴ (spatially large ripples) and is

This amount of unfocusable noise is not sufficient to model the temporal dips observed in actual lasers. Therefore, when large fractions of the beam are converted to perturbation noise (at which point

ARGON LASER WITH 2.8 TW GAINS AND SPATIAL FILTERS - ONE OF TWO BEAMS													
PULSE DURATION	50000	NANOSECONDS											
LASER WAVELENGTH	1.06410	MICRONS											
NUMBER OF ZONES	10												
INIT PEAK-TO-AVG	1.70000	INPUT	1.83773	ACTUAL									
FIRST TIME SLICE	0.00000	NANOSECONDS											
NUMBER OF SLICES	31												
DELTA TIME SLICE	0.00000	NANOSECONDS											
P-IN (MW)	P-OUT (MW)	E-OUT (J)	CHAIN B-INT	MAX-MIN	MAX-MIN	MAX-MIN	MAX-MIN	MAX-MIN	MAX-MIN	MAX-MIN	MAX-MIN	MAX-MIN	MAX-MIN
2.000	788.8	428.1	2.215	4.384	2.321	986	1.591	398	398.3	400.3	795.8	425.0	9
4.000	1514	708.1	5.430	8.877	3.880	983	4.108	370	328.3	331.7	1510	705.9	9
6.000	1848	908.3	7.044	8.468	4.542	989	7.534	191	281.0	284.4	1840	905.1	9
8.000	1952	1061	8.337	8.884	5.153	992	12.35	138	244.0	248.2	1944	1055	9
10.000	2140	1180	9.312	10.22	5.553	974	20.77	98	214.0	221.7	2130	1175	9
12.000	2284	1272	10.04	10.66	5.863	963	32.48	071	190.4	198.3	2272	1267	9
14.000	2370	1348	10.58	10.93	6.041	951	46.93	057	169.3	180.7	2316	1329	9
16.000	2429	1404	11.02	11.07	6.135	937	64.27	045	151.6	164.8	2413	1385	9
18.000	2468	1448	11.31	11.17	6.189	922	84.04	042	138.4	151.2	2457	1438	9
20.000	2482	1482	11.70	11.37	6.170	906	105.6	038	126.1	139.3	2482	1472	9
22.000	2480	1507	12.01	11.87	6.218	890	127.9	035	113.2	126.7	2488	1486	9
24.000	2481	1528	12.31	12.08	6.444	875	151.2	032	103.4	119.8	2483	1513	9
26.000	2481	1539	12.61	12.43	6.632	859	175.3	028	98.76	111.2	2480	1525	9
28.000	2482	1544	12.89	12.70	6.824	841	202.0	026	90.02	99.8	2488	1533	9
30.000	2482	1548	13.10	13.00	6.981	827	224.7	022	83.08	97.03	2488	1533	9
32.000	2482	1555	13.28	13.31	7.130	818	244.3	018	77.97	91.31	2480	1538	9
34.000	2481	1555	13.28	13.26	7.239	802	268.1	015	74.97	80.33	2487	1537	9
36.000	2482	1557	13.68	13.78	7.340	781	284.4	016	70.84	87.29	2507	1538	9
38.000	2481	1551	13.81	13.81	7.428	763	299.4	015	67.02	77.18	2508	1541	9
40.000	2482	1550	13.82	14.01	7.483	777	311.0	014	63.24	70.07	2489	1545	9
MAX FRACTIONAL TAIL POWER 4.671E-03													

Fig. 2-294. Summary output for firings at increasing input powers. The line at 30-GW input corresponds to the detailed printout given in Fig. 2-293. This mode permits rapid scanning of the capabilities of a laser system.

the linearized theory no longer applies), a beam catastrophe is simulated by taking the unfocusable fraction of the beam as

$$\delta = \eta + \exp[20(\eta - 0.7)] \quad (115)$$

The spatial filter transmission in each zone is then

$$T(b) = \max [(1 - \delta), 0] \quad (116)$$

By an appropriate choice of ϵ and f , the properties of actual lasers can be closely simulated. Typical transmission curves are shown in Fig. 2-292.

Fig. 2-295. A teleprinter graph of the pulse shape at the end of the firing shown in Fig. 2-293. The pulse has been shifted and distorted by saturation. The temporal dip near the peak is due to stripping at the spatial filters.

Program Output

As the pulse is propagated through the laser, the results at each component are printed out on the user's teleprinter (Fig. 2-293). The peak total pulse power and total pulse energy are printed along with the maximum power and energy densities. The saturated power gain of each component is also provided as are the maximum added B integral and the highest accumulated B-integral value in any zone. At each spatial filter, the values for the energy deposited on the pinhole, the zone-maximum incremental B integral since the last spatial filter, and the filter energy transmission are printed.

After leaving the laser, the beam is often directed toward a target. To avoid counting the laser output that misses the target, a spatial-filter-type calculation is carried out with values of ϵ and f that are appropriate to the angular acceptance of the target. The power and energy on target are thus obtained. The value of the B integral through the whole chain should also be noted because perturbations whose spatial frequencies are low enough to pass through the filters will have grown by $(1 + 2B^2)$ from the beginning of the chain, setting an upper limit on the whole-chain B.

A summary format of output is also available, in which a number of pulses are fired through the system and the basic quantities from the one-shot full printout are given (Fig. 2-294). This feature allows rapid exploration of the limiting processes in a laser as the input is increased.

Finally, various details of the pulse zone-by-zone properties can be printed or graphed on the teleprinter. For example in Fig. 2-295, the power

summed over spatial zones is plotted as a function of time for a pulse that was distorted by saturation and by stripping at spatial filters.

References

173. J. McMahon, *Optimization of Nd:Glass Lasers with Phosphate-Laser Glass*, Naval Research Laboratory, Memorandum Rept. 3411 (1976), p. 32.
174. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p. 239.

Authors

J. B. Trenholme
E. J. Goodwin

2-6.4 Bepalov-Talanov Ripple Growth Calculations in Laser Systems

The nonlinear growth of amplitude and phase perturbations on a laser beam is an important limiting process in fusion lasers. The numerical calculation of such growth therefore has been extended so that we can determine ripple growth throughout actual laser systems. The resulting computer program enables us to find the sources of major ripple features in actual lasers and to determine the effect of suggested changes in laser layout. In addition, with this program, new lasers can be evaluated before they are built.

The calculation of ripple growth in a series of un-tilted slabs in a parallel beam was reported in last year's Annual Report.¹⁷⁵ To extend this calculation to actual laser systems, we have added a number of features.

- Partial allowance for the effects of tilted slabs.
- Calculation of gain and saturation effects.
- Determination of the results of beam divergence.
- Consideration of filtering and propagation effects of spatial filters.
- Capability to follow ray paths through the laser.
- Provision for easy laser-system specification and editing.
- More complete graphic and numeric output.

Fig. 2-296. When a laser beam strikes a tilted slab, the intensity is reduced and ripple patterns are stretched in the direction of tilt. At Brewster's angle, the stretch factor is the refractive index. The path length is also increased above the slab thickness.

Ripple Growth

A tilted slab has a number of effects on ripple growth (Fig. 2-296). An initially circular beam will spread into an ellipse and the intensity will be reduced correspondingly. The intensity inside the slab is expressed as

$$I_{IN} = \frac{I_{OUT}^n \cos \theta}{\sqrt{n^2 - \sin^2 \theta}} \quad (117)$$

where θ is the tilt angle of the slab with respect to the beam and n is the refractive index. It is this reduced intensity which must be used in the ripple-growth calculation. Because of the tilt-induced beam spread, the ripples also spread. If we consider sinusoidal ripples, we see that the amount by which they are stretched is somewhere between the same factor by which the intensity is reduced and unity, depending on the orientation of the ripples with respect to the plane of the tilt. Because ripple gain depends on ripple size, the stretch must be accounted for in the ripple-growth calculation. In

addition, we must do the entire calculation for a number of different initial orientations of ripples. Because of the tilt, the path through the slab is increased to greater than the thickness of the slab;

$$l = \frac{t}{\sqrt{n^2 - \sin^2 \theta}} \quad (118)$$

where t is the slab thickness. Finally, when a slab is tilted, the ripple pattern travels different distances to get to different parts of the slab. Thus, the pattern just inside the slab is a mixture of ripples of different frequencies, even when only one ripple frequency is incident. This effect is important only when a ripple component diffracts by a large amount between the top and bottom of a tilted disk; only high-spatial-frequency ripples are calculated incorrectly if the effect is ignored. However, these frequencies are removed by spatial filters anyway. More importantly, if we do not calculate the differential diffraction, the computer program is considerably speeded up. If desired, the consequences of the tilt-plus-diffract effect can be found by using a partial-differential-equation program that accepts tilted boundaries.¹⁷⁶

Amplifier Gain

Gain in laser rods or disks is handled by slicing the medium into a number of pieces. The intensity is held constant inside each piece and is increased for the next piece. The actual smoothly increasing intensity is thus approximated by a series of step functions (Fig. 2-297). Saturation is approximated by

Fig. 2-297. The effects of gain are approximated by slicing the material into short pieces. The intensity is constant in each piece at the average value of the actual intensity.

changing the intensity according to the Frantz-Nodvik energy gain:

$$G_{FN} = \ln [1 + G_{ss} (e^R - 1)] / R \quad (119)$$

where G_{ss} is the small-signal gain and R is the ratio of pulse energy per unit area to saturation energy per unit area inside the material (accounting for tilt). This approximation assumes that the pulse shape remains unchanged. In fact, the intensity is less in deep saturation because the pulse broadens, causing the ripple growth to be overestimated.

Divergence or convergence of the beam, including the effects of spatial filter optics, is handled by using equivalent parallel propagation distances. Visualize a parallel beam striking a lens of focal length f . On the exit side, the beam is converging or diverging. If, however, we view the situation through the lens, we see a beam that appears to remain parallel (Fig. 2-298). If an actual point on the beam is a distance z from the lens along the optic axis and a distance r perpendicular to the optic axis, then simple ray tracing tells us that the coordinates as seen through the lens appear to be

$$z' = \frac{z}{1 - (z/f)} \quad ,$$

$$r' = \frac{r}{1 - (z/f)} \quad (120)$$

If the parallel beam radius is r_0 , then $r' = r_0$ because the beam appears parallel when seen through the lens. In addition, the beam magnification at distance z is

$$M = r/r_0 = 1 - (z/f) \quad (121)$$

This magnification is negative if we exceed the focus of a converging lens ($f > 0$); this means simply that a ray on the beam margin is now on the other side of the optic axis. The distance seen by an observer looking through the lens — the equivalent propagation distance of a parallel beam — is

$$z' = \frac{z}{1 - (z/f)} = \frac{z}{M} = \frac{zr_0}{r} \quad (122)$$

Thus, we can ray-trace to find the radius of the beam margin at any point and then use the ratios of radii to find an equivalent distance of parallel propagation.

This propagation equivalence also applies to diffraction. Talanov¹⁷⁷ has shown that the paraxial equation is invariant under the above lens transformation except for a phase factor that goes to zero for a lens with a flat field. Note that devices such as spatial filters with a real beam focus have negative magnification and thus a negative equivalent-parallel-propagation distance. Thus, they introduce *negative optical length* in a system, an extremely useful feature for reducing the effects of diffraction (see the section "Performance Improvements Through Relay Imaging" in this annual).

Ray paths must be traced through the laser because the interelement spacing will vary because of the presence of the tilted disks. This effect is small but not negligible. However, the surface intersection calculations are relatively easy to implement and thus, it is included in the program.

Program Input

The computer program has extensive facilities for the input and modification of laser systems. We attempted to make this system specification phase as painless as possible because it is the most time-consuming part of laser analysis using the program. In an input list (Fig. 2-299), each component in the laser is specified by seven numbers:

- 1 The beam diameter at the component.
- 2 The thickness of the component.
- 3 The small-signal gain of the component.
- 4 The component's tilt angle relative to the optical axis.
- 5 The component's refractive index.
- 6 The component's nonlinear refractive index.
- 7 The distance from the front of this component to the front of the next component.

In addition, a 10-character identification word is associated with each component. In the input phase, the component data is entered in blank-delimited free format. The program prompts for each item with a descriptive phrase; the experienced user may enter several items on one line and avoid the prompting and speed up the input phase. Once a system is entered, it can be stored on a disk file for later retrieval. Components in a description may be

Fig. 2-298. A beam striking a positive lens begins to converge. If we view the situation through the lens, however, the beam appears to remain parallel. Both ray-tracing and paraxial diffraction theory agree that there is complete equivalence between a converging (or diverging) beam and a parallel beam that propagates a different distance.

copied, moved, deleted, or replaced. Also, another system on disk can be merged with the present one.

Calculation

With the system specified, the ripple growth can be calculated. The user specifies lower and upper ripple eigenvalues as well as the number of eigenvalues to be run. These values are given in terms of the equivalent ripple angle that a plane wave must have with respect to the main beam to make a pattern of parallel ripples with the specified eigenvalue. At each eigenvalue, the coefficient of the perturbation is a complex number that gives the amplitude of the electric field in the perturbation and its phase with respect to the main laser beam. If we write this coefficient in terms of a vector of its real and imaginary parts, each region in the laser transforms the coefficient by a 2-by-2 matrix:

$$\begin{bmatrix} R \\ I \end{bmatrix} = \begin{bmatrix} E & F \\ G & H \end{bmatrix} \begin{bmatrix} R_0 \\ I_0 \end{bmatrix}$$

This 2-by-2 matrix completely characterizes the region for the particular eigenvalue. Because the 2-by-2 matrix of the next region multiplies the results of the present region, we can keep track of the effect of the entire laser by initializing a set of 2-by-2

matrices, one for each eigenvalue, and then multiplying them by the matrices of successive regions. The program therefore initializes all the matrices to

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

and then computes the effects of air and solid regions.

Air paths are simple. The matrices are multiplied by the rotation matrices,

$$\begin{bmatrix} \cos \psi & -\sin \psi \\ \sin \psi & \cos \psi \end{bmatrix},$$

where the rotation angle is

$$\psi = (1/2)kzo^2.$$

Here, $k = 2\pi/\lambda$, z is the equivalent parallel propagation distance, and the eigenvalue σ of the perturbation function P is found from

$$\nabla^2 P = k^2 \sigma^2 P$$

The calculation of the 2-by-2 transition matrix in a solid is more complicated. The resulting matrix¹⁷⁵ is

$$\begin{bmatrix} \cosh \psi s & \frac{-\sinh \psi s}{s} \\ -s \sinh \psi s & \cosh \psi s \end{bmatrix},$$

where

$$s = \sqrt{\frac{2B}{\psi} - 1}.$$

THING NUMBER	THING I.D.	DIAM (CM)	THICK (CM)	S.S. GAIN	ANGLE (DEG)	REFR. INDEX	NONLN INDEX	DIST INDEX (CM)
1	SATURATION	3.830	JOULES	PER SQUARE	CENTIMETER			
2	DUMMY ATTN	2.500	.0	.001	.0	1.000	.0	.0
3	APODIZER	2.500	2.000	.800	.0	1.507	1.240	1.000
4	POLARIZER	2.500	.700	.980	56.43	1.507	1.240	10.00
5	TURN PRISM	2.500	6.000	.980	.0	1.507	1.240	10.00
6	RELAY LENS	2.500	1.000	.990	.0	1.507	1.240	300.0
7	PINHOLE	TRANSMISSION	.997000	CUTOFF	99.999	MILLIRADIANS		
8	RELAY LENS	2.500	1.000	.990	.0	1.507	1.240	20.00
9	ROD 25MM	2.500	25.40	5.000	.0	1.556	1.410	50.00
10	ROD 25MM	2.500	25.40	9.500	.0	1.556	1.410	30.00
11	SLICE	MIRROR	2	PIECES.	3.0000	CM APART		
12	POLARIZERS	2.500	1.400	.960	56.43	1.507	1.240	8.000
13	ROTATOR	2.500	1.250	.960	.0	1.678	2.000	8.000
14	TWIST	COMPONENT ANGLES BY	45.00	DEGREES				
15	ROD 25MM	2.500	25.40	9.500	.0	1.556	1.410	30.00
16	SLICE	MIRROR	2	PIECES.	3.0000	CM APART		
17	POLARIZERS	2.500	1.400	.960	56.43	1.507	1.240	8.000
18	ROTATOR	2.500	1.250	.960	.0	1.678	2.000	20.00
19	TWIST	COMPONENT ANGLES BY	45.00	DEGREES				
20	POCKELS	.500	6.500	.850	.0	1.470	1.000	20.00
21	SLICE	MIRROR	2	PIECES.	3.0000	CM APART		
22	POLARIZERS	2.500	1.400	.960	56.43	1.507	1.240	100.0
23	DIVER LENS	2.500	.500	.990	.0	1.507	1.240	110.0
24	ROD 40MM	3.900	25.40	5.300	.0	1.556	1.410	163.0
25	PIX	DISTANCE FROM LAST COMPONENT FRONT	163.000	CM.				
26	SF 40MM	4.300	.800	.990	.0	1.507	1.240	128.0
27	PINHOLE	TRANSMISSION	.996000	CUTOFF	.341	MILLIRADIANS		
28	SF 86MM	8.600	.950	.990	.0	1.507	1.240	34.00
29	SLICE	MIRROR	2	PIECES.	20.0000	CM APART		
30	POLARIZERS	8.600	2.400	.960	56.43	1.507	1.240	93.00
31	ROTATOR	8.600	2.500	.960	.0	1.678	2.000	59.00
32	TWIST	COMPONENT ANGLES BY	45.00	DEGREES				
33	SLICE	MIRROR	6	PIECES.	17.0000	CM APART		
34	DISK 86MM	8.600	14.10	3.650	57.27	1.556	1.410	161.0
35	SLICE	MIRROR	6	PIECES.	17.0000	CM APART		
36	DISK 86MM	8.600	14.10	3.650	57.27	1.556	1.410	137.0

Fig. 2-299. Input data for the ripple gain program. Each component is specified by a descriptive name and seven parameter values. Special control words such as SATURATION, PINHOLE, SLICE, TWIST, and PIX initiate appropriate action by the program.

Fig. 2-300. Ripple-power growth as a function of the angle that would be cut off by a spatial filter. This is a radial slice through a circularly symmetric pattern. The four curves are for four different initial ripple orientations.

Fig. 2-301. Near-field intensity ripple growth that would be observed in a picture of the beam. This is different from the previous figure because much of the low-frequency power growth is in phase rather than amplitude growth.

and B is the B integral through the solid. This B integral is found by the method described in the section "Cost-Optimal Design of Laser Amplifiers" in this annual.

Spatial filter pinholes are handled by resetting all the matrices above a maximum equivalent-ripple angle to unity. The angle chosen is the angular size of the pinhole,

$$\phi = \frac{r}{f} ,$$

where r is the pinhole radius and f the focal length of the input lens.

Program Output

Once all the matrices have been advanced through the laser, the results can be shown. If the total matrix at one eigenfunction is

$$T = \begin{bmatrix} E & F \\ G & H \end{bmatrix} ,$$

then the ripple power gain (the power is proportional to the square of the electric field), averaged over the phase of the initial perturbation, is

$$G_{AV} = (1/2) (E^2 + F^2 + G^2 + H^2) .$$

The growth of the near-field interference pattern resulting from a weak beam proceeding at an angle to the main beam is

$$G_{NF} = \sqrt{E^2 + F^2}$$

Both of these gains as well as the actual components of the transition matrix are plotted vs the equivalent ripple angle in Figs. 2-300 through 2-302. These plots may be produced at intermediate points in the laser as well as at the end. Analysis of a laser system may then be carried out at a number of intensities. The results help us to understand the operation of existing systems and to predict the performance of hypothetical new systems.

Fig. 2-302. Transition matrix elements from which the previous figures were calculated. A ripple at the input is specified by its real (in-phase) and imaginary (quadrature) components. It is then converted to output real and imaginary parts by these matrix elements which are a function of the ripple size.

References

175. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), pp. 237-238.
176. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), p. 215.
177. V. I. Talanov, *JETP Lett.* 11, 199 (1970).

Authors

J. B. Trenholme
E. J. Goodwin

2-6.5 MALAPROP: Light Propagation in a Nonlinear Medium with Stochastic Perturbations

MALAPROP is a computer code for studying light propagation in laser media in the presence of noise. Introducing noise, i.e., stochastic perturbations in phase and amplitude, mimics the effect of

surface irregularities due to imperfect optical finishing (phase noise) and scattering from dirt, scratches, and inhomogeneities on the optical surfaces (amplitude noise). Phase and amplitude fluctuations arising from these sources grow in the presence of an intense light beam as a result of the nonlinearity of the refractive index of the medium. This growth can be described by the linearized, Bespalov-Talanov theory¹⁷⁸ as long as the perturbation is small compared with the main beam; however, in the large-signal regime, no adequate nonlinear theory exists. MALAPROP provides an accurate model of the breakup of intense laser beams well into this large-signal regime.

MALAPROP exists both in one- and two-dimensional forms. The two-dimensional calculation is extremely time-consuming if a large number of grid points are carried along. Therefore, in the following discussion, we generally refer to the one-dimensional code. Extensions to two dimensions, which we have implemented, are also described.

The propagation of light is treated in the paraxial approximation. The electric field is described by a scalar function ψ , where

$$\tilde{E}(r,t) = \frac{1}{\sqrt{2}} \tilde{\psi}(r) \exp [i(kz - \omega t) + \text{c.c.}] \quad (123)$$

Here, $k \doteq n_0 \omega / c$, and n_0 is the linear refractive index of the medium. The nonlinearity of the refractive index is represented by writing the index as

$$n = n_0 + n_2 \langle E^2 \rangle, \quad (124)$$

where the angle bracket indicates time averaging and the coefficient n_2 is the index nonlinearity of the medium.

The paraxial equation¹⁷⁹ then assumes the form

$$2ik \left(\frac{\partial \psi}{\partial z} - \frac{g_0}{2} \psi \right) + \nabla^2 \psi + 2k^2 \left(\frac{n_2}{n_0} \right) |\psi|^2 \psi = 0, \quad (125)$$

where g_0 denotes gain in the medium. Here, the Laplacian only operates transverse to the direction of beam propagation,

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \quad (126)$$

In the absence of diffraction effects, Eq. (125) yields the value of the nonlinear phase shift,

$$\psi \sim \psi_0 \exp(iB + g_0 z/2), \quad (127)$$

where

$$B = \int dz \, k(n_2/n_0) |\psi|^2.$$

The quantity B (the so-called B integral) is also a measure of the growth of small-scale instabilities in the beam, based on the Bespalov-Talanov theory.¹⁷⁸

MALAPROP distinguishes between free-space propagation and propagation in a nonlinear medium. In free space, propagation is represented by the fast Fourier transform (FFT) in one or two dimensions. In the nonlinear medium, the differential equation [Eq. (125)] is integrated using finite differences. Other elements that can be represented in MALAPROP are spatial filters, apertures, beam expanders, and beamsplitters. The treatment of each of these elements is discussed below, as is the treatment of noise.

In its present form, MALAPROP does not carry the temporal history of the pulse. Instead, it integrates Eq. (125) at a particular instant of retarded time, i.e., at a particular position in the incident pulse. A technique was developed to allow analysis of saturated amplifiers in single- or multiple-pass configurations without requiring the retention of the pulse temporal history and the gain medium. This technique is also described in this report.

An example of MALAPROP is given at the end of this article to illustrate the features of the code and the format of the output. The code was used to illustrate the respective effects on beam breakup of spatial filtering, zero-path relays, and long-path (near-field) filtering. These results are discussed at the end of this article.

Detailed Description

In MALAPROP, a laser system or propagation path is represented as a series of elements, each of a given type. At present, the element types include nonlinear media, free paths, apertures, spatial filters, beam expanders, and beamsplitters. Other types can be added to the list as need dictates. In this section, we describe the physical assumptions and mathematical techniques used to analyze light propagation through each type of element.

To start the calculation, we must specify the width of the computation domain and the number of grid points across that domain along with the vacuum wavelength of light, the incident peak-power density, and the pulse width. The pulse width is only used to model saturated amplifiers. We also specify the points at which output is desired and the nature of the output (paper, 35-mm film, or microfiche).

Nonlinear Media. A nonlinear gain element is specified by its effective active length L , linear refractive index n_0 , index nonlinearity n_2 , and initial gain g_0 (or loss $\alpha = -g_0$). For a saturating amplifier, the saturation fluence J_s is also specified. The propagation equation [Eq. (125)] is integrated with a finite difference scheme (see Fig. 2-303). The solution ψ is advanced from one value of z to the next over a step size d , following an implicit method. Replacing the transverse derivatives by central differences leads to the difference equation

$$\left[1 - (g_0 d/4) - i(d/4h^2)\delta_n^2 - ikd(n_2/n_0)|\psi_n^-|^2/2 \right] \psi_n^+ = \left[1 + (g_0 d/4) + i(d/4h^2)\delta_n^2 + ikd(n_2/n_0)|\psi_n^-|^2/2 \right] \psi_n^- \quad (128)$$

To avoid an iterative scheme, the quantity $|\psi|^2$ in the nonlinear index is assumed to vary slowly enough to be adequately represented over the integration by $|\psi^-|^2$. To investigate this assumption, we temporarily ignore diffraction and analyze the plane-wave solutions of Eq. (128). If we define the constants

$$a = g_0 d,$$

$$b = kd(n_2/n_0)|\psi_n^-|^2,$$

we can write the plane-wave solution of Eq. (128) as

$$\psi_p = \psi_0 \left[\frac{(1 + a/4)^2 + (b/2)^2}{(1 - a/4)^2 + (b/2)^2} \right]^{p/2} \exp(i\phi) \quad (129)$$

where p is the number of steps in the z direction from $z = 0$ and

$$\phi = p \left\{ \tan^{-1} [2b/(4 + a)] + \tan^{-1} [2b/(4 - a)] \right\} \quad (130)$$

It is evident that there are two requirements on the a and b coefficients so that the numerical solution will approximately equal the exact plane-wave solution,

$$\psi_e(z) = \psi_0 \exp(ap/2 + ibp) \quad (131)$$

Clearly, as long as $a = g_0 d \ll 4$, gain or attenuation will be accurately modeled. In addition, the nonlinear phase accumulation will be accurately modeled as long as the argument of the arc tan in Eq. (130) is less than 0.2. [For $x > 0.2$, $(\tan^{-1} x - x) > 0.01x$.]

Fig. 2-303. Diagram of grid used in MALAPROP integration. Symbols are defined in Eq. (128).

Thus, to maintain accuracy for plane-wave solutions, we require that the gain or loss in a z step satisfy $g_0 d \ll 1$ and that the index nonlinearity satisfy $b < 0.02$. To satisfy the diffraction criterion, a relation exists between the longitudinal step d and the transverse grid size h : $d \ll kh^2$. The implicit algorithm is stable for any step size; thus the step size is determined entirely by accuracy considerations.

For two-dimensional calculations, these same considerations apply. The alternating direction implicit¹⁸⁰ method (ADI) is used to integrate Eq. (125) with successive steps sweeping in the x and y direction, alternately. The resultant tri-diagonal matrices, in either one- or two-dimensional calculations, are inverted using Gauss' elimination¹⁸¹ with periodic boundary conditions.¹⁸²

As we have seen from Eq. (123), the function ψ is normalized so that $|\psi|^2 = \langle E^2 \rangle$. Because it is convenient to specify the intensity of the light wave in vacuum rather than the electric field strength, we redefine the amplitude of ψ by the relation,

$$\psi = \sqrt{I} = [c\epsilon_0 \langle E^2 \rangle]^{1/2}. \quad (132)$$

This requires a redefinition of the way in which n_2 is entered into the program.

Aside from Fresnel reflection, which is treated as a beamsplitter, MALAPROP does not adjust the amplitude of the wave inside a dielectric medium. Consider a beam of intensity I (W/cm^2). In vacuum we have

$$\langle E^2 \rangle_0 = I_0 / c\epsilon_0, \quad (133)$$

and in a dielectric medium of index n_0 , we have

$$\langle E^2 \rangle_n = I_0 / n_0^2 c\epsilon_0 = \langle E^2 \rangle_0 / n_0^2. \quad (134)$$

If the dielectric is at Brewster's angle to the beam, the beam area also changes, and

$$\langle E^2 \rangle_B = I_0 / n_0^2 c\epsilon_0 = \langle E^2 \rangle_0 / n_0^2. \quad (135)$$

Accordingly, because we define $\psi = (c\epsilon_0 \langle E^2 \rangle_0)^{1/2}$, we must write the induced index change as

$$n_2 \langle E^2 \rangle_n = (n_2 / n_0) \langle E^2 \rangle_0 = (n_2 / n_0) |\psi|^2 / c\epsilon_0. \quad (136)$$

The quantity that is actually entered in the code for elements at normal incidence is

$$\gamma = (n_2 / c\epsilon_0 n_0) = 4.189 \times 10^{-11} (n_2 / n_0) [\text{m}^2/\text{GW}], \quad (137)$$

with n_2 expressed in 10^{-13} esu, the customary units. For elements at Brewster's angle, the quantity $\gamma' = \gamma / n_0$ is entered and the effective thickness of the element is taken as $t' = t(1 + 1/n_0^2)^{1/2}$, where t is the perpendicular thickness. We verified the code by comparing the computed on-axis phase shift with the analytic value, obtained from Eqs. (127).

Gain Saturation. The dynamics of a saturating amplifier can be expressed in terms of a saturation function $\Phi(\tau)$ given by

$$\Phi(\tau) = -1 + \exp [J(\tau)/J_s], \quad (138)$$

where J_s is the saturation fluence for the medium and $J(\tau)$ is the fluence up to the time indicated by the parameter τ :

$$J(\tau) = \int_{-\infty}^{\tau} dt I(t).$$

If the pulse entering the amplifier is described by the function $\Phi_0(t)$, then at each point z in the amplifier, the saturation function will satisfy¹⁸³

$$\Phi(z, \tau) = \Phi_0(\tau) \exp (g_0 z), \quad (139)$$

where g_0 is the small signal gain at the start of the pulse. From Eqs. (138) and (139), we obtain

$$\frac{d}{dz} I(z, \tau) = \frac{I(z, \tau) g_0}{[1 + \Phi(z, \tau)]}, \quad (140)$$

so that the entire effect of saturation can be expressed at a given point in the pulse and in terms of the local value of the saturation function Φ .

In the version of MALAPROP used for saturating amplification, both the complex function $\psi(x, z)$ and the real function $\Phi(x, z)$ are computed. The small signal gain in Eq. (128) is reduced, as indicated in Eq. (140), to account for saturation.

To treat multiply passed amplifiers, we modeled the gain reduction and possible subsequent recovery by means of lower level relaxation. Here again, the saturation function Φ plays an important role. As is seen in Eq. (140), the quantity

$$G_{\text{eff}} = G(z, \tau) [1 + \Phi(z, \tau)] , \quad (141)$$

is conserved throughout the pulse (G is the local multiplicative gain). Thus, at the end of the pulse, the multiplicative gain is given by

$$G_f(z) = G_i(z) \frac{(1 + \Phi_i)}{(1 + \Phi_f)} , \quad (142)$$

where Φ_i is the saturation function for the entire pulse at $z = 0$ and Φ_f is the saturation function at $z = \ell$ after it emerges from the amplifier. For thin elements, the spatial variation of G can be neglected and the initial gain G_0 can simply be reduced according to Eq. (142). If a long propagation path intervenes between successive passes through the gain medium, the inversion density will increase according to the degree of lower level relaxation. If the lower level empties completely and we ignore degeneracy factors, the gain will recover to the value given by

$$G_f = G_i \left[\frac{(1 + \Phi_i)}{(1 + \Phi_f)} \right]^K , \quad (143)$$

where $K = 0.5$. Partial recovery could be modeled by setting the recovery constant K to some intermediate value ($1 > K > 0.5$), but this feature has not yet been incorporated into MALAPROP.

Because a given element may be used several times in a regenerative amplifier, a record must be

kept for each element of that fraction of the gain reduction which has been fully recovered ($K = 0.5$) and that fraction which is unrecovered ($K = 1.0$). Equivalent information is maintained in MALAPROP by carrying the array Φ in two parts, one recovered and one unrecovered, as the pulse propagates through the system.

In the above discussion, we assume that the amplifying medium is represented by a two-level, homogeneously broadened system with equal degeneracies. This is only approximately valid for Nd:glass. Experimental data on ED-2¹⁶⁴ indicate that the value of K in Eq. (143) should be taken at 0.55 instead of 0.5, to account for the effective degeneracy ratio.

Initial Value. The input pulse in MALAPROP is defined in terms of a spatial variation $f(x)$ and a Gaussian temporal shape. (Any other temporal shape could easily be inserted.) Initially, the intensity is given by

$$I = |f(x)|^2 \exp(-t^2/T^2) , \quad (144)$$

where $f(x)$ is a complex function defined using either internal routines or an external routine employing MATHSY (see § 2-6.7). Here, T is the Gaussian width parameter of the pulse and is related to the FWHM of the pulse by the expression $\text{FWHM} = 1.665 T$. The total energy density in the pulse is given by

$$J(x) = |f(x)|^2 T \sqrt{\pi} = 1.065 (\text{FWHM}) |f(x)|^2 . \quad (145)$$

At a particular point in the pulse, corresponding to a value of $t = \tau$ in Eq. (144), the energy density is given in terms of the error function,

$$J(x, \tau) = 1.065 (\text{FWHM}) |f(x)|^2 [1 + S \operatorname{erf}(\tau/T)]/2 \quad (146)$$

where S is the sign of τ . The erf is evaluated with the rational approximation given in the NBS *Handbook of Mathematical Functions*.¹⁸⁵ Thus the input consists of the values of the complex function $f(x)$, specifying the initial phase and amplitude, the FWHM, and the τ value at which the propagation is

analyzed. The function Φ is evaluated from the values of $J(x)$, both at τ and at the end of the pulse.

Free Space Propagation. Free space propagation is evaluated with the fast Fourier transform (FFT). If the complex amplitude is defined at the plane $z = 0$ as $\psi_0(x)$, then at a subsequent value of z we can write

$$\psi(x, z) = (2\pi)^{-1/2} \int dk \tilde{\psi}(k, 0) \exp i(kx - \kappa^2 z/2k), \quad (147)$$

where the initial Fourier amplitude is defined as

$$\tilde{\psi}(k, 0) = (2\pi)^{-1/2} \int dx \psi(x, 0) \exp (-ikx).$$

Thus the propagation of the beam from $z = 0$ to z corresponds to the sequence of operations: FFT, multiply by a phase factor, and inverse FFT.

"Hard" apertures, i.e., apertures for which the transmission goes to zero discontinuously at some given radius, are readily treated using this approach. The x -integral in Eq. (125) simply is carried out only over the domain $(-L < x < L)$ to model an aperture of half-width L . For two dimensions, a circular aperture is assumed. The masked function is then propagated over the desired distance with Eq. (147) and thus the specification "aperture plus propagation path" is included in MALAPROP as a single element.

Care must be exercised in interpreting the value of ψ at a distance from the aperture that is comparable to the aperture diameter. The sagittal equation solution is an asymptotic solution to the scalar wave equation and so is not valid unless the distance z from an aperture of dimension L satisfies $z > L$.

We assume that the saturation function Φ remains unchanged over free-space propagation paths (the validity of this assumption is discussed later) and Φ is set to zero outside a limiting aperture.

Spatial Filtering. The spatial filter truncates the Fourier spectrum of the complex amplitude by inserting an aperture in the focal plane of a collimating telescope. If the aperture lies within the depth of focus but not exactly in the focal plane, it

acts like a "soft" aperture, yielding a gradual cutoff in spatial frequency rather than a sharp cutoff. The passage of a beam through a spatial filter imposes a phase curvature on the beam. The output of a symmetric spatial filter of focal length F is related to the complex amplitude at the input by the succession of operations — FFT, multiply by phase factor, mask in transform space, inverse FFT, and change sign. At frequency κ , the phase factor is $\exp(i\kappa^2 F/k)$. This corresponds to the negative of the phase curvature that would have resulted from free-space propagation through a distance $2F$ and is the basis for the "zero-path" relay (see § 2-1.3).

The filter transfer function is described by three parameters — the focal length F , the aperture radius R , and the displacement of the aperture from the focal plane, D . The cutoff frequency κ_0 is given by

$$\kappa_0 = k R/F. \quad (148)$$

Each spatial frequency is mapped onto a point in the focal plane at a radius from the origin given by

$$\rho(\kappa) = F\kappa/k. \quad (149)$$

If the filter plane is displaced a distance D from the focal plane, the spot corresponding to each spatial frequency is blurred, with a blur circle radius given by

$$\Delta\rho = (4\pi D/k)^{1/2}. \quad (150)$$

We can calculate the transmission of the spatial filter from the geometry of overlapping circles (see Fig. 2-304). The governing parameters are

$$\nu = (\kappa/\kappa_0) = \rho(\kappa)/R, \quad (151)$$

and

$$\xi = (\Delta\rho/R). \quad (152)$$

The spatial filter transmission then is given as

$$\begin{aligned} 0 < \nu < 1 - \xi : & T = 1, \\ 1 - \xi < \nu < 1 + \xi : & T = (\theta_1 + \xi^2 \theta_2 - \nu \sin \theta_1) / \pi \xi^2, \\ 1 + \xi < \nu : & T = 0. \end{aligned} \quad (153)$$

Here,

$$\cos \theta_1 = 1 - [\xi^2 - (1 - \nu)^2] / 2\nu, \quad (154)$$

and

$$\tan \theta_2 = \sin \theta_1 / (\xi^2 - \sin^2 \theta_1)^{1/2}. \quad (155)$$

For $(\nu^2 + \xi^2) > 1$, we take $\pi - \theta_2$ instead of θ_2 . In Fig. 2-305, the transmission is plotted as a function of ν for two values of ξ . It is very nearly a universal curve, depending only on the ratio $(\nu - 1)/\xi$.

This analysis is applicable to two-dimensional filtering and mimics two-dimensional features, even

when MALAPROP is run in a one-dimensional case. For actual two-dimensional cases, the magnitude of the vector κ is used in the above analysis. An asymmetric spatial filter is treated as the combination of a symmetric filter plus a beam expander. The saturation function Φ is assumed not to vary when the beam passes through a symmetric filter.

Beam Expansion. A beam expander consists of a negative lens of focal length $-F_1$ and a positive lens of focal length F_2 , separated by a distance $F_2 - F_1$. As the beam emerges from the second lens, it is magnified in area by a factor $m = F_2/F_1$. By the Talanov transformation, the effective distance traveled by the beam is $(F_2 - F_1)/m$. Thus, the beam expander corresponds to an aperture and propagation path of length $(F_2 - F_1)/m$, an expansion of scale by a factor m (in each transverse coordinate, if two dimensions are used), and a reduction in intensity by a factor m^2 .

This magnification factor m is appropriate to two-dimensional propagation. MALAPROP assumes that, even in a one-dimensional case, the intent is to mimic the propagation of a real beam. Thus the code assumes that a magnification factor of m yields an intensity reduction of m^2 .

The saturation function Φ is appropriately reduced when the beam passes through a beam expander by the substitution of $\Phi'(x)$ for $\Phi(x)$, where

$$\Phi' = -1 + (1 + \Phi)^{1/m^2}. \quad (156)$$

In addition to the expansion of the beam, a residual phase curvature corresponding to a deviation from perfect collimation in the beam-expander telescope can be included in MALAPROP at any beam expander.

Beamsplitter. The modeling of a beamsplitter closely follows the modeling of the beam expander. If the beam is split N ways, the intensity is

Fig. 2-304. Geometry of overlapping circles [see Eqs. (148) through (155)].

Fig. 2-305. Spatial filter transmission for $-1 \leq \nu < 1 + \xi$, with $\xi = 0.05, 0.25$, and 0.5 . All three curves are plotted vs $(\nu-1)/\xi$ to emphasize the universality of the result.

diminished by a factor N , the complex amplitude is diminished by a factor $\sqrt{N}$, and the saturation function transforms according to

$$\Phi' = -1 + (1 + \Phi)^{1/N} \quad (157)$$

Noise. The principal feature of MALAPROP is the inclusion of stochastic amplitude and phase perturbations in a code to model nonlinear propagation, at least within the approximations implicit in the sagittal equation. To specify the perturbation added at any given surface, we select a mean square amplitude of the fluctuation and a correlation length. The fluctuation is then modeled as a Gaussian random process in the frequency domain to reproduce to the desired power spectrum. We can choose from a number of tractable model distributions: MALAPROP uses the absolute exponential distribution. That is, the correlation function across the aperture is given by

$$F(x_1 - x_2) = \epsilon^2 \exp(|x_1 - x_2|/\ell) \quad (158)$$

where ℓ is the correlation length. The rms magnitude of the fluctuation ϵ , and correlation length ℓ , are separately specified for phase and amplitude.

Equation (158) is not adequate for the periodic boundary conditions assumed in MALAPROP. For

a real periodic function defined on a regular grid over the interval $(1 < n < N)$, where $x = nh$ and with a correlation $\ell = n_0 h$, the correlation function must satisfy the condition

$$F(n - \nu) = F(\nu) \quad (159)$$

In place of Eq. (158), we take the correlation function

$$F(\nu) = \left\{ \epsilon^2 / [1 + \exp(-N/n_0)] \right\} \times \left\{ \exp(-\nu/n_0) + \exp[-(N - \nu)/n_0] \right\} \quad (160)$$

where n_0 is the correlation interval and ϵ is again the rms value of the fluctuation.

The digital transform of this correlation function is the desired power spectrum. Explicit evaluation yields the result for the power spectrum $H(\mu)$

$$H(\mu) = \frac{\epsilon^2}{N} \frac{\tanh(N/2n_0) \sinh(1/n_0)}{\cosh(1/n_0) - \cos \mu 2\pi/N} \quad (161)$$

The functional form of $H(\mu)$ is shown in Fig. 2-306 for various values of correlation interval. It closely resembles the transmission function for a Fabry-Perot interferometer. The maximum value of $H(\mu)$ is $[(\epsilon^2/N) \tanh(N/2n_0) / \tanh(1/2n_0)]$ while the minimum value is

$$[(\epsilon^2/N) \tanh(N/2n_0) \tanh(1/2n_0)]$$

Fig. 2-306. Power spectral density $H(\mu)$ for several values of the correlation interval n_0 . The computation interval is taken as $N = 100$. The power spectral density $H(\mu)$ is normalized to its maximum value.

It is interesting to compare the result for the digital transform with the analytic result obtained by transforming the periodic correlation function:

$$\bar{F}(x) = \left\{ e^2 / [1 + \exp(-L/\ell)] \right\} \times \left\{ \exp(-x/\ell) + \exp[-(L-x)/\ell] \right\}. \quad (162)$$

Performing the analytic transform over the interval $(0 < x < L)$ yields

$$H(\kappa) = (e^2/L)(2/\ell) \tanh(L/2\ell) \left\{ \left(\frac{1}{1/\ell^2 + \kappa^2} \right) + \left[\frac{1}{1/\ell^2 + (2\pi N/L - \kappa)^2} \right] \right\}. \quad (163)$$

The relation between the analytic result, Eq. (163), and the digital form, Eq. (161), is clear. As the interval size goes to zero, $n_0 \gg 1$, and $\mu \ll N$. Under these conditions, Eq. (161) reduces to Eq. (163). Equation (163) also has an added term to allow for the periodic nature of the effect. For every spatial frequency ν there is an equivalent value $(2\pi N/L - \kappa)$ at which the power spectrum must be the same. In the digital spectrum, this condition is satisfied automatically by the cosine term.

This one-dimensional analysis offers a guide to handling the two-dimensional problem. In two dimensions, the correlation function takes the form

$$\tilde{F}(\underline{r}) = e^2 \exp(-|\underline{r}|/\ell), \quad (164)$$

where $\underline{r} = \underline{r}_x - \underline{r}_y$ is the distance between two points in the plane. The digital transform does not immediately succumb to analysis. The analytic transform over the domain $(0 < x < L_x, 0 < y < L_y)$ can be performed to give

$$H_1(\kappa) = \frac{(2\pi e^2/L_x L_y \ell)}{(1/\ell^2 + \kappa^2)^{3/2}}. \quad (165)$$

This is only one term of the true power spectrum, however. In the domain of interest, there are four equivalent points. Thus we write

$$\begin{aligned} K_x &= 2\pi N_x/L_x, \\ K_y &= 2\pi N_y/L_y, \end{aligned} \quad (166)$$

where N_x and N_y are respectively the numbers of points in the two transverse dimensions. Equivalent points lie at the following pairs of spatial frequency values:

$$\begin{aligned} (\kappa_x, \kappa_y) \quad \text{and} \quad (\kappa_x, K_y - \kappa_y), \\ (K_x - \kappa_x, \kappa_y) \quad \text{and} \quad (K_x - \kappa_x, K_y - \kappa_y). \end{aligned} \quad (167)$$

This doubly periodic behavior can be represented in digital form by the digital transform

$$H(\nu, \mu) = \frac{(\pi^2 N_x N_y \ell^{1/2} \sinh(1/n_0))}{[1 + \cosh(1/n_0) - \cos(2\pi\mu N_x) - \cos(2\pi\nu N_y)]^{3/2}}. \quad (168)$$

where ν and μ denote the points in the x and y directions. We assume that the grid spacing h is the same in both directions and that the correlation length is $m_0 h$. Equation (168) represents the model noise spectrum in two dimensions.

A convenient algorithm exists¹⁸⁶ for generating a pair of random variables, u and v , satisfying a Gaussian distribution over the interval $(-\infty, \infty)$ with a zero mean and unit-mean-square amplitude. In one dimension we write the Fourier amplitude of the perturbation (assumed to be real) in the form

$$\tilde{e}(\mu) = (u + iv)[H(\mu)/2]^{1/2}, \quad (169)$$

for $\mu = 1, 2 \dots (N/2-1)$, with the companion amplitude

$$\tilde{e}(N - \mu) = \tilde{e}(\mu)^*, \quad (170)$$

for $(N - \mu) = (N/2 + 1)$ to $(N - 1)$. The amplitudes $\tilde{e}(N/2)$ and $\tilde{e}(N)$ are real and are given by

$$\begin{aligned} \tilde{e}(N/2) &= u[\Phi(N/2)]^{1/2}, \\ \tilde{e}(N) &= v[\Phi(N)]^{1/2}. \end{aligned} \quad (171)$$

The extension to two dimensions is straightforward. Each Fourier amplitude pair as specified above is generated by a call to the Gaussian random variable generator. If, before the introduction of noise at an optical surface in the system, the complex amplitude of the light wave is given by $\psi_0(n,m)$, then an amplitude perturbation creates a new function,

$$\psi_1(n,m) = \alpha \psi_0(n,m) [1 + e_a(n,m)] \quad (172)$$

where e_a is generated as described above. The coefficient α is determined to conserve power in the beam:

$$\alpha^2 = \frac{\sum_{n,m} |\psi_0(n,m)|^2}{\sum_{n,m} |\psi_0(n,m) [1 + e_a(n,m)]|^2} \quad (173)$$

If a phase perturbation is also present, the complex amplitude is further modified to yield

$$\psi_2(n,m) = \psi_1(n,m) \exp [i \tan^{-1} e_\phi(n,m)] \quad (174)$$

where e_ϕ is generated in the same manner as e_a , but with an independent specification of ϵ and ℓ . At each surface in MALAPROP, the root-mean-square magnitude and correlation length for both amplitude and phase fluctuation can be specified.

The approximate treatment of saturation employed in MALAPROP is based on the assumption that ray optics is valid along each path through the system. This assumption fails if very long propagation paths are used or if very fine structure develops on the beam so that the path lengths in the system are large compared to $2\pi a^2/\lambda$ (a is the scale of the structure).

Clearly, the stochastic perturbation applied to the beam creates this latter condition. However, as long as the beam is not too badly broken up, the saturation formula applies in an average sense. Furthermore, beam breakup occurs at the peak of the pulse whereas saturation is a cumulative effect, much of

which occurs before the breakup has developed. For a badly broken-up beam, the saturation analysis will be in error, especially because no account is taken of losses through the spatial filters. However, we are not interested generally in modeling badly broken-up beams because the condition in itself comprises catastrophic failure of the laser system.

MALAPROP Example: Efficacy of Filtering

To demonstrate the use of MALAPROP and to illustrate some of the features of noise amplification in laser systems, the model system in Fig. 2-307 was analyzed. The system consisted of three amplifiers, each with an unsaturated gain of 2X and a thickness of 10 cm. The input pulse was temporally Gaussian with a peak intensity of 4 GW/cm² and an FWHM = 0.06 ns. The spatial profile is a sixth-power super Gaussian (see Fig. 2-308). The amplifiers are assumed to be Brewster-angle disks of ED-2 with effective values of $\gamma = 2.44 \times 10^{-7}$, $n = 1.556$, and $J_s = 4.86 \text{ J/cm}^2$. These values take into account the Brewster tilt of the disks. The net value of B through the system is about 5 rad.

Four cases were run with different filtering strategies (see Table 2-72). Case (a) had no filtering and the successive entrance apertures of the amplifiers were separated by an effective propagation path of 6 m. In Case (b), a long path (60.16 m) was inserted between amplifiers to simulate near-field spatial filtering in lieu of vacuum spatial filters, as advocated by the University of Rochester.¹⁸⁷ In Case (c), the zero-path optical relay was inserted between the amplifiers, corresponding to use of a spatial filter with no limiting aperture. In Case (d), the limiting aperture in the spatial filter was inserted with a half-angle cutoff of 133 μ rad.

Fig. 2-307. Diagram of the model system, consisting of three amplifiers, A₁, A₂ and A₃. The filters F₁ and F₂ represent either propagation paths, vacuum spatial filters, or both, in the cases examined.

Table 2-72. MALAPROP filtering strategies

Case	Net propagation distance between amplifiers, m	Spatial filtering
A	6	No
B	60.16	Near field
C	0	No
D	0	133 μ rad, half-angle

The pulse was short to avoid pronounced saturation effects. Even so, weak saturation was observed. A 2.5% amplitude noise with a correlation length of 1 mm was introduced at each amplifier. This figure is not unreasonable in light of our experience. A figure of about 1% per exterior surface yields results seemingly in agreement with experimental values. Interior surfaces are considerably cleaner. Thus, a figure of 2.5% was taken for a three-element disk amplifier. Dropping the noise level to 1% per amplifier reduced the output modulation proportionately but did not alter the qualitative features of the result in any way.

A typical beam profile at the output of the first amplifier is shown in Fig. 2-309. The intensity modulation at this point is about 5% across the top

Fig. 2-308. Initial beam profile.

Fig. 2-309. Output of first amplifier, with 2.5% amplitude noise at the entrance surface.

of the pulse. The beam profile at the output of the final amplifier for each of the four cases is presented in Fig. 2-310. The effects of the four strategies are clearly seen.

Without filtering and with a net propagation over 12 m, the beam is severely modulated with an intensity variation of 50% from the average value of 25 GW/cm². With near-field filtering, the high spatial frequencies are suppressed ("diffracted out") but the low frequency modulation is as severe as in the unfiltered case. With only the zero path relays, however, the depth of modulation is significantly reduced although the high frequency components are still strong.

Introduction of an aperture at each filter smooths the beam markedly. Only about 0.4% of the beam power is lost at the apertures in the filtered example of case (d). About 0.1% is lost through vignetting in the long path case. However, 0.1% of 25 GW still represents significant power deposition on the apertures and leads to noticeable interference modulation of the beam. When the spatial filter is used without perfect compensation of the optical path, a pronounced reduction of the small scale modulation is obtained, but low frequency perturbations are still allowed to develop.

In Figs. 2-311 and 2-312 we see the log power spectrum and cumulative power spectral density of

the output beam in each case. The main beam is contained, in all cases, in the narrow center lobe. The effect of spatial filtering on the growth of the power spectrum is clearly seen: high spatial frequencies are suppressed by twenty times over the unfiltered cases. The cumulative power spectral density represents the distribution of energy in the focal plane. The broad flare that develops without spatial

filtering is clearly seen extending to several milliradians in Cases (a) and (c), less pronounced in Case (b), and strongly suppressed in Case (d).

This example illustrates some of the features of MALAPROP, both in its modeling capability, and in terms of its graphical output. It represents a unique and powerful tool for the analysis of light propagation in large glass laser systems.

Fig. 2-310. Output of final amplifier for the four cases considered. (Note that the intensity scale varies from case to case.)

Fig. 2-311. Logarithm of the power spectral density (PSD) vs spatial frequency for the four cases considered. Spatial frequencies are converted to the far-field angle.

References

178. J. B. Trenholme, "Review of Small-Signal Theory," and references therein, *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), pp. 179-191.
179. L. A. Vainshtein, *Sov. Phys.-Tech. Phys.* 9, 157 (1964).
180. John Todd, *Survey of Numerical Analysis* (McGraw-Hill, New York, 1962), ch. 11.
181. G. E. Forsythe and W. R. Wasow, *Finite-Difference Methods for Partial Differential Equations* (John Wiley and Sons, New York, 1960), Sec. 13.3.
182. Y. Sahinkaya and E. Yaya, *Engineering Sciences Newsletter*, July-August, 2-3 (1973).
183. L. Frantz and J. Nodvick, *J. Appl. Phys.* 34, 2346 (1963).
184. G. A. Hayward, private communication, Lawrence Livermore Laboratory (September 21, 1976).
185. M. Abramowitz and I. A. Stegun, Eds., *Handbook of Mathematical Functions* (U. S. Govt. Printing Office, Washington, D.C., 1964), Eq. 7.1.26.
186. D. J. Evans and L. V. Atkinson, *The Computer Journal* 13, Algorithm 51, (1970).
187. *Prototype Beam Performance (Beta)*, Laboratory for Laser Energetics, University of Rochester, prepared for ERDA Review, (January 6-7, 1977).

Authors

A. J. Glass
W. E. Warren

Major Contributor

A. Greenbaum

Fig. 2-312. Cumulative power spectral density (PSD) vs spatial frequency (or far-field angle) for the four cases considered, corresponding to cumulative power distributions in the focal plane.

2-6.6 MCHARTSC: A Milestone Chart Constructor

Historically, whenever a manager wants to make a milestone chart for his project, he must first sketch out his data. After many erasures and line juggling, he hands in his sketch to a draftsman who produces a presentation chart. Every so often, an error appears on the draftsman's product. The manager has to proof the chart to ensure that it is accurate and

correctly reflects his ideas. If changes have to be made because of error or changes to the original data, the entire chart has to be redrafted.

The process described above may require several days before a finished product results and requires the attention of at least two persons. If several different charts are needed, this manual process is costly both in time and in personnel. Here at LLL, we have a computer system that is easily accessible to everyone. It takes the place of the draftsman and reduces to 1 min. the interim time of waiting for the finished product.

MCHARTSC is an interactive computer tool that can create and update milestone charts. The chart being made is displayed on the TMDS (Television Monitor Display System) as each sequence of changes is made (see Fig. 2-313). This allows the

user to receive immediate feedback for each set of his instructions. The time lag and the cost of a draftsman as a middle person is eliminated. The computer generates the same (identical) format for any of the charts made. Proofing of the chart is

Fig. 2-313. MCHARTSC output as it appears on a television monitor. Note the presence of the miniature numbers, the instruction menu, and the message board.

Fig. 2-314. MCHARTSC output. The dividing lines are optional. Vertical lines, horizontal lines, neither, or both may be specified. If a field in the chart-identification section is not defined, its label is not displayed.

done immediately by the user. The finished product, Fig. 2-314, can be output to either the RJET (Remote Job Printer) or the FR80 (35-mm film device). The RJET output can be obtained in a minute or two. The FR80 output will be delivered by the beginning of the next working day. The data used in creating the chart may be kept in storage. Modifications can be made by getting the data and modifying only those items to be changed. Therefore, the status of any project can be kept current and a milestone chart can be generated whenever required.

Capabilities

The data file generated by MCHARTSC represents the chart made by the user. The user can specify the filename as he wishes. To begin, a file may be created. During the run, data will be calculated and stored. When a file save is done, the data will be written into the file. Should the user wish to start afresh, MCHARTSC provides the option of a file destroy. Charts can be updated by reading in the respective data files and then using MCHARTSC to update the information.

The television display includes not only the chart but also an instruction menu and a message board. The message board will provide the user with confirmation of commands and/or error messages. The commands are one letter codes that allow the user to identify the following:

- descriptive phrases for up to 15 items.
- actual time range for each item.
- planned time range for each item.
- completion date of each item.
- any item to be totally erased (description, actual and planned time ranges).
- identification of the chart originator (reporter).
- title of the chart.
- identification of the program/division/project.
- report number.
- time range spanned by the chart.
- colors to be used in the chart.
- any command for which user requires help.
- name of file to be created.
- name of file to be read and updated.
- output device to which the display is to be sent.

To minimize the time the user has to spend

waiting for computer response, MCHARTSC handles multiple instructions per input line. The instructions are separated by the linefeed (the "escape") character. Because of the size limitation on the message board, five is the maximum number of instructions which should be lumped together. Lumping more than five may cause the messages to be overwritten and, hence, unreadable.

Output Devices

The TMDS is always linked to the MCHARTSC program. Other output devices are available to obtain the charts in hard copy form. The most convenient and the quickest is the RJET system. In this system, the chart is drawn on a Versatec printer. The quality of the picture is highly dependent upon the condition of the individual printer.

For high quality resolution, the FR80 is recommended. The resulting hard copy (35-mm film) has been requested by TID (Technical Information Department) whenever formal documents are being prepared. Presentation slides can also be made from the film. MCHARTSC has the option of making a file with instructions for the Dicomed Color Film Recorder interspersed in the FR80 data. If this option is used, the user can make a tape from this file and then take the tape to the Dicomed for color processing.

Author
J. S. Chin

2-6.7 MATHSY: An Interactive Language for Mathematical Operations

The Octopus computer network at LLL is powerful and complex, requiring skill and experience of the user. Casual users tend to be inhibited by the complexity and, in many cases, potential users refrain from investing sufficient time and effort to master the system. To ameliorate this problem, we have developed a programming system called MATHSY that provides the casual user with an

easily mastered language for mathematical operations on the Octopus network.

MATHSY is a computer graphics system that has interactive, array processing, and mathematical capabilities. The system operates much like a pocket calculator except that it is much more powerful and its operations are multidimensional. It is interactive in the sense that commands can be given directly from a keyboard and results are displayed on a video monitor after each set of commands is given. It is an array processor in the sense that a command such as SIN takes the sine of all the elements in an array. Most of the mathematical operations found on a pocket calculator and in Fortran are available. In addition, there are many operations which work across vectors or on entire arrays. Results of operations can be displayed in a variety of formats. Pictures are automatically scaled. Vectors or arrays can be displayed as single line traces, families of curves, and transparent or solid three-dimensional surfaces. Arrays can also be represented by contour or isodensity plots, and by continuous gray level pictures.

Background and Motivation

MATHSY is an outgrowth of the MOLSF system at the University of California at Santa Barbara. Even though MOLSF has a number of limitations, it is very easy to create and examine functions with it. Although MATHSY was not originally planned to replace Fortran programming, it has become evident that MATHSY programs have some major advantages over Fortran for many applications.

MATHSY can be run directly from a keyboard, a program file, or both. The results of a function generation or data manipulation can be displayed numerically or graphically at any place in the generation or manipulation. The language is very versatile, yet only about one-tenth as many program lines are needed for a given application as would be required in Fortran. (One MATHSY program with 68 lines of actual instructions does more than the 900-line Fortran program it replaced). Since it is a high-level language, a program requires no compilation (being an interpreter), and is very easy to debug; programming time is very short. (The 68-line program was written in about two days.) Rapid programming is also promoted by the fact that all the system calls to graphics, input/output, and mathematical routines are transparent to the

programmer. Thus, the normal bookkeeping required with Fortran is almost completely eliminated. One other important item is that since MATHSY is a very high-level language and needs few bookkeeping type commands, most routines are easily understood, even by nonprogrammers.

Interaction

Interaction between the computer and user is completely determined by the user at all times. A program or sequence of commands can be interrupted easily at any place in the sequence. When interrupted, data can be examined or manipulated before continuing. Unless otherwise specified, the working array is displayed on the TMDS (Television Monitor Display System) in the manner specified by the user before the interruption. Separate commands, program lines (macros), or routines (one or more macros) can be run at any time. Furthermore, a program can be restarted at any macro. Note that new commands can be defined by the user and looping can be done on any macro or routine.

Array Processing

MATHSY commands operate on arrays, just as easily as on vectors or single values. For example, to find $\sin(\pi/4)$ all we have to do is type the pocket-calculator-like sequence " $\pi/4$ SIN" on a typewriter-like keyboard. The result is automatically displayed on a TV screen that is part of the TMDS. The keyboard and TMDS are connected to LLL's vast computer system. To find a vector of 100 numbers $\sin(X(i))$, where X covers the range $[-2,10]$ linearly, all we need do is type " $\text{DIM } 100 \text{ SPAN } -2,10 \text{ SIN}$ ". The extension from single numbers to vectors carries over to arrays. If array A is some function or set of data points, the array $\sin(A(i,j))$ is generated with " A SIN". Thus, the SIN operator automatically operates on a single number (as with a hand calculator or the SIN function in Fortran) as well as on vectors or arrays. LOG, LN, EXP, TANH, and many other commands operate in a similar manner. An operation such as " $A+B$ " results in the working array being made equal to the sum of corresponding elements in arrays A and B .

Special Functions

Array processing allows for many special functions to be executed with a single command. The running difference function and the running sum function are generated with the DIF and SUM commands. The maximum or minimum across each row of an array and of entire arrays are found with MAX, MIN, MAXA, and MINA, respectively. Zeros or zero crossings of a function or set of data points is found with ZEROS. TRANS transposes arrays. In addition to these simpler types of operations more complex things can be done. Histograms, least squares fits with any degree polynomials, and FFTs (fast fourier transforms) can be made. Another very versatile command is FITS, which fits data with a basis spline routine. The basis spline allows the weighting of data points and the placement of knots or derivative continuity conditions at arbitrary values. The routine also computes specified derivatives and uses a specified polynomial degree for the fitting.

Graphics

In addition to data values being displayed numerically, the data in arrays can be displayed graphically in many different ways. If the arrays are dimensioned one by one, only a single point is displayed. If the arrays have more than one column and only one row, a vector or single line function picture is displayed. If the arrays have more than one column and more than one row, the data will appear as a three-dimensional picture. Commands can be given to display data points only, the points connected with lines, and identifying characters on the points or lines. The three-dimensional pictures can be rotated for different viewing angles. Displays can have linear or log scales and grid lines. Two-dimensional arrays can be displayed either as surfaces, contours, solid objects, or transparent objects. They can also be represented by a continuous gray picture, like a newspaper picture. Also, two or three arrays can be plotted such that they specify X and Y or X, Y, and Z coordinates in a three-dimensional space. This allows for the display of complex ($a + ib$) functions.

Programming

MATHSY can execute commands given from a

keyboard or from a program file. Often, a function can be generated with one or two lines of commands. In this case it is usually informative to enter it directly from the keyboard and display the function every few steps to watch its construction.

If a complicated set of operations is going to be performed or something is going to be repeated several times, it usually is easier to write a program file. The program file can be created within MATHSY or can be created with a text editor, such as LLL's TRIX AC. When writing a program or debugging an existing one, commands can be given directly to MATHSY instead of running the program. If the programmer stops after every few commands, errors are usually very obvious on the TMDS picture displayed.

MATHSY uses overlays, which keeps it from becoming a monster program requiring the whole computer for itself. The core space allocation for data varies as the dimension is changed and as new arrays are defined or deleted. Once a picture has been generated to the user's satisfaction, it can be sent to an RJET (Remote Job Entry Terminal) or the FR80 (film processor). Data can also be written onto disk in binary form or in character form using a specified format.

The set of special commands, along with the basic Fortran-like commands has proved to be versatile. These, along with the graphics commands, mesh calculations with graphic output and feedback. The flexibility of the system has proved useful for users as well as programmers. Many times data were taken in a manner not covered by a MATHSY program. Usually, a few standard MATHSY commands were all that was necessary to transform the data so that the program could be run.

Since MATHSY is an interpreter programmed in Fortran, any given problem could be programmed to run faster in pure Fortran. Intelligent programming with lower level languages might save from 10 to 20% of computer running time, but this seems to be negligible compared to the programming expense that would occur otherwise.

The latest version of the detailed report that describes MATHSY is available on the LLL computer system.

MATHSY Examples

If there were three columns of data, each containing 100 items they might be combined by $[A(i)]$

+B(i))/C(i). Of course, many keys would have to be pressed on a hand calculator for the 100 results. The results could also be obtained by writing a small Fortran program, compiling it, and then running it. With MATHSY, the sequence "A+B/C" immediately displays the results. If, for example, we wanted to know the sum of 100 values of the function $\exp(-X(i)**2)$ for equally spaced values of X over the interval [-1.1], MATHSY could produce the answer with "DIM 100 ID**2 NEG EXP SUM".

At the end of this section are a number of sample MATHSY outputs that illustrate various output possibilities. For example, PDSMIES (Fig. 2-315) analyzes x-ray microscope data. This is the program that was written in about two days; its 68 lines of actual MATHSY instructions do more than the original 900-line Fortran program.

Figures 2-316 and 2-317 from PDSTENS are only two of 15 types of pictures the program generates with its 83 lines of code. It enabled someone who had never been on the LLI computer system before

Fig. 2-315. Output from PDSMIES: a numerical output, a contour plot, and vector or single-line plots.

Fig. 2-316. Output from PDSTENS: two contour plots on the same display. The small spots to the right and left of the center indicate places of maximum intensity.

to start getting data after about one day of training. Most of the learning time was spent on non-MATHSY information. This illustrates an important point: many general purpose programs try to satisfy users' present and future needs. Thus, they are slower and usually much more interactive than needed for a particular job. Since MATHSY programs are relatively easy to change, they can be written so as to minimize the interactions to do only what is needed.

Fig. 2-317. Output from PDSTENS: the array in Fig. 2-316 as a three-dimensional surface.

PDSVECTOR (Fig. 2-318) now takes only a few seconds to produce results which previously required several hours of user time. POWER (Figs. 2-319 and 2-320) replaces another program, which was too cumbersome for effective use.

Torus

The program TORUS (Fig. 2-321) is a four-line sequence of MATHSY instructions, which displays a torus. As can be seen from the TORUS picture, relatively few instructions are needed. The following partly explains the program. The first line is ignored. NOSAVE does a partial reset of things

Fig. 2-318. Output from PDSVECTOR: three overlaid vectors.

other programs may have done. TVX0 and TVY1 tells MATHSY that the program or macro listing is to be displayed at the upper left of the picture. FRONT,60,,20,,11 tells the program to rotate the torus 60 degrees about the X axis, 20 degrees about the Z axis, and to translate 11 units in the Z direction (back into the picture). DIM25; indicates that all arrays are to be 25 by 25. IDZ+1*PI A= puts the A array equal to a linear sweep across the range $[0, \pi]$ in the Z direction. ID+1*PI B= puts the B array equal to the same values across the X direction. COS C= and B SIN S= put the C and S arrays equal to the cosine and sine of B, respectively. A

Fig. 2-319. Output from POWER: a continuously shaded picture.

$\text{COS}+3^*C \text{ X} = \text{XAXX}$ puts the X array equal to $C(3 + \cos(A))$ and then specifies that the X array is to be used for the X axis (X position in three-dimensional space). A $\text{SIN Z} = \text{ZAXZ}$ puts the Z

array equal to $\sin(A)$ and specifies that the Z array is to be used for the Z axis. A $\text{COS}+3^*S$ puts the working array (Y) equal to $S(3 + \cos(A))$. (The working array is always used for the Y direction.) **HIDE MACD RETURN** respectively displays the data by hiding lines behind front surfaces, displays the macros, and ends the program. The picture of the macros and the torus then appears on the TMDS.

Author
G. G. Peterson

2-6.8 DLOGE: A Procedure for Interpreting Optical Densitometer Records

In analyzing both optical densitometer records of laser intensity distributions and x-ray imagery records, it is essential that a reliable and convenient procedure exist for the interpretation of these film density records. We use an optical densitometer to retrieve the film density record, along with a step-wedge calibration curve, from the film. The calibration and film density records of the image are stored on tape and read into the computer as the calibration file and the image file, respectively. The following procedure has been incorporated into a number of programs in use at LLL for film record interpretation.

The first step is to read the calibration file, and then fit the data with a fifth-degree polynomial. Figure 2-322(a) is then displayed on a TMDS. The lower solid curve is the fit through all the input data points, which are marked with "X". The upper solid curve and the points marked with "O" are just an expanded view of the lower-left portion of the lower curve. At this point the user has the option of changing the degree of the polynomial used to fit the data. He can eliminate some of the points at the left or right end of the input data, or he can indicate his satisfaction with the present fit.

Fig. 2-320. Output from POWER: an Argus laser beam intensity output as a function of time.

Because the fit was not good at the left end, one point was clipped off the left end, and the polynomial degree was increased to seven. This resulted in Fig. 2-322(b). This curve is good, and the user gave his approval; Fig. 2-322(c) was generated. This shows the complete range of input density values allowable. If the density goes below 0.6 or above 4.0, the log of the exposure will be zero.

Figure 2-323(a) shows a fit to a different type of calibration curve. The difference in type is not important, but the difference in density range is. Note that this curve only goes to a density of about 2.8. The data to be converted with this curve exceeds 2.8. Thus the curve is extrapolated, as in Fig. 2-323(b). Since the data to be converted was assumed not to exceed the linear region of the curve, no roll-off was made at higher density values.

Attempts to fit this type of curve with polynomials is not new. In the past, attempts have been made to fit automatically with various complexities of functions and methods. The interactive method described here has worked very well for

MACRO

```
1: -- TORUS 1-11-77
2: NOSAV TVXO TVY1 FRONT,60,,20,,11
3: DIM25; IDZ+1*PI A= ID+1*PI B= COS C= B SIN S=
4: A COS+3*C X= XAXX A SIN Z= ZAXZ A COS+3*S
   HIDE MACD RETURN
```

Fig. 2-321. Result of running the TORUS program.

Fig. 2-322. DLOGE (density vs log of exposure) sequence: (a) curve fit with fifth-degree polynomial; (b) data fit with seventh-degree polynomial after first point on left is clipped; (c) final approved curve.

Fig. 2-323. DLOGE curve (a) with small density range; (b) as extrapolated.

hundreds of calibration files. It does take a few seconds of a user's time, but the accurate fits obtained from the few simple commands necessary are preferred by the users over the curves obtained previously.

Author

G. G. Peterson

SOLID STATE PROGRAM

John Holzrichter - Program Leader
Tom Gilmartin - Deputy Program Leader
Bob Kuckuck - Assistant to Program Leader
Patt Page - Secretary

Experimental Physics Group

Marvin Weber - Group Leader - Materials and Advanced Development
Karen Wenzinger - Secretary

Pulse Shaping

Bill Martin - Studies
Bert Johnson - Studies (Electronics)

Optical Spectroscopy

Allyn Saroyan - Laser materials
Champ Dobler - Mechanical Technician support
Dick Morgret - Electronics Technician support
Jeanne Lynch - Electronics Technician support
Tony DeGroot - Computer programming

Damage

Dave Milam - Laser damage experimental studies
Gary Murphy - Electronics support

Oscillator Development Group

Howard Lowdermilk - Group Leader
Jim Murray - Development physics
Steve Davis - Electronics technician
Dennis Downs - Electronics technician

Amplifier Development Group

Gary Linford - Group Leader - Rod and Disk Amplifiers
Stan Yarema - Development
Reeve Johannis - Mechanical Technician
Stan Roberts - Mechanical Technician

Optical Materials Group

Perry Wallerstein - Mechanical Engineering/optical procurement
Tom Marchi - Mechanical Engineering
Warren Allerton - Mechanical coordination
Dick Dunham - Mechanical coordination

Mechanical Engineering Projects

Bill Crothers - Engineering component development
Don Clark - Drafting of amplifier design
Hunt Kuhn - Mechanical coordination

Electronics Engineering Projects

Bill Gagnon – Engineering projects responsibility

Bank Maintenance

Ernest Padillo – Electronics Technician

D. L. Johnson – Electronics Technician

R. D. Demaret – Electronics Technician

D. Martinez – Electronics Technician

Electronics Coordination

Gerry Vieira – Electronics coordination

Joe Cathey – Electronics procurement

Fabrication

C. J. Nelson – Electronics Technician Supervisor

Lamp Evaluation

S. J. McGuinness – Flashlamp evaluation

Shiva Project Management

Bob Godwin – Project Manager

Jim Glaze – Technical Director

Doug Crippen – Budget and Scheduling

Sam Tindell – Secretary

Diane Kelly – Secretary

Laser Systems Group

Bill Simmons – Engineer

Bill Hagen – System design for upgrade

Bruce Carder – Upgrade studies

Bill Fountain – Components

Roy McWilliams – Mechanical Technician

Alignment Group

Erlin Bliss – Systems

Mark Summers – Electronics Engineer

R. L. Cody – Engineering

Power Conditioning

Bill Gagnon – Project Engineer

Ken Whitham – Electronics Engineer

Installation and Maintenance

E. A. Ataide – Electronics Technician Supervision

R. L. Parker – Maintenance effort

Todd Pelley – Controls development

Controls

Paul Rupert – Electronic Engineer

Al Pemberton – Electronic Technician for controls and flashlamps

Dave Badley – Electronic Technician

L. W. Berkbigher – Electronics Engineer

L. W. Thorsen – Programming

G. J. Norell – Printed circuit design

Ken Snyder – Electronics design

J. H. Lane - Electronics design
Ron Holloway - Electronics coordination

Alignment Controls

F. W. Holloway - Electronic Engineer
G. L. Snyder - Electronics interface
R. G. Gant - Electronics Technician
P. J. VanArsdall - Electronics hardware design

Beam Diagnostics

Bob Ozarski - Electronics Engineer
Bob Boyd - Electronics Technician
Dick Duffus - Mechanical Technician
T. S. Whitney - Electronics Technician

Mechanical Engineering Systems

Chuck Hurley - Project Engineer
G. S. Bradley - Mechanical Designer
M. G. Demos - Mechanical Designer
G. K. Governo - Mechanical Drafting

Rotators/Polarizers

John Myall - Mechanical Engineer - Design

Front End/Spatial Filters

Chuck McFann - Mechanical Engineer - Design
John Braucht - Mechanical Designer

Mirror Mounts-Gimbels

Elaine Ashby - Mechanical Engineer - Design
B. J. Kowalskie - Mechanical Engineer - Design
M. Martin - Mechanical Technician

General Assembly

Steve Brajkovich - Mechanical Technician - Supervisor
Lou Rhodes - Mechanical Technician
Jim Rommelfanger - Mechanical Technician

Mechanical Coordinators

Howard Rien - Project Coordinator
Dick Sites - Mechanical Coordinator
Chuck Sanner - Mechanical Coordinator

Clean Assembly

Howard Patton - Mechanical design and supervision
Irv Stowers - Engineering research in techniques
W. A. Jones - Mechanical hardware design
D. W. Neal - Mechanical drafting
Don Wentworth - Mechanical Technician Supervisor
Clean Room Technicians:

K. D. Poor
S. K. Guntrum
C. J. Shurtleff
G. D. Estes
E. D. Harms
M. R. Spragge
J. W. Moore

Target Chamber

Bill O'Neal - Mechanical Engineer - Design

Julio Monjes - Mechanical Engineer - Components

Shiva Nova Project Team (Solid State personnel only)

T. Gilmartin	J. Myall
J. Trenholme	H. Patton
W. Hagen	I. Stowers
W. Martin	B. Carder
H. Lowdermilk	W. Gagnon
W. Simmons	R. Holloway
M. Weber	P. Rupert
B. Johnson	E. Bliss
G. Linford	J. Glaze
D. Milam	F. Holloway
A. Saroyan	J. Hunt
P. Wallerstein	R. Ozarski
T. Marchi	G. Snyder
C. Hurley	M. Summers
W. Fountain	W. O'Neal
E. Ashby	R. Godwin
G. Bradley	D. Crippen
B. Kowalskie	R. Kuckuck
C. McFann	

Theory and Design Analysis Group

Alex Glass - Group Leader

Audrey Heine - Secretary

Aaron Budgor - Statistical methods, mathematical physics

Janet Chin - Systems and applications programming

David Eimerl - Field theory, stimulated processes

Ed Goodwin - Machine language programming, user interaction

John Hunt - Laser design, wave/light propagation physics

Geylord Larsen - Computer technician

Giles Peterson - High level languages, microcomputers

Paul Renard - Computer graphics, large scale applications

John Trenholme - Laser physics, systems analysis and optimization

Bill Warren - Applications programming

Section 3

FUSION EXPERIMENTS

PROGRAM

Contents

Section 3 — FUSION EXPERIMENTS

PROGRAM	3-5
3-1 Experimental Facilities	3-7
3-1.1 Janus	3-7
Spherical Illumination System	3-9
Janus Upgrade—Phoenix	3-13
3-1.2 Cyclops	3-15
3-1.3 Argus	3-18
Laser Operations	3-19
Laser Gain Adjustments, Alignment and Stability	3-20
Target Chamber	3-22
Target Alignment	3-24
3-1.4 Shiva	3-27
Target Chamber	3-27
Incident Beam Diagnostics Package	3-29
Reflected Beam Diagnostics (RBD) Package	3-29
3-2 Diagnostics Development	3-32
Diagnostics Equipment and Techniques	3-32
Control, Data, and Processing Systems	3-33
3-3 Optical Diagnostics	3-34
3-3.1 Ultraviolet Probing of Laser Fusion Targets at 2660 Å	3-34
3-3.2 Argus Beam Diagnostics	3-37
Diagnostic Instruments	3-38
Interpreting the Diagnostic Data	3-42
Derivation of Equivalent Plane Location and Magnification	3-47
Summary	3-50
3-3.3 Ellipsometry of the Scattered Light	3-51
3-3.4 Scattered-Light Calorimeters	3-55
3-3.5 Optical Streak Cameras	3-55
3-3.6 Ultrafast Framing Cameras	3-60
3-3.7 Active Imaging	3-63
3-4 X-Ray Diagnostics	3-67
3-4.1 Time-Resolved X-Ray Spectral Data	3-67
3-4.2 Time-Resolved X-Ray Images of Laser-Imploded Fusion Targets	3-68
3-4.3 Critical Angle Reflection Spectrometry	3-70
3-4.4 High-Resolution Spectrographs	3-71
3-4.5 Spectrographs of Lead Myristate Crystals	3-73
3-4.6 Low-Resolution Subkilovolt X-Ray Detectors	3-74
Calorimeter	3-75
Lead Stearate Bent-Crystal Spectrograph	3-75
Silicon Surface-Barrier Detectors	3-76
Use of Detectors	3-76
3-4.7 Laser Fusion X-Ray Microscopy	3-77
Axisymmetric X-Ray Microscope Development	3-77
Four-Channel X-Ray Microscope Development	3-82
3-4.8 X-Ray Microscopy of Laser Fusion Targets Using Coded Imaging Techniques	3-83
3-4.9 X-Ray Image Detection with Charge-Coupled Devices	3-90
3-4.10 Applications Prospects of Fast Scintillator Evaluations	3-91
3-5 Particle Diagnostics	3-93
3-5.1 Particle Calorimeters	3-93
3-5.2 Ion Spectrometers	3-95
Operating Modes	3-96
Calibration	3-98
3-5.3 Infrared Imaging of Plasma Energy Distribution	3-99
3-5.4 Argus Neutron Time-of-Flight System	3-102
3-5.5 Neutron Yield by Copper Activation	3-105
3-5.6 Radiochemistry of Target Debris	3-108
3-5.7 14.7-MeV Proton Detector	3-109
3-5.8 Pinhole Imaging of 3.52-MeV Alpha Particles	3-111
3-5.9 Zone Plate Coded Imaging of Alpha Particle Emission from Laser Fusion Targets	3-115
3-5.10 Quadrupole Triplet Time-of-Flight Spectrometer	3-118
3-5.11 Permanent-Magnet Alpha Time-of-Flight Spectrometer	3-121
3-6 Real-Time Data and Control Systems	3-123
3-6.1 Target Data Acquisition and Analysis System	3-123
3-6.2 Target Diagnostics Electronics for Argus Laser Irradiation Facility and Proposed System for Shiva	3-126

Conventional System on Argus	3-126	3-6.4 Systems Software Development	3-133
Target Diagnostics on Shiva	3-129	3-6.5 Computer Networking	3-134
3-6.3 Digital Acquisition Modules		3-6.6 Photographic Image Processing	3-135
and Systems	3-131	3-6.7 Film Calibration Method for	
CAMAC Data-Acquisition Modules .	3-131	Analysis of Laser Light	
Video Image Data-Acquisition System	3-133	Energy Distributions	3-138

Section 3

FUSION EXPERIMENTS PROGRAM

The responsibilities of this program are designing, performing, and analyzing experiments with targets irradiated by high-intensity lasers (those being used and those being built). All these lasers are large systems with many subsystems. They are state-of-the-art systems whose construction and operating technologies are being devised as they are built. So laser diagnosis under conditions of rapid change is a significant part of our effort.

Diagnosis of experiments is a second major thrust. Performance and repeatability of target experiments require exquisite control of the focusing of the laser intensity on target. The targets are presently microscopic, posing difficult diagnostics problems. For each individual shot we must measure many physical parameters, both on the laser and on the plasma. The complexity is analogous to nuclear test measurements at the Nevada Test Site, performed at the rate of 10 to 20 target shots per week instead of a nominal one nuclear test per month.

A third major thrust is development of the specific diagnostic tools needed for our measurements. As shown in Table 3-1, the requirements are comprehensive and far-ranging. This table lists the diagnostic instruments for Argus shots, what they measure, and how the data are recorded. Much of the data is acquired in digital form and reduced by minicomputers. For Shiva, microprocessors will initially handle the controls and data acquisition; later a central bank of minicomputers will control the reduction and archiving of shot data. Development and refinement of this computer system is our fourth major area of effort.

Operationally, the Fusion Experiments Program has two functional groups: the Laser/Plasma Interaction Group and the Diagnostics Development Group. Responsibilities of these groups are as follows:

Laser/Plasma Interaction Group

- Planning and scheduling laser fusion experiments.

- Designing and implementing target chamber and target focusing systems.
- Implementing diagnostics on the experiments.
- Developing new diagnostic concepts.
- Operating the Fusion Experiments laser facilities.
- Collecting and reducing target and laser data.
- Analyzing experimental results and feedback to the Fusion Targets Program.
- Coordinating with the Solid State Program on laser developments needed for future target experiments.

Diagnostics Development Group

- Developing new concepts, instrumentation, and techniques for target measurements in the ranges

$$\begin{aligned}10^{16} < n_e < 10^{26} \text{ cm}^{-3} \\1 \text{ eV} < h\nu < 500 \text{ keV} \\1 \text{ eV} < E < 15 \text{ MeV} \\1000 \text{ \AA} < \Delta x < 1 \text{ cm} \\1 \text{ ps} < \Delta t < 20 \text{ ns}.\end{aligned}$$

- Developing laser diagnostics for power levels to 100 TW, intensities of 10^{14} W/cm^2 , and times of less than 1 ps.
- Developing efficient data acquisition systems.
- Developing data reduction techniques.
- Developing the data management system.

In this section we describe developments and improvements in the laser target facilities and the illumination systems. Also presented are results of our continuing developments of high-quality, calibrated, high-resolution diagnostics. The experimental program and results of the experiments are described in Section 4. In 1976 Janus was operated solely with the 4π illumination system. We continued to operate Cyclops until May 16, 1975, at which time the diagnostics and data acquisition equipment were moved to Argus. Argus began target experiment operations on June 2 with a single beam at 1.0 TW and has subsequently progressed to two-beam operation at 2 TW. Improvements in the

Table 3-1. Diagnostic instruments for Argus laser fusion experiments

Measurement	Instrument	Record
Neutron count	1 copper activation counter 1 time-of-flight detector (2 fluor-PM) 2 fluor-PM systems (6 detectors)	Special coincidence counter system 6 traces + 8 CAMAC channels 12 traces
X-ray spectrum	Active gypsum flat crystal RAP bent crystal CAR carbon reflector Lead stearate bent crystal 7 channel K-edge filters 4 channel K-edge filters	Ditigized image from reticon array Film Film Film 7 CAMAC channels 3 traces + 1 CAMAC channel
X-ray spatial distribution	1 axisymmetric x-ray microscope 2 x-ray microscopes (4 channels each)	Film (8 images) 2 Film
X-ray temporal character	4 LEXD Filtered x-ray streak camera	4 traces Film (10 images)
X-ray calorimetry	4 SiSB detectors 3 tantalum foil x-ray calorimeters	4 CAMAC channels 3 chart records
α spectrum	1 quadrupole triplet spectrometer 2 magnetic-TOF spectrometers	3 traces 6 traces
Ion energy spectrum	2 magnetic spectrometers 1-4 channel CN detector	4 traces 4 Films
Ion spatial distribution	8 Faraday cups 11 differential calorimeters 1 pinhole camera	12 traces 11 chart records Film
Electron energy spectrum	Magnetic spectrometer	9 CAMAC channels
Second harmonic conversion efficiency	2 PIN diodes	2 CAMAC channels
Laser temporal and spatial distribution both incident and scattered	2 target plane multiple image cameras 2 target plane streak cameras Forward and backscatter streak camera 2 forward and backscatter multiple image cameras	2 Films (50 images) 2 Films (6 images) 1 Film (3 images) 2 Films (10 images)
Optical energy balance	North- and south-incident calorimeters North- and south forward and backscatter calorimeters 40 PIN diodes 10 1.06- μ m calorimeters or box calorimeter	Computer (2 channels) Computer (2 channels) 40 CAMAC channels 10 chart records 6 chart records

Table 3-1. (Continued)

Measurement	Instrument	Record
Laser system performance	Oscillator streak camera	1 trace
	Switched out pulse energy diode	1 trace
	Pulse train monitor	1 trace
	Spark gap timing monitor	1 trace
	Prepulse monitor	1 trace
	7 interstage calorimeters	Computer (7 channels)
	6 nearfield beam photos	6 Films
	Flashlamp current monitors	20 traces
	Faraday rotator field monitors	10 traces
Total for one shot:		
	85 oscilloscope traces	
	82 data channels from computerized acquisition system	
	102 photographic images	
	24 chart records	
	1 digitized image (1024 data at computer output)	
	1 coincidence counter output	

fill factor and apodizing techniques have increased the on-target power capability by more than a factor of 2.

The Shiva project team is responsible for the laser design and construction; for pointing, alignment, and focusing; and for the target chamber. The Fusion Experiments Program is responsible for the target diagnostics design and implementation, including incident and forward and backscattered beam diagnostics.

In diagnostics developments, we have four major efforts: optical diagnostics, x-ray diagnostics, particle diagnostics, and real-time data acquisition and control systems. We have devoted significant effort in each of these areas so as to provide a fuller picture of the experimental parameters and perform this function expeditiously.

Author
H. G. Ahlstrom

3-1 EXPERIMENTAL FACILITIES

3-1.1 Janus

During 1976, the Janus laser system (Fig. 3-1) was upgraded in three areas:

- In September, the A disk heads — the most easily and frequently damaged components in the

system — were replaced with a 4-cm rod amplifier. The amplifier performed well during the remainder of the year.

- The photographic apodized aperture was replaced with one constructed by a metal vapor deposit technique. Troubles with the original cell drying out were thereby eliminated.

Fig. 3-1. James layout in 1976.

- The optical gate electronics were encased in a metal housing. Consequently, shots were no longer lost because of noise pretriggering the switch.

In December 1976, the optical diagnostic and alignment system, positioned at the target end of the Janus laser, was improved by

- Removing the diagnostic splitters between the final turning mirrors and the target chamber. (This decreased the B integral value and reduced beam losses resulting from reflections.)

- Antireflection (AR) coating the Faraday rotator glass. (This reduced beam losses resulting from reflections.)

- Performing optical diagnostics and alignment with the beams transmitted through the final turning mirrors. (The Faraday rotator glass position was unstable, resulting in frequent misalignment.)

The improved system (Figs. 3-2 and 3-3) has been made compact by moving the east and west diagnostics to the east and west laser tables. To make this change we moved amplifiers B4 and B6 from the outside of the laser tables (Fig. 3-1) to the inside.

Spherical Illumination System

Aligning the Janus laser involves backlighting (illuminating) the laser target. In 1976, we installed an ellipsoidal-mirror spherical illumination system¹ and used it — in conjunction with Janus — to make time-integrated and time-resolved x-ray images in

which one side and both sides of laser targets were illuminated. Because introduction of the illumination system increased the time needed to align Janus, only 120 targets were irradiated in 1976, compared with approximately 300 in 1975. Another 20 shots were fired to calibrate the system.

For the past year, LLL has been using this 4π sr system to study the Janus laser's interactions with plasma. The system design (Fig. 3-4) was previously discussed in the 1974 Laser Program Annual Report. In that design, $f/4.7$ lenses focus the two beams of Janus through openings in the ellipsoidal mirrors.* The beams are then spread out on the surface of the opposing mirror and focused on the target. The marginal ray was designed to be 81.5° from the beam axis. Figure 3-5 shows the designed relative intensity at the target surface for a single beam. Figure 3-6 shows the "actual" beam profile. This actual profile was determined by taking into account the radial profile of the experimental beam (Fig. 3-7), the deviation of the ellipsoidal mirror from the design (Fig. 3-8), and the best way to overlap the two beams so as to produce the most uniform distribution possible.

*The ellipsoidal mirrors were diamond-turned at LLL. The result showed that excellent large-aperture optics can be produced in this way. A maximum slope error of $22.5 \mu\text{rad}$ was achieved, which corresponds to a maximum ray position error of up to $3 \mu\text{m}$ at the target.

Fig. 3-2. New optical diagnostics: east.

Fig. 3-3. New optical diagnostics: west.

Fig. 3-4. James spherical illumination system.

The experimental laser beam has roughly the desired design shape (super-Gaussian)

$$I = I_0 \exp [-(R/R_0)^5], \quad (1)$$

but in fine detail it has hot spots caused by small-scale self-focusing and diffraction rings. The rings

Fig. 3-5. Relative intensity at target surface for a single Janus beam.

Fig. 3-6. Actual beam profile. The best illumination occurs when the foci are overlapped 20-24 μm .

arise as a result of using hard apertures in the final amplifier stages. The largest error in design is an underestimation of beam size (Fig. 3-7).

In the design configuration, the foci of the two converging beams overlapped by 28 μm . However, we found that when we used that overlap we had to refocus the mirrors to produce relatively uniform illumination (Fig. 3-6). Experimentally, the most uniform x-ray radiation occurs when the overlap is 18 to 22 μm . The experimentally determined overlap is in excellent agreement with calculations performed using the actual measured beam profiles.

Fig. 3-7. Comparison of the radially averaged experimental beam and the design beam.

Fig. 3-8. Intensity variations at the target surface.

Fig. 3-9. Present Janus staging showing aperture (A.A.), the location of the four main lenses, their spacings, the amplifier locations, and the beam splitter locations. The solid lines show the marginal rays of the laser beam as defined by the intensity radius ($\sim 10^3$) beyond the apodizing aperture (A.A.). The dashed lines enclose the useful portion of the beam. The rest of the beam cannot be used because of clipping in the output amplifiers.

Fig. 3-10. Janus upgraded to Phoenix. No new amplifier hardware is needed, but five new vacuum spatial filters will have to be installed.

We aligned the system by first positioning all components with the aid of transmitted and reflected beams and then adjusting the positions with the aid of a Twyman-Green interferometer and a gold alignment ball at the target position. Precise alignment was complicated by the fact that the optical system had 20 degrees of freedom while the target chamber had an additional five. Furthermore, because the optical system exhibited mechanical hysteresis with respect to the target chamber, it was necessary to repeat the alignment procedure for each target.

Janus Upgrade—Phoenix

The conceptual Phoenix laser system grew out of a study performed to find out how to upgrade Janus.² The designs considered were greatly influenced by two practical programmatic constraints. First, costs had to be minimized by using existing amplifiers. Second, the system, including the control room, had to fit into the high ban clean room area of Building 381. Table 3-2 shows the estimated costs of moving the Janus components to Bldg. 381 and upgrading the system.

Several versions of the Phoenix system were studied with J. B. Trenholme and E. J. Goodwin's

**Table 3-2. Estimated cost of building
Phoenix including labor**

	Cost thousands of dollars
Moving costs	
Power conditioning	73
Moving laser amplifiers and hardware	60
Target electronics	39
Target chamber	2
	174
Upgrade costs	
Spatial filters	40
Upgrade target electronics	50
Kuizenga type oscillator	100
Optical tables	30
	210
Total estimated cost of upgraded system	394

BALLS code.³ This code, which has been successful in simulating Argus, contains a B integral analysis of a laser amplifier chain. As analyzed by the code, the present Janus laser (Fig. 3-9) suffers from several staging faults:

- The amplifiers at the beginning of the chain are not properly filled by the diverging beam, resulting both in unnecessary astigmatism and high B values for a given power level. Partly to compensate for the latter, but mainly to achieve a ≤ 200 -GW beam at $\Sigma \Delta B \geq 4.5$, the final two B amplifiers are severely overfilled.

- Although the ≤ 200 -GW beam is focusable within a 300- μ rad cone, the diffraction pattern caused by the hard aperturing adds significant distortion to small-scale-induced aberrations already present.

- No use is made of the spatial filter technology developed on Cyclops and Argus.

In Fig. 3-10 we propose a Phoenix staging configuration designed to meet the shortcomings mentioned above. Note that the beam is split after passing through the 25-mm rod amplifiers rather than after the second B amplifier, as on the present Janus system. The new staging equipment consists of five spatial filters, one Faraday rotator isolator and a Kuizenga type actively mode-locked oscillator. The target chamber is a spare Argus chamber and is already on hand. A 4th harmonic probe beam for interferometric or holographic measurements is also included in this design. Figure 3-11 shows how this equipment would fit into the available space.

We have compared the anticipated performance of the Phoenix laser to that of the present Janus system (Fig. 3-12). The input power is amplified linearly until small-scale self-focusing effects limit the power/beam focusable on a target. Measurements have shown that Janus is presently capable of delivering about 80% of its output power within a 300- μ rad cone at an amplifier chain B value of about 4. With the Janus staging (Fig. 3-9), a B value of 4 at the target implies that a 180-GW beam can be focused, with f/1 lenses, on a spot with a diameter of about 30 μ m. With the same ΔB value of 4 at the target, the Phoenix staging should be capable of delivering about 450 GW/beam into a 300- μ rad cone. In experiments with the Argus laser, we have already achieved >400 GW/beam out of a similar aperture laser at the B to C spatial filter. Figure 3-13 shows data taken on both the north and south arms of Argus. The measured output power

Fig. 3-12. BALLS code estimates of Janus and Phoenix performance. The power that can be focused through an $f/1$ lens to a $100\text{-}\mu\text{m}$ -diam microsphere target is plotted vs chain input power from the existing oscillator/preamp system.

Fig. 3-13. Measured power of a beam after it has passed through a spatial filter at an acceptance angle of $400\text{ }\mu\text{rad}$.

of a spatial filter, with an acceptance angle of about $400\text{ }\mu\text{rad}$, has been plotted vs the measured input power.⁴ These data demonstrate that Phoenix will be capable of delivering about 900 GW well inside the acceptance angle of a $100\text{-}\mu\text{m}$ spherical microsphere target in the focus of an $f/1$ lens. Among the advantages of such a system, besides the

improved output power, is that the use of a more stable environment and a better oscillator will improve the reliability of the system. Another, less obvious, advantage is that by moving Phoenix to the Argus high bay area, technicians working on both laser systems can help each other with maintenance and alignment tasks.

References

1. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, UCRL-50021-75, pp. 384-386.
2. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, UCRL-50021-74, pp. 35-42.
3. J. B. Trenholme and E. J. Goodwin, "Fast Lumped Element Analysis of Laser Systems," *Laser Program Annual Report—1976*.
4. These data were taken by D. R. Speck and J. T. Hunt.

Authors

K. R. Manes
J. E. Swain

Major Contributors

F. Rienecker
D. E. Campbell
E. K. Storm
H. G. Ahlstrom
J. A. Monjes
T. C. Stewart
B. W. Radke
K. L. Andrus
T. D. Schwinn
A. J. Glass

3-1.2 Cyclops

The Cyclops laser was first assembled as the test bed on which solid state laser components could be developed, improved, and tested. As such, it was the proving ground for components developed for Janus II, Argus, and Shiva. Starting in early 1975, Cyclops was used almost exclusively as an interim target irradiation facility; it had more power than Janus and Argus was not yet operational. In May 1976, to make available the resources needed to bring Argus into full operation, Cyclops was shut down. The following September, it reverted to a beam propagation facility and component test bed,

especially in connection with beam pointing, tracking, and focusing studies related to the Shiva alignment system.

In contrast with previous years during which laser staging changes were made at rapid intervals, 1976 saw only two major changes to the overall Cyclops configuration. We replaced the A-disk amplifiers with one 4-cm rod amplifier and we spatially overfilled the output 20-cm amplifier stages. The 4-cm rod amplifier yielded a much cleaner spatial profile because the number of optical surfaces in this stage was reduced from 24 to 2. Extensive online testing of this rod amplifier subsequently was conducted on Cyclops.

The spatial overfill was accomplished by replacing the output lens of the spatial filter and restaging all the C-size components. This increased the output-beam diameter to 20 cm, lowering the B in

the output stages and thereby yielding more efficient pulse propagation.

For the target experiments, we used an equivalent plane viewing system to record the temporal history of the laser pulse and the energy density in the target plane. Figure 3-14 shows typical data obtained with this system.

There are two spatial filters in the Cyclops system. One is located early in the chain after the preamplifiers; the other, a vacuum spatial filter, is situated midway between the B and C stages. Small-scale self focusing, which originates earlier in the chain, generates high frequency spatial noise. This is largely removed when the pulse is focused through the vacuum spatial filter pinhole.

Figure 3-15 shows that the experimentally determined transmission of this filter falls off gradually for peak input powers in excess of about 100 GW.

Fig. 3-14. Cyclops beam properties in the target plane (shot 56020501). The time-integrated equivalent plane photograph is shown on the left and the time-resolved streak photograph of the same image is shown on the right.

Fig. 3-15. Cyclops vacuum spatial filter transmission declines according to $T \approx 1 - 4P^2$ for $P = E/\tau$ in TW.

The solid curve drawn through the data in Fig. 2 is given by $T \approx (1 - 4P^2)$ for $P = E/\tau$ in TW. We have shown experimentally that the transmission of the Cyclops spatial filter scales approximately as

$$T \approx 1 - 1/3(B/B_c)^2, \quad (2)$$

where B is the instantaneous nonlinear phase retardation accumulated along the path from the input spatial filter to the vacuum spatial filter.

The value of B for peak transmitted power, B_c , is related to the focusing parameters and input beam quality in a complicated fashion. For the particular staging of Cyclops used in these experiments, $B \approx 15P$ at the vacuum spatial filter. The available data suggest that B_c^2 is approximately proportional to the angle subtended by the spatial filter pinhole at the input lens. In this case,

$$B_c \approx 132(d/f) = 2.3 \text{ rad}, \quad (3)$$

where d is the pinhole diameter and f is the focal length of the input lens. This form for T is apparently valid for $B/B_c \gtrsim 1.7$ and has been obtained by assuming temporally Gaussian and spatially parabolic input pulses.

Because the gain of the output stages (including passive losses) is fixed at 4.7, there is a maximum attainable output power of approximately 0.7 TW, of which approximately 0.6 TW is focusable on a small target. In Cyclops, the single available vacuum spatial filter was located so that half of the nonlinear phase distortion would occur before and half after the filter on a high power shot.

With such a spatial filter transmission, Gaussian input pulses should be distorted in time. Pulses with input powers at the vacuum spatial filter of 0.2 TW or less suffered flattening of their temporal peaks but little distortion otherwise. By contrast, pulses with input powers of 0.25 GW or more showed a strong temporal dip.

The variability of the temporal and spatial output of the laser made it necessary to measure these parameters at the system output on each target shot. Figure 3-16 shows powers measured at the target,

Fig. 3-16. Because self focusing removes energy from the beam at the peak of the pulse, estimates of focusable power based on input pulse duration are often wrong. Measured input and output pulse durations were averaged to produce this plot.

demonstrating that estimates of focusable output power based on input pulse duration will be in error when self-focusing removes energy from the beam.

During 1976, Cyclops was fired 157 times as a full system. This included target, calibration, amplified spontaneous emission (ASE), and noise-measurement shots, of which the success rate was 78%. A total of 100 successful target-related shots were taken in one- and two-beam configurations. Of all laser components, the oscillator demanded the most attention because these shots had target pulse-width requirements from 30 to 500 ps. Peak pulse powers ranged up to 0.7 TW with single-arm energies extracted from the laser up to 200 J.

The target results of Cyclops were limited by its ability to generate spatially and temporally clean focusable pulses. Nevertheless, it did provide an expanded data base for a large variety of targets.

When corrected for actual focused power, the Cyclops data points are in good agreement with lower and higher power shots from Janus and Argus, respectively. This included the first repeatable milestone of greater than 10^7 thermonuclear reactions from single-beam illuminated targets.

Author
F. Rainer

3-1.3 Argus

As described in the previous section, Argus became available early in June 1976 for single-sided

target irradiations with short (<100 -ps) pulses. By mid-July the second arm was operational, permitting two-sided target irradiations at approximately 2 TW on target. Construction and characterization were completed the following month, and we launched a full schedule of target irradiation experiments.

Since then, Argus' operation has focused on two program goals: to provide high-quality, well-diagnosed beams for the experiments, and to improve the laser output power and reliability. Both goals are being met. We are constantly upgrading our capabilities and, by late December, had more than doubled the focusable output power—to more than 4 TW—for 100-ps pulses. Target irradiation experiments that have produced more than 10^9 neutrons per shot⁵ have also addressed some important aspects of laser-plasma interaction and laser-induced compression of thermonuclear fuels.

In parallel, we have designed and built the target facility including the target chamber, target diagnostics, data-acquisition systems, and target alignment systems. This effort, a cooperative endeavor involving many groups in the laser program, has carried through from specification writing to setup and checkout of the laser focusing, output beam diagnostics, and laser alignment systems. In this article we describe our operations to date with Argus and several of these systems.

Laser Operations

From June 1 through December 31, the Argus team fired 257 full-system shots and more than 630 characterization and setup shots involving the firing of only the oscillator and rod amplifiers. Table 3-3

Table 3-3. Argus shots from June 1 through December 31, 1976

Type and purpose	Number
Oscillator + all rods: System setup and characterization	631
Full-system shots:	257
Target experiments	79
Beam-propagation studies	92
System check and calibration	86

Fig. 3-17. Number of shots from Argus for given output power intervals. All available data are shown.

categorizes these shots according to purpose. Figure 3-17 plots the full-system shots vs output power for all those on which output power data are available.⁶

To accomplish this many shots and perform routine and required maintenance on the laser has required a full-time crew of four scientists, nine laser technicians for the laser and target rooms, and four technicians for the target-data recording and readout system. These people collectively man the facility 16 hours a day, 5 days a week. System and component maintenance and modifications are often done by other program personnel with specialties in specific areas (e.g., clean-room personnel for amplifier assembly, electrical technicians for power supply and bank maintenance). Five full-time workers are allocated to Argus operations for these purposes.

The system firing rate is determined by the cooling time of the C disk amplifiers and Faraday rotators. The nonuniform heat distribution in these elements, after a shot, causes significant beam aberrations and deflections. With the present cooling system, these effects have diminished enough after about 2.5 h so that alignment for the next shot can begin. With a 30-min minimum alignment time, the time between full system shots is thus at least 3 h.

During a normal day of target irradiation shots, the laser crew performs the following tasks:

- Adjusts and characterizes the oscillator to get the desired pulse duration.
- Adjusts and characterizes the laser gain to get the desired energy on target.
- Aligns the laser beam and spatial filter.

Table 3-4. Diagnostics on typical laser shot

Diagnostic	Total quantity	Purpose (quantity)
Fast photodiodes	3	Oscillator pulse train (1) Selected oscillator pulse (1) Prepulse detector (1)
Calorimeters	11	Preamp output (1) 1-in. rod output (2) B-booster output (2) Laser output (2) Equivalent-plane energy (2) Target reflected energy (2)
Near-field cameras	6	1-in. rod output (2) B-booster output (2) Laser output (2)
Streaking cameras	4	Preamp output (reticon readout) (1) Equivalent target plane (2) Target reflected pulse (1)
Multiple-image cameras	4	Equivalent-plane array (2) Target return (2)
Oscilloscope traces	31	Pockels cell timing (1) Amplifier flashlamps (20) Faraday rotator current (10)

- Sets up the laser diagnostics.
- Positions the target and aligns the beam on the target.
- Sets up the target diagnostics.
- Takes, processes, and records the diagnostics data.
- Keeps records of all experiments.
- Performs whatever maintenance is needed to keep the laser and diagnostics operating at best efficiency.

Because the laser and target alignment are done manually and the firing rate for rod shots to set up the system is 1 shot/5-min interval, characterization is both time-consuming and manpower-intensive. As an example of the effort required, Table 3-4 summarizes the laser diagnostic data taken on a typical

target shot. All of these diagnostics—for each shot—are set up, taken, labeled, interpreted, and stored. Each is needed for checking a critical element of the laser operation or interpreting the target experiments. Specific details of many of these measurements are given elsewhere in this report or in prior reports.^{7,8}

Laser Gain Adjustments, Alignment, and Stability

For optimum short-pulse performance, the Argus laser is fired with the flash-lamp voltages of all amplifiers beyond the first 25-mm-diam rod amplifier

in each arm set for near maximum gain.⁹ Adjustments to change output energy and to balance the two arms are made by changing the flashlamp voltages on the 12-mm-diam rod amplifiers and on the first 25-mm-diam rod amplifier in each chain. In practice, this is done by measuring the energy at the output of the 25-mm-diam rod stages on shots in which only the oscillator and rod amplifiers are fired. Adjustments to the voltages of the flashlamp bank are made until the desired rod output energy — appropriate to the desired energy on target — is obtained.

Alignment of the Argus chain is done manually with the aid of a cw YAG alignment laser colinear with the pulsed oscillator, insertable crosshairs, ir-sensitive television imaging systems, and handheld portable ir viewers. At the front of the chain, the oscillator output beam is aligned to the 12-mm preamplifiers, the front-end spatial filter, and the beam expansion optics. The cw YAG is aligned to the front-end spatial filter and the beam expansion optics. Thereafter, through the amplifier chain, the cw beam and pulse beam are colinear and optically equivalent. Permanently installed ir-sensitive TV cameras with insertable crosshairs are used to check the alignment of the cw beam through the stages of the 25-mm-diam rod amplifiers.

Day-to-day alignment of the main chains consists principally of aligning the five vacuum spatial filters in each arm. The cw alignment beam and optics system shown in Fig. 3-18 are used in the alignment.

To do the alignment, all pinholes in the spatial filters are removed from the beam path and the Galilean telescope is adjusted to image the beam waist in the plane of the reference crosshair, which in turn is imaged on the TV camera by the relay lens. The mirror at the front of the chain is adjusted to center the beam on the reference crosshair. The rotating diffuser is then inserted in the beam to illuminate the television screen fully. The pinholes are brought into position, moved transversely to center on the crosshair, and then moved along the beam line until the pinhole edges are in sharp focus. This procedure is repeated for all five pinholes. After the best focus positions are found, the pinholes are translated along the beam line to compensate for the focal zoom calculated¹⁰ for the desired laser output power. The reproducibility of the pinhole manipulators makes only an occasional checking of the pinhole focus necessary.

In our experience, this adjustment need not be made any better than the depth of focus of the f/10 lenses of the spatial filter. Transverse alignment of the beam and centering of the pinholes is done before each shot. For a single arm, this alignment is accomplished by two technicians in about 10 min.

The large number of shots done on Argus were possible only because of the very good alignment stability of the laser. The long-term angular alignment stability of the beam is better than $50 \cdot 10^{-6}$ radians for periods of days. Alignment corrections larger than this are usually necessary only when a

Fig. 3-18. Optical system used to align the Argus spatial filters. Each spatial filter is labeled according to its location in the chain. A single setting of the Galilean telescope focuses the beam waist and the five spatial filter pinholes, when they are properly positioned, onto the reference crosshair and the ir-sensitive TV cameras.

beam steering component is replaced. The short-term stability is better than $10 \cdot 10^{-6}$ radians for periods of more than an hour, simplifying the often time-consuming target and diagnostic alignment.

Author
D. R. Speck

Target Chamber

The Argus target chamber¹¹ (Fig. 3-19) is designed for two-sided irradiation of fusion targets with beams of up to 280 mm in diameter. The target

vacuum chamber, which is cylindrical in shape with spherical end bells, maintains a vacuum of less than 10^{-5} Torr. Beam entrance is through AR-coated windows mounted in the spherical end bells. Diagnostics are mounted in the interior of the chamber and on port flanges of the cylindrical section of the vacuum chamber. Flanges are a standard size, simplifying the installation and rearrangement of the diagnostics. The design permits the target and all focusing elements to be positioned under vacuum with a resolution of $1 \mu\text{m}$. This required that the beam optics, target positioner, and target alignment optics be supported in a stress-free spaceframe isolated from vibration, temperature changes, and vacuum load (see Fig. 3-20). The chamber was designed to accommodate any of four

Fig. 3-19. Cross section of the Argus target chamber, showing $f/1$ focusing lenses.

Fig. 3-20. Closeup photograph of the Argus target chamber with one of the end sections removed. Major chamber subassemblies are labeled.

focusing systems, but to date it has been used only for irradiation by two beams with $f/1$ lenses.

The design vacuum of 10^{-5} Torr is maintained in spite of the internal motors and cables to numerous diagnostics. The vacuum system uses dual circuits, each consisting of a cryopump, turbomolecular pump, cryotrap, and roughing pump. Vibration from pumps is negligible because of careful shock mounting and flexible, low-spring rate bellows. Lateral air-pressure loads are eliminated by placing the circuits in opposition.

The $f/1$ lens micropositioners precisely move the lenses in three orthogonal translational and two rotational directions within the vacuum chamber. The motions are actuated by stepping motors and gear reducers that drive precision screws. Single steps of the motors translate into $0.25\text{-}\mu\text{m}$ incremental movements at the output of the activators.

The target alignment optics (TAO) are used to aid in the alignment and positioning of targets inside the vacuum chamber. The optical system consists of a positive relay lens combined with an achromatic Barlow lens. The system relays the image of the target out of the chamber and onto a reticle at $5\times$ magnification. The image on the reticle is then viewed through a microscope with $20\times$ magnification or projected onto a TV screen. The TAO's are mounted 90° apart, directly onto the spaceframe, and decoupled from the chamber by bellows.

The target manipulator was designed for precise alignment to within $0.5\text{ }\mu\text{m}$ and to have the capability for replacing targets without breaking the vacuum. To insert a target, the vacuum interlock is closed at the bottom of the shield tube. The target is installed on the rod and retracted, the rod is installed on the chamber, and the vacuum interlock is opened. The motorized z-axis extends the target into the chamber for positioning.

Two-beam focusing systems have been procured for focusing the Argus beam onto the target. The simplest system consists of two diffraction-limited $f/1$ aspheric lenses with 200-mm apertures, which have better than $\lambda/7$ wave front distortion and less than $0.01\text{ }\lambda/\text{mm}$ slope error. Up to the time of this report, all target irradiation experiments on Argus have been done with this focusing system. The second focusing system, which is presently being implemented, consists of two $f/0.68$ doublet lenses with 200 apertures and two high-aperture ellipsoidal mirrors.¹² This system provides nearly uniform illumination over the surface of target balls with diameters greater than $50\text{ }\mu\text{m}$.

Author
S. S. Glaros

Major Contributors
F. Rienecker
M. W. Kobierecki

Fig. 3-22. Photographs of the television monitor for C_1 taken during the alignment of a target on Argus: (a) the target illuminated by the diffused cw alignment beam and imaged on the television camera, (b) the alignment beam in the target plane imaged on the same television camera, and (c) a snapshot photograph of an oscillator pulse superimposed on the target.

the beam transmitted through the second turning mirror is used to produce the image. The optics consist of the opposite focusing lens and a Galilean telescope (see Fig. 3-21) that projects magnified images of the target and the two beams to planes referenced by crosshairs CH_1 and CH_2 . The auxiliary lenses L_7 and L_8 reimage the crosshair planes onto infrared-sensitive television cameras C_1 and C_2 , permitting magnification changes in the imaging system to accommodate different size targets.

To accomplish the alignment, the diffuser D_1 is first placed in the beam to illuminate the target. Lenses L_2 and L_4 are adjusted to image the target on CH_2 and television camera C_2 . The target is moved to center its image precisely on CH_2 . The target image is recorded on a video recorder and traced on the television monitor for C_2 . Figure 3-22(a) is a photograph of a transparent ball target taken from the TV monitor for C_2 .

The target and diffuser are moved out of the beamline. Lens L_1 is moved to position the beam and to set the beam size relative to the previously recorded target image. Figure 3-22(b) is a photograph of the cw beam in the target plane and is taken in the same way as the target photograph in 3-22(a).

The diffuser D_1 is replaced and the target returned to its previous position by observing the image on C_2 . Diffuser D_2 is placed in the beam and the procedure is repeated to set L_2 without disturbing the setting of L_1 . When the target is moved it is

carefully returned to its reference position. After setting lens L_3 , negative lens L_6 is adjusted to focus the target on CH_2 . At the completion of the alignment, the target and the focused beams at the target plane can be viewed on the television cameras C_1 and C_2 . The pulse beam alignment may now be checked by viewing attenuated oscillator pulses through the same optical system. Figure 3-22(c) is a photograph of the television screen showing an oscillator pulse superimposed on the target. This step is not necessary, because if both CW and pulse beams are carefully aligned to the spatial filters, they will coincide at the target. After completion of the alignment, the beams are positioned on the target to $\pm 2 \mu\text{m}$, and their sizes are accurately set to match the target focusing requirements.

References

5. E. K. Storm, H. G. Ahlstrom, M. J. Boyle, D. E. Campbell, L. W. Coleman, S. S. Glaros, H. N. Kornblum, R. A. Lerche, D. R. MacQuigg, D. W. Phillion, F. Rainer, F. Rienecker, V. C. Rupert, V. W. Slivinsky, D. R. Speck, C. D. Swift, and K. G. Tirsell, *Laser Fusion Experiments at 3 TW*, Lawrence Livermore Laboratory, Rept. UCRL-79031 (1976), submitted to *Phys. Rev. Lett.*
6. D. R. MacQuigg and D. R. Speck, *Beam Diagnostics on Argus*, Lawrence Livermore Laboratory, Rept. UCRL-78447 (1976).
7. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021 (1974), pp. 290-299.
8. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021 (1975), pp. 380-384, 398-401.

Fig. 3-23. Shiva target chamber.

9. J. A. Glaze, "High Energy Glass Lasers," *Opt. Eng.* **15**, 136 (1976).
10. J. A. Glaze, D. R. Speck, and J. T. Hunt, *Geometrical Theory of Nonlinear Phase Distortion of Intense Laser Beams*, Lawrence Livermore Laboratory, Rept. UCRL-76834 (1975).
11. F. Rienecker, S. S. Glaros, and M. W. Kobierecki, *Argus Target Chamber*, Lawrence Livermore Laboratory, Rept. UCRL-77248 (1975).
12. C. E. Thomas, "Laser Fusion Target Illumination System," *Appl. Opt.* **14**, 1267 (1975).

Author

D. R. Speck

3-1.4 Shiva

Target Chamber

The Shiva target room is $60 \times 60 \times 80$ ft high with 4-ft-thick walls of reinforced concrete. It will accommodate thermonuclear yields of up to 10^{16} 14-MeV neutrons without excessive radiation exposure of personnel.

The 20 laser beams enter the target room from the laser bay and are reflected by two turning mirrors per beam into the target chamber. The second of these turning mirrors has a reflectivity of 97%, allowing 3% to pass through for diagnostics of the incident beam, alignment of spatial filter pinholes, alignment of the beams and targets, and measurements of the forward and backscattered energy during a shot.

The target chamber is a 1.6-m-diam stainless-steel sphere (Fig. 3-23) with a total of 240 ports of various sizes for mounting target diagnostics equipment. Figure 3-24 lists the diagnostics that will be available for the first Shiva target experiments and shows their locations in the target chamber. (See Section 2 for a description of the chamber.)

Existing target chambers at Janus and Argus contain numerous motors, detectors, and coaxial cables that contribute to outgassing loads and result in minimum operating pressure on the order of 10^{-5} torr. Future cryogenic targets will survive only if the pressure is well below 10^{-6} torr, thus every effort has been made to reduce the amount of equipment inside the chamber. The bare chamber will attain a

base pressure of 2×10^{-7} torr. All O-ring gaskets are of fluorocarbon rubber to reduce the outgassing contribution of the seals.

Many laser/plasma interaction phenomena (e.g., light scattering and charged-particle production) are directional, and arrays of detectors must be provided to investigate that directionality. This requirement, coupled with the need to keep all wires outside the vacuum, dictated a large number of access ports with small incremental angles. Therefore, there is a port every 15° in latitude and every 18° in longitude. The 18° increment provides a good match with the five-sided space frame. The ports are standardized, where possible, to a 4-in.-i.d. pattern, allowing flexibility in placing experiments with respect to the incident beams and to the external support structure. Short experimental packages will be cantilevered directly from the target chamber. Longer ones exceeding about 2 m will be braced from the space frame. Very long units will be supported entirely from the space frame and flexibly coupled through bellows to the vacuum chamber.

A modular approach was taken for an energy balance module (EBM), a clustered package that contains two charged-particle calorimeters, one x-ray calorimeter, two photodiodes, and a Faraday cup. Initially 40 of these modules will be mounted in arrays with respect to the laser beams to investigate angular distribution of energy.

A box calorimeter collecting as much as possible of the light energy reflected from the target is being designed to measure absorption. It completely surrounds the target except for two apertures to admit the light beams and one opening through which the target is supported. No other diagnostics (except neutron fluence and one x-ray microscope looking down the beam cluster) can be performed when the box calorimeter is installed.

The clustered beam geometry allows placing diagnostics equipment between the individual beams. An x-ray microscope will be placed in the center of one cluster, providing an unprecedented view of the target x-ray source. Two other x-ray microscopes will be installed on the horizontal equator of the target chamber to provide three orthogonal views. The x-ray spectrum will be measured by a variety of detectors. Continuous, time-integrated spectra in the 200-eV to 5-keV range are recorded by bent crystal spectrometers on film and on solid-state arrays. Higher energy spectra are

- Laser beam
- (Plasma) calorimeter
- X-ray microscope
- Energy balance package
- X-ray spectrometer

- D-H³ proton detector
- X-ray streak camera
- Target viewers
- α -spectrometer
- Neutron detector

measured by detectors with selected filters to separate energy bands.

Charged-particle detectors will include alpha particle spectrometers, electron spectrometers, proton detectors, and ion calorimeters.

Neutron fluence will be measured by a pair of fluor/photomultiplier detectors at different distances from the target to provide a coarse measurement of energy by time-of-flight techniques. A more precise measurement of energy broadening around the 14.1-MeV region is provided by a 100-m time-of-flight detector. Absolute measurement of the total 14.1-MeV neutron fluence is done by a copper activation measurement.

Target debris will be collected and transported via a pneumatic rabbit to a counting station for radiochemical analysis.

See § 3-3 through 3-6 for descriptions of the target diagnostics techniques mentioned above.

Incident Beam Diagnostics Package

A complete laser fusion experiment requires an extensive array of diagnostics monitoring the laser-target interaction phenomenon. However, part of the philosophy of the LLL laser-plasma interacting-effort has been that no target experiment is complete unless it is complemented by equally careful measurements of the characteristics of the laser pulse that irradiates the target. In keeping with this tradition, an incident beam diagnostics (IBD) package (Fig. 3-25) has been designed for the Shiva laser. The package will furnish data on items such as the total energy and the focusable energy out of the laser chain, and the spatial and temporal energy and power distribution at the target plane.

Each IBD package samples about 2% of the 1.06- μ m light that is transmitted through the final-beam turning mirror. Diagnostics included in IBD are:

- A Galilean telescope to focus the beam through a pinhole and onto the other diagnostic elements.

- A calorimeter to measure the total integrated energy contained in the pulse.

- An equivalent plane calorimeter to measure the energy passing through a pinhole corresponding to the target in size and position.

- A fast photodiode to record pulse shape on long (greater than 1 ns) Gaussian and shaped pulses.

- An array camera to record on film the time-integrated spatial energy distribution at various equivalent planes near the focal point.

- A TV camera to view alignment of the beam into the IBD and also to aid in aligning spatial filter pinholes.

- An emerging beam that can be focused onto a streak camera via fiber optics to record the temporal power distribution.

A separate IBD will be provided for each of the 20 beams. Remote focusing of the telescope will allow an "equivalent plane" to be imaged onto the pinhole, the TV camera, and the multiple array camera. The equivalent plane is defined as the plane in the IBD that corresponds to the plane in the actual beam focal region where the target is placed.

Initially, the IBD packages will be mounted on the laser space frame to aid in spatial filter pinhole alignment and to verify the milestone goal of 10 KJ in less than 1 ns. They will then be moved to their permanent position on the target room space frame.

Reflected Beam Diagnostics (RBD) Package

Understanding laser-plasma interactions requires knowledge of the amount of 1.06- μ m light energy that is scattered in various directions from the target. The light energy that is scattered toward the beam focusing lens is analyzed by a reflected beam diagnostic (RBD) package containing a calorimeter, a multiple image camera (MIC), and a TV camera (Fig. 3-26).

The TV camera verifies alignment of the target and aids in imaging the correct focal plane onto the MIC. This focal plane will vary with the size and type of target and generally will not coincide with the best focus point.

The MIC is a simple film holder equipped with an IR transmitting black-glass filter to prevent fogging of the film by ambient light. A remotely adjusted lens system focuses the desired focal plane onto the film. A pair of beam splitters produces a series of images on the film, each image reduced in exposure by one-half of the previous image.

Part of the beam is split off to a calorimeter that measures the total integrated energy that has been forward and/or backscattered into the RBD. A portion of the pulsed beam can be split off and focused

Fig. 3-25. Shiva incident beam diagnostics.

Fig. 3-26. Shiva reflected beam diagnostics.

into a streak camera to record reflected energy as a function of time.

The RBD package is mounted to the pointing, focusing, and centering (PFC) package as an addition, to take advantage of the existing PFC focusing lens and TV camera. A total of 20 RBD packages are provided, one for each beam.

Author
F. Rienecker

Major Contributors
H. G. Ahlstrom
E. K. Storm
K. R. Manes
D. E. Campbell
M. W. Kobierecki
S. S. Glaros
R. G. Ozarski
E. S. Bliss

3-2 DIAGNOSTICS DEVELOPMENT

Detailed diagnosis of laser fusion experiments is difficult because of the microscopic size of the targets, the short duration of irradiation and implosion, and the high temperatures involved. Yet accurate data must be obtained on lasers, laser-plasma interaction processes, and laser-heated target compression. One requisite is the ability to make many diverse physical measurements with high enough spatial and temporal resolution (1 μm and 1 ps) to accurately study the processes under investigation. Another is the ability to provide complete data sets on single shots rather than depending on sampling over many shots. Much work still confronts us—for example, to provide adequate data for comparison with target code calculations—but we are making substantial progress on a wide front including improvement of our diagnostic equipment and techniques and implementation of a computer-interfaced system for control, data acquisition, and analysis of experiments.

Diagnostic Equipment and Techniques

Our present technical capabilities for high-resolution diagnostics are:

$$\Delta t = 6 \text{ ps (infrared)}$$

$$= 15 \text{ ps (x-ray)}$$

$$\Delta x = 1 \mu\text{m (infrared, visible, ultraviolet, time-integrated over pulse duration)}$$

$$\approx 3 \mu\text{m (x-ray, time-integrated)}$$

$$= 6 \mu\text{m (x-ray, 15-ps time resolution)}$$

$$\approx 50 \mu\text{m (200 ps, full frame)}$$

$$100 \text{ eV} < h\nu < 100 \text{ keV (time-integrated)}$$

$$1 \text{ keV} < h\nu < 20 \text{ keV (15-ps time resolution)}$$

$$10^{16} \text{ cm}^{-3} < n_e < 10^{21} \text{ cm}^{-3} \text{ (time-integrated, } \approx 30\text{-ps exposures)}$$

$$\Delta(h\nu) = 1 \text{ eV at } 1 \text{ keV}$$

$$\Delta E \approx 100 \text{ keV for } 14\text{-MeV neutrons and } 3.5\text{-MeV } \alpha \text{ particles.}$$

In our optical diagnostics effort, we have improved and refined streak cameras and demonstrated a prototype ultrafast framing camera that is also applicable to the x-ray regime. We have improved our short-pulse uv probing measurement capabilities for studying target plasmas. A high-quality system for Argus beam diagnostics is now operational. We have made advances in optical calorimetry and provided detailed scattered light intensity and polarization diagnostic systems for target experiments. We are now investigating the properties of solid state array devices for diagnostic imaging, to provide "real-time" acquisition and presentation of quantitative data.

New target implosion data have been obtained from a time-resolved x-ray imaging system based on our x-ray streak camera. We have also used this

streak camera to provide a broader range of time-resolved x-ray spectral data. Several x-ray spectrometers designed to provide particular spectral and resolution capabilities have been built and applied to target experiments. Improved fabrication techniques have been devised for axisymmetric x-ray microscopes, enhancing their resolution to provide better x-ray imaging capabilities. We have developed and applied a complementary x-ray imaging technique using a zone-plate-coded aperture. Solid state arrays (CCD's) have been successfully applied to x-ray image detection; continued study of fast scintillator materials has demonstrated 200-ps resolution and suggested new applications.

Several configurations of ion calorimeters have been designed, built, and implemented on target experiments. Now being implemented is an infrared imaging technique for studying the target plasma energy distribution.

The Argus neutron time-of-flight spectrometer is operational and has provided neutron spectral data on fusion target experiments. Our present copper activation system accurately measures neutron yields of 10^8 or more. In order to be able to diagnose the compressed state of the higher density target implosions toward which we are progressing we are now developing another diagnostic technique, based on neutron reactions with ^{28}Si in the glass pusher.

Diagnostics systems for spectral measurements of the charged-particle fusion reaction products from targets — alpha particles and protons — have provided important target performance data. Alpha-particle imaging systems using both pinhole cameras and zone-plate cameras have successfully pictured the thermonuclear burn region in the compressed target.

We have expanded efforts to develop and implement our computer-interfaced control, data acquisition, and analysis systems, as described below. The ADAS hardware and software system for Argus has been improved and expanded; it now acquires and processes a greater variety of data. Important work has been accomplished on the design, development, and implementation of the Shiva control and data systems. Study has gone into techniques for data reduction and analysis compatible with the computer-interfaced and data-base-management systems.

A modest off-line laser and target irradiation facility, Monojoule, continues to provide essential

diagnostic development capability. Of similar importance is an off-line computer system analogous to ADAS, which is used extensively for software and hardware development.

Author

L. W. Coleman

Control, Data, and Processing Systems

Daily operation of our two target irradiation facilities, Argus and Janus, has reinforced our need for automatic control, data acquisition, and analysis of experiments. The forthcoming Shiva laser system will add substantially to the load.

Our computer-interfaced control, acquisition, and analysis systems have expanded consistent with the Laser Program's experimental needs. This development—from the Janus and Cyclops systems based on small PDP-11/10 minicomputers to the Argus system based on a PDP-11/40—continues toward the integrated system that will serve Shiva. An important step toward integration has been to standardize on Digital Equipment Corporation PDP-11 minicomputers for all systems, based on competitive bids and careful analysis of our overall requirements. The continuity in both hardware and software realized from this evolutionary development has substantially reduced the design effort for new systems.

The overall philosophy for data acquisition and control is modularity and distributed processing. Data-acquisition elements are located near signal sources; isolated digital signals are sent long distances to the computers. This philosophy is implemented on Argus with a CAMAC serial highway over a fiber-optic link to a PDP-11/40. Modular software built on high-level languages augments the hardware modularity.

Distributed processing is extended into the Shiva control system design with a functional hierarchical computer network. For example, for target data, a CAMAC serial highway will connect to a front-end processor (LSI-11) that forms part of the computer network. The LSI-11 connects to a PDP-11/34

minicomputer, which in turn connects to a PDP-11/70 shared with other diagnostic and control functions. This network allows the easy addition of new capabilities or the replacement or amputation of failed system components. Various backup positions are available in case of subsystem failure. Thus, target experiment data acquisition may proceed with only an LSI-11 and the CAMAC highway. This capability has been demonstrated on Argus and will be carried forward into Shiva.

Modularity has allowed new instrumentation and software to be developed and tested off-line on separate development facilities without impacting the normal experimental activities. These off-line facilities are also used to diagnose failed components and check out new components. A calorimeter digitizer CAMAC module and a Reticon interface module were both developed on these facilities. In addition, the fiber-optic communications link was also implemented without impacting the on-line systems.

One important aspect of the experimental data acquisition process not yet integrated into the computer systems is the acquisition, analysis, and display of two-dimensional images. These data are presently digitized off-line and processed in the LLL Octopus computer system. Analysis, archiving techniques, and systems are being developed. Work is in progress to collect these data digitally through suitable array cameras and to send them into the Shiva system.

Data analysis, reduction, comparison with calculations of previous data, storage, and report writing are all done through the Octopus system. The planned connection of the Shiva system to the Octopus system will allow direct access for rapid shot evaluation, data archiving, and shot-to-shot or shot-to-LASNEX comparisons.

Author

J. R. Greenwood

3-3 OPTICAL DIAGNOSTICS

3-3.1 Ultraviolet Probing of Laser Fusion Targets at 2660 Å

The plasma atmosphere surrounding targets irradiated by subnanosecond Nd laser pulses is of interest to the laser fusion program because it is in this area that energy is absorbed and transported to the core region. Optical probing of the target atmosphere is a powerful diagnostic tool for characterizing this important region. This technique can be used to determine electron density distributions in the 10^{20} to 10^{21} e/cm³ range. Typical target/laser interactions involve 100-μm-diam targets irradiated by 100-ps, 1.06-μm pulses with laser intensities on the target of 10^{14} to 10^{16} W/cm². In these situations, axial scale lengths for electron density are in

the 1 to 20 μm range, and critical density contours move with velocities from zero to greater than 10^7 cm/s, depending on target wall thickness, time of observation, and characteristics of the irradiating pulse.

A description of the probing technique, the advantage of probing with short wavelengths, and the need for large numerical aperture optics (corrected for spherical aberration) was given in the 1975 Laser Program Annual Report.¹³ During the past year, we have made significant progress in this work, particularly with interferometry, which we emphasize in the following paragraphs.

Understanding optical absorption of laser-produced plasmas requires a knowledge of electron density distributions in the critical density region. The axial scale length for density decay plays a crucial role in determining which of several competing mechanisms account for the absorption and

reflection of incident laser light. Because the refractive index is simply related to free electron concentration in these highly ionized plasmas, interferometry can be used to unambiguously determine the density distribution. For the plasma model described in Ref. 13, we can determine a required spatial resolution for the interferometer in terms of fringe spacing at 10^{21} e/cm³ as

$$(\Delta Z)_{\text{resolution}} \approx \frac{3\ell\lambda_h^2}{L\lambda_p} \quad (4)$$

where ℓ is the axial scale length, L is the lateral extent of the plasma, λ_p is the probe wavelength, and λ_h is the laser heating wavelength. For typical parameters, Eq. (4) gives a required resolution of 1 μm . Because the contours of constant electron density (refractive index) can move with high velocity, we must use a sufficiently short duration probing pulse, which is given to first order by

$$(\Delta t)_{\text{resolution}} < \frac{(\Delta Z)_{\text{res}}}{4\bar{V}_c} \quad (5)$$

where $\bar{V}_c$ is the velocity of the critical density contour (10^{21} e/cm³ for $\lambda_h = 1.06 \mu\text{m}$) during passage of the probe pulse. For probe pulse durations greater than that described in Eq. (5), the interferometric fringes will smear, lose contrast, and eventually be lost. For contour velocities between 10^6 and 10^7 cm/s, we need probe pulse durations of 100 to 10 ps, respectively. By irradiating thin-walled targets and probing them during reversal of contour motion ($\bar{V}_c \approx 0$), we can minimize the smearing effect in that case.

The interferometer we use is shown in Fig. 3-27. It is holographic, provides the required spatial resolution, and permits simple and accurate imaging, factors of great importance for studying strongly refracting density fields. Figure 3-28 shows a reconstruction from a single exposure hologram, made for reference imaging purposes, of an 80- μm -diam glass shell before irradiation. The hologram was made with a single 100-ps, 2660- $\text{\AA}$ pulse and was reconstructed with a cw He-Ne laser. Diffraction rings with a separation of 1.5 μm are evident.

Figure 3-29 shows the same target 800 ps after irradiation from the left by 1/4-J, 150-ps Nd laser

Fig. 3-27. High-resolution holographic interferometer. With a wavelength of 2660 $\text{\AA}$ and $f/2.5$ collection optics, this system provides a spatial resolution of 1 μm .

pulse. The intensity of the 1.06- μm heating pulse at the target was approximately 10^{14} W/cm^2 . Again 100-ps, 2660- $\text{\AA}$ diagnostic probing pulses were used, this time in the double pulse mode. The time between exposures was five minutes. Figure 3-29 shows that this target was hit 12 μm low and that as a result the blowoff is not coaxial with that of the heating laser pulse. Note also that the irradiated side shows a flat fringe field, while the far side appears to blow off in a more isotropic manner. This is presumably due to radiative forces on the irradiated side during the period of high laser intensity. Abel inversion of the flat field fringes indicates a peak electron density of $7 \times 10^{20} \text{ e/cm}^3$ with an axial scale length at that density of 11 μm . Since this data

Fig. 3-29. Reconstruction of a double exposure hologram of the same target shown in Fig. 3-28. The second exposure was made 800 ps after irradiation by a 1.06- μm laser heating pulse.

is obtained after a delay of 800 ps, a time during which hydrodynamic expansion is known to play a significant role, we may assume that the scale length was considerably shorter during the period of peak laser heating. Higher electron densities were not observed here because of temporal smearing of the fringe data. Since a 100-ps probe pulse was used, we can estimate that the contour velocity was approximately $2 \times 10^6 \text{ cm/s}$.

Because the probe pulse is strongly refracted in passing through the higher density regions of the plasma, it exits at an angle significantly different from that of a reference ray traversing the same initial ray path in vacuum. As a consequence, imaging accuracy is very significant in interpreting the data. Additional fringes appear as one images farther and farther behind the mid-plane of the plasma (away from the collecting lens). Figure 3-30 shows the effect of the imaging plane. Figures 3-30(a) and (b) are imaged on the initial support stalk of the ball. Figure 3-30(c), reconstructed from the same hologram as (b), shows the effect an 80- μm imaging error would have in a conventional (nonholographic) interferometer. The additional fringes are due only to the noncollinear nature of object and reference beams. They do not indicate higher electron density, but they could mislead one to believe that densities in excess of 10^{21} e/cm^3 were recorded had they been observed in a conventional manner.

Fig. 3-28. Reconstruction of a single exposure hologram of an unirradiated 80- μm -diam glass microsphere. The hologram was made at 2660 $\text{\AA}$ with a 100-ps exposure time. The hologram was reconstructed with a cw He-Ne laser.

Fig. 3-30. This figure shows the importance of image plane accuracy for interferometry of strongly refracting plasmas. The reconstructions in the center (reference position) and to the right (-80- μm image plane displacement) are from the same hologram.

Efforts to reduce the probe pulse duration have led to more recent results which show 1.3- μm peak-to-peak fringe separations for a 25-ps, 2660- $\text{\AA}$ probe pulse. This probing diagnostic is currently being implemented on the Janus laser system where it will be used for both interferometric and Faraday rotation measurements.

Reference

13. *Laser Program Annual Report-1975*, Lawrence Livermore Laboratory, UCRL-50021-75 (1976), p. 428.

Author

D. T. Attwood

Major Contributors

E. L. Pierce

D. W. Sweeney

L. W. Coleman

3-3.2 Argus Beam Diagnostics

The performance of laser fusion targets depends critically on the characteristics of the incident beam. The spatial distribution and temporal behavior of the light incident on the target vary with the shot-to-shot fluctuations in output power of the laser and depend also on parameters of the laser system such as choice of apodized aperture, location of spatial filters, and gain of each stage in the amplifier chain. Our experience with previous laser systems¹⁴⁻¹⁷ has shown us that it is crucially important to have a complete diagnosis of the incident beams on each target shot.

Diagnostic Instruments

Figure 3-31 shows a schematic of the beam diagnostics on each of the two arms of Argus.¹⁸ Two percent of the beam from the laser is transmitted through the turning mirror and focused by a Galilean telescope onto the various diagnostics. This type of telescope provides a large magnification in a short distance and has no internal focus where air breakdown could occur. The telescope is adjusted by moving the negative lens to form an image at the crosshair of the energy distribution at the appropriate plane in the target chamber. This is not a direct image, but an image of the equivalent plane in the incident beam. Comparison of these equivalent plane images with direct images of the beam in the target chamber has given us confidence that there are no significant aberrations in either system — i.e., the equivalent plane image is a very accurate and reliable representation of the direct image.

The diagnostics shown here include a near-field camera (upstream from the telescope), to photograph the laser output energy distributions,

and several instruments at the equivalent plane (downstream from the telescope). An array camera records the time-integrated energy distributions. A streak camera provides time-resolved data. A calorimeter with an aperture at the equivalent plane measures the total energy. The TV camera is used for system alignment. The optical distance from the telescope to each of the diagnostics is adjusted to match the distance to the crosshair.

The principle of the equivalent plane system is illustrated in Fig. 3-32 for a pair of simple lenses. Given two ideal diffraction-limited lenses which focus the same beam, and a plane some distance δ_1 from the focus of lens 1, there will be an equivalent plane at a distance δ_2 from the focus of lens 2 at which the energy distribution is the same except for a magnification factor. The location and magnification at this equivalent plane can be derived from geometrical optics or from diffraction theory,^{19,20} as is done later in this article. The formula for the two-lens system is shown in Fig. 3-32. For more complicated systems, such as Argus, it is easier to compute the relations numerically.

Fig. 3-31. The diagnostics shown here are included on each of the two arms of the Argus laser.

Fig. 3-32. Principle of the equivalent relationship between beam conditions in the target chamber and those observed by the diagnostic instruments.

Images of the time-integrated energy distributions at several planes near the focus are recorded with an array camera. This instrument utilizes a series of beam splitters to generate multiple images of the focusing or diverging beam. The first pair of beam splitters, with mirrors spaced close together, generates a vertical column of images with known intensity ratios. The second mirror pair splits this one column into several columns, each of which images a different plane near the focus. The spacing between equivalent planes at the target locus is determined by the spacing between the second pair of beam splitters and the longitudinal magnification of the system.

Figure 3-33 shows a typical set of images obtained with the array camera on the Argus north beam with an output of 70 J in 63 ps. The equivalent planes cover a region from 230 μm inside focus to 14 μm beyond focus. The second column in this set shows the energy distribution at a plane where a 100- μm target ball would be placed. The images in each column are identical except for intensity level. Computer analysis of a pair of these images provides a photographic-density-to-energy-density conversion curve and eliminates the need for a separate calibration exposure. Variations in exposure and processing make it necessary to have a separate calibration curve for each plate. The

method used to calculate the calibration is discussed in § 3-6.7.

A streak camera provides information on the temporal behavior of the focused beam. The slit of the streak camera²¹ is centered on the energy distribution at the equivalent plane. The image of this slit is then swept rapidly across the film (Fig. 3-34). Multiple images are generated optically using a glass etalon for typically a 300-ps time delay and a beam-splitter pair to generate a row of images with varying intensity. The etalon provides a precise calibration of the sweep speed, and the intensity steps ensure that at least one image will have an optimum exposure. The scanning and computer analysis of these images is similar to the procedure used for the array camera images, except that a step-wedge film calibration is used. The multiple-image method depends on an exposure ratio which is hard to determine in these streak images due to lack of uniformity in the response of the streak tube.

The near-field camera records the laser output energy distributions. Figure 3-35 shows a typical image from the near-field camera on an Argus target shot. The ripple pattern is the result of beam breakup due to small-scale self-focusing in the laser glass. The low spatial frequencies in this beam pattern are transmitted by the spatial filter. The features seen in this near-field image are larger and

Fig. 3-33. Array camera photographs are of time-integrated energy distributions. The five series of exposures shown here correspond to five different equivalent planes.

smoother than those we have observed at the output of our lasers without beam-breakup vacuum spatial filters. Analysis of this image shows that the energy peaks are typically twice the average energy density.

A parabolic apodizer shaped the cross section of the beam in Fig. 3-35 to provide a soft edge and avoid diffraction effects. This reduced the effective diameter of the beam from the 20-cm clear aperture to 14 cm (the effective diameter is defined here as the diameter containing 90% of the energy). The fill factor was 38%. We have recently replaced the apodizer with a hard aperture, using a relay-lens projection technique²² to increase the fill factor at the output to 70%. The output fill factors are determined by computer analysis of the near-field photographs.

The images shown in Fig. 3-36 are from the array and streak cameras for a typical target shot. The array camera image gives us the time-integrated

energy distribution in the focusing beam. The streak camera image shows the time-resolved intensity distribution along a narrow slit across the center of the beam. We can see a good correlation here between features in these two images. The 16° tilt of the slit is a result of the nonplanar layout of the optical system.¹⁸ These images are from an equivalent plane of the north beam 158 μm inside the focus in the target chamber. The energy distribution at this plane is about 100 μm in diameter. The orientation with respect to the target looking north at the oncoming beam is shown by arrows in the figure.

We can see several features in these images which are relevant to target performance. The overall symmetry of the distribution shows that the aberrations are well under control. This symmetry is essential to obtain a symmetric implosion with high compression and high yield. At high power, even with spatial filters, the beam at the target will be broken

Fig. 3-34. Streak camera photographs of time-resolved energy distributions.

Fig. 3-35. Near-field camera photographs show laser output energy distributions.

Array camera record,
time-integrated

Streak camera record,
time-resolved

Fig. 3-36. Array camera and streak camera photographs of the energy distribution in a typical Argus high-power beam at a location 158 μm inside the $f/1$ lens focus. Argus north beam, shot 36060801, energy 70 J, pulse duration 63 ps, power 1.1 TW, neutrons produced 7×10^{-7} .

up into small intense filaments.²³⁻²⁵ The speckled structure of the energy which intercepts the target may reduce the efficiency of absorption and stimulate the growth of instabilities in the imploding target shell.

In the streak image we see a slight inward curvature of features at the edge. This is a result of whole-beam self-focusing, which causes an inward shift of the focus at peak power. This shift was calculated to be 14 μm at 1.5 TW for the $f/1$ lenses in Argus.²⁶

Interpreting the Diagnostic Data

To obtain quantitative information on the spatial distribution of energy and on the total power on target vs time, these images are scanned on a microdensitometer and analyzed by computer. Figure 3-37 shows an image from the array camera after digitization and processing. This is a half-tone

Fig. 3-37. Computer-processed image of the array camera photograph of Fig. 3-36.

simulation generated on one of the TV monitors which are part of the LLL computer network. Comparison of these images with the original photographic images verifies the scanning and processing.

The densitometer data is converted point by point to relative energy density using a film calibration curve determined automatically by a computer routine which statistically analyzes the density levels in two adjacent images (see § 3-6.7). The energy in the entire image is then normalized to the

calorimeter reading. The centroid of the energy distribution is computed and marked with a cross, as shown in Fig. 3-37; the lines mark the bounds for row and column averages.

The results of this computer analysis of an array camera image are shown in Fig. 3-38. Row and column averages provide plots of the averaged energy density across the focal spot. The radial average is used in computing the focal spot diameter and generating beam profiles for input to LASNEX. The edge of the focal spot is defined as

Fig. 3-38. Results of computer analysis of the array camera photograph of Fig. 3-36.

the radius containing 90% of the energy. The row and column averages confirm the good symmetry seen in the photograph. Comparison of these plots with theory indicates that low-order aberrations are less than one wave. The initially parabolic profile is flattened in the center. This is expected, since the losses to small-scale breakup in the laser are more severe in the central, more intense part of the beam. The hole in the center is probably a small random aberration.

The ratio of peak-to-average energy density is reduced in these averaged plots. A better picture of

the structure of the filaments is seen by comparing photos from different planes on the same shot. Figure 3-39 shows images from two different planes separated by 72 μm . Notice the correlation of features in these two images. The structure of the hot spots is almost identical in the two planes. From these photos we see that the filaments are typically 10 μm in diameter and hundreds of μm long. The peak-to-average energy density from a single-line scan is about 3:1, as shown in Fig. 3-39(c). These filaments are not projections of the pattern in the near field; no correlation is seen with hot spots in

Fig. 3-39. Similarity of images of beam energy distribution at two planes spaced 72 μm apart shows filamentary structure of the energy distribution near the focus. Argus north beam, shot 36060906, energy 68 J, pulse duration 61 ps, power 1.1 TW.

Fig. 3-40. Computer-processed image of the streak camera photograph of Fig. 3-36.

the near-field photos. The size, shape, and contrast of the filaments are characteristic of a speckle pattern. The size and shape are consistent with theory,²⁷ and the high contrast is an inherent property of the speckle pattern.

The array camera images give us a complete picture of the time-integrated energy distributions near the focus. To learn more about how these distributions change in time during the pulse, we need to analyze the streak camera images. Figure 3-40 shows a streak camera image after digitization and processing. Time runs from bottom to top. The horizontal axis is distance across the slit. The conversion and normalization of the density data are the same as for an array camera image, except that a calibration exposure is used to determine the density-to-energy conversion curve, rather than the multiple-image method.

In Fig. 3-41, we show a power plot obtained by taking a column average over the entire image of Fig. 3-40, then normalizing the total integrated energy to the calorimeter reading. The instantaneous structure of the focal spot is revealed by

row and column averages through the center of the streak image (Fig. 3-42). The loss of energy in the center at the peak of the pulse is much more pronounced than in the time-integrated energy distributions.

Driving the laser beyond its peak power capability results in excessive beam breakup and loss of transmission at the spatial filters. This loss appears as a dip in the peak of the output power pulse. A severely overdriven shot is shown in Fig. 3-43. Improvements in the apodization and staging of the laser have increased the peak output power to 2.8 TW per arm. See Section 2 for a discussion of the current best performance.

Our reliance on streak cameras to measure the laser output power depends on the assumption that the energy which falls on the slit is representative of the entire focal spot. This assumption is supported by the consistency of the results from shot to shot and from one image to another on a given shot. We believe these figures on peak power are accurate within 25%.

Fig. 3-41. A column average over the entire streak camera photograph of Fig. 3-36 provides a plot of power on target vs time.

Fig. 3-42. Row and column averages from the streak camera photograph of Fig. 3-36 reveal the spatial and temporal structure of the pulse.

Fig. 3-43. Badly overdriven shot shows loss of power at the peak of the pulse. Argus north beam, shot 36050604, energy 65 J, pulse duration (input) 65 ps.

Derivation of Equivalent Plane Location and Magnification

Given two lenses which focus the same beam, but with different focal lengths, a plane some distance δ_1 from the focus f_1 of lens 1, there will be an equivalent plane a distance δ_2 from the focus f_2 of lens 2 at which the energy distribution is the same except for a magnification factor (see Fig. 3-32, earlier in this article). This isomorphism can be derived directly from scalar diffraction theory^{19,20} (assuming paraxial approximations) or from geometrical optics, using the lens law

$$\frac{1}{f} = \frac{1}{d_1} + \frac{1}{d_2}, \quad (6)$$

which relates the distances of the object and image planes to the focal length of a thin lens.

Approximate formulas for the location and magnification of the equivalent plane are given by

$$\delta_2 = (f_2/f_1)^2 \delta_1 \quad (\delta_1 \ll f_1, \delta_2 \ll f_2), \quad (7)$$

$$M = f_2/f_1, \quad (8)$$

where δ_1 and δ_2 are, respectively, the distances from best focus for the lens with focal lengths f_1 and f_2 . A more exact relation for the two lenses is shown in Fig. 3-32.

The Argus optical system is somewhat more complicated (Fig. 3-44). A Galilean telescope is used to provide a long effective focal length in a short distance on the table. The focal length, and hence the location of the equivalent planes, is adjusted by moving the negative lens of the telescope.

The location and magnification of the equivalent planes for Argus is determined numerically in a step-by-step computation using the basic lens law. Starting at the array camera image plane near the focus of the telescope, we compute the location and magnification of the virtual image from the negative lens. The computation proceeds step by step through each lens to the focus of the output spatial

Fig. 3-44. Simplified optical schematic of the Argus beam diagnostic system.

filter, then back to the focus in the target chamber. The overall magnification is the product of the magnifications at each step, with a 7% correction factor to allow for the thickness of the target chamber lens (see Fig. 3-45). This factor results in the correct diameter for the focal spot at the target plane (a parameter of great importance) and exaggerates by 7% the radial position of features in the center of the spot (an error of no significance).

The equations for the system in Fig. 3-44 were programmed into a desktop calculator to produce the plots in Fig. 3-46. As can be seen from these curves, the equivalent plane position is a nonlinear function of the lens position, and the steps between planes in the array camera are not uniform.

The following is a derivation of the equations for calculating the location and magnification of equivalent planes in a multielement lens system.

For a single thin lens the lateral (M_x) and longitudinal (M_z) magnifications can be found by differentiating Eq. (6):

$$M_x = d_2/d_1, \quad (9)$$

$$M_z = \Delta d_2/\Delta d_1 = (d_2/d_1)^2. \quad (10)$$

These relations are true for both negative and positive focal lengths.

For a multielement system, the total magnification is simply the product of the magnifications at each stage:

$$M_x = M_{x1} M_{x2} \dots M_{xn}, \quad (11)$$

$$M_z = M_{z1} M_{z2} \dots M_{zn}, \quad (12)$$

$$M_z = M_x^2. \quad (13)$$

To utilize Eqs. (9-13), it is necessary to calculate the distance d at each stage. This is done using the lens law of Eq. (6). In manipulating a series of equations for a multielement system, it is easier to

Fig. 3-45. Origin of the 7% correction factor for beam diameters near the Argus f/1 focus.

Fig. 3-46. Location of equivalent planes for the array camera as a function of displacement from best focus of the negative lens in the telescope.

specify wavefront curvatures ($c = 1/R$) than focal distances at each point in the system. If we assume propagation from left to right and adopt the convention that positive curvature represents an expanding wave, then the following relations may be derived for propagation through a lens and through free space.

Propagation Through a Lens. For this case [Fig. 3-47(a)] we have

$$c_i = 1/R_1,$$

$$c_f = 1/f,$$

$$c_2 = 1/R_2,$$

with

$$c_2 = c_1 - c_f. \quad (14)$$

Propagation Through Free Space. For this case [Fig. 3-47(b)] we have

$$c_2 = c_1/(1 + c_1 z). \quad (15)$$

These equations may be inverted from right-to-left propagation:

$$c_1 = c_2 + f, \quad (16)$$

$$c_1 = c_2/(1 - c_2 z). \quad (17)$$

With Eqs. (14-17) as background, we now give the details of the calculation for the Argus system (see Fig. 3-44):

Given: $f_0, f_1, f_2, f_3, d_{01}, d_{2c0}, \Delta, d_n, d_{03}$.

Calculate: δ (the equivalent plane), and M (magnification from the equivalent plane to the image plane).

	Programmed equation
$c_{2i} = -1/d_{2i}$	—
$d_{2i} = d_{2c0} - \Delta + d_n$	—

Programmed equation

$d_n = (n - 2) 2s \cos \theta$	1
$c_{2i} = 1/d_{2c0} - \Delta + d_n 0$	2
$c_{21} = c_{2i} + 1/f_2$	3
$M_2 = c_{21}/c_{2i}$	4
$c_{12} = c_{21}/[1 - c_{21}(d_{120} + \Delta)]^a$	5
$c_{10} = c_{12} + 1/f_1$	6
$M_1 = -c_{10}/c_{12}$	7
$c_{01} = c_{10}/(1 - c_{10}d_{01})$	8
$c_{0i} = c_{01} + 1/f_0$	—
$M_0 = -c_{0i}/c_{01}$	—
$\delta_0 = f_0 - 1/c_{0i}$	—
$c_{30} = c_{01}/(1 + c_{01}d_{03})$	9
$c_{3i} = c_{30} - 1/f_3$	10
$M_3 = -c_{30}/c_{3i}$	11
$\delta = -1000(1/c_{3i} + f_3) (\mu m)$	12
$M = M_2 M_1 / (M_3 \times 1.07)^b$	13

^aWe calculate d_{120} from d_{2c0} and the assumption that the wavefront between f_0 and f_1 is collimated when $\Delta = 0$.

$$d_{120} = f_1 - d_{2r0}, \text{ where } d_{2r0} = 1/(1/d_{2c0} - 1/f_2).$$

^bThe factor 1.07 is the correction for the thickness of the $f/1$ target chamber lens.

Summary

We have set up beam diagnostic systems on Argus based on the principle of equivalent planes to provide full diagnosis of the beam on target on each and every shot. We have developed a method for automatic reduction of the photographic data to energy density. We have determined the beam characteristics, both spatial and temporal, which are relevant to laser fusion experiments. These include the focal spot symmetry, radial energy profiles, ray angles, the size, shape, and contrast of the filaments in the energy distributions at the target plane, and loss of energy at the peak of the pulse.

Fig. 3-47. Propagation through a lens and through free space.

We have measured the power on target and verified the peak focusable power as greater than 2 TW per beam.

References

14. D. R. Speck, J. F. Holzrichter, D. R. MacQuigg, and J. E. Swain, *Critical Considerations in the Use of High Power Nd-Glass Laser Systems for Laser Fusion Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-77077 (1975).
15. J. A. Glaze, W. W. Simmons, and W. F. Hagen, "Status of Large Neodymium Glass Lasers," in *Proceedings of the SPIE Meeting*, Reston, Va., March 1976.
16. K. R. Manes, H. G. Ahlstrom, D. T. Attwood, M. J. Boyle, K. M. Brooks, L. W. Coleman, R. A. Haas, J. R. Holzrichter, H. N. Kornblum, K. J. Pettipiece, D. W. Phillion, F. Rainer, V. C. Rupert, V. W. Slivinsky, E. K. Storm, J. E. Swain, and K. G. Tirsell, "Laser-Plasma Interaction Studies at the Lawrence Livermore Laboratory," to be submitted to *J. Opt. Soc. Amer.*
17. E. Storm, H. G. Ahlstrom, and J. F. Holzrichter, *Exploding Pusher Targets Illuminated Using f/1 Lenses at ~0.4 TW*, Lawrence Livermore Laboratory, Rept. UCRL-78729 (1976).
18. D. R. Speck and W. W. Simmons, *Argus Laser Fusion Facility*, Lawrence Livermore Laboratory, Rept. UCRL-78438 (1976).
19. J. W. Goodman, "Fourier Transforming and Imaging Properties of Lenses," Ch. 5 in *Introduction to Fourier Optics* (McGraw-Hill, New York, 1968).
20. M. Born and E. Wolf, "The Three-Dimensional Light Distribution Near Focus," in *Principles of Optics* (Pergamon Press, Oxford, 1975), 5th ed., p. 435.
21. L. W. Coleman and C. F. McConaghy, *Ultrafast X-ray Streak Camera*, Lawrence Livermore Laboratory, Rept. UCRL-75923 (1974).
22. J. T. Hunt, P. A. Renard, and W. W. Simmons, "Improved Performance of Fusion-Lasers Using the Imaging Properties of Multiple Spatial Filters," *Appl. Opt.* (April 1977).
23. V. I. Bespalov and V. I. Talanov, *JETP Lett.* 3, 307 (1966).
24. E. S. Bliss et al., "Propagation of a High-Intensity Laser Pulse with Small-Scale Intensity Modulation," *Appl. Phys. Lett.* 25, 448 (1974).
25. J. F. Holzrichter and D. R. Speck, "Laser Focusing Limitations from Nonlinear Beam Instabilities," *J. Appl. Phys.* 47, 2549 (1976).
26. J. A. Glaze, D. R. Speck, and J. T. Hunt, *Geometrical Theory of Nonlinear Phase Distortion of Intense Laser Beams*, Lawrence Livermore Laboratory, Rept. UCRL-76834 (1975).
27. L. I. Goldfisher, "Autocorrelation Function and Power Spectral Density of Laser-Produced Speckle Patterns," *J. Opt. Soc. Amer.* 55, 247 (1965).

Author

D. R. MacQuigg

Major Contributors

D. R. Speck
G. G. Peterson
F. Rienecker
D. E. Campbell
J. R. Severyn
K. R. Manes

3-3.3 Ellipsometry of the Scattered Light

Measurements of the polarization of scattered light lead to a better understanding of laser-plasma

interactions. Only the p-polarized component of the light is resonantly absorbed near critical density, unless the critical density surface is unstable, and rippling or cavitation occurs. Thus, we can directly measure the fraction of the light that is resonantly absorbed by measuring the polarization of the scattered light. Since the relative phase shift that the two polarization components undergo upon reflection is very dependent upon the electron density gradient ∇n_e near the turning density $n_e = n_c \cos^2 \theta_0$, we can find the density scale height near critical density as well. These measurements and their interpretation are given elsewhere in this report; here we only describe the diagnostic technique.

When measuring the polarization ellipse of a continuous light source, a Soleil-Babinet compensator²⁸ and a polarizer prism can be used. Since the compensator can transform any elliptical polarization state into any other, the measurement involves searching for a null in the light transmitted by the polarizer. The compensator introduces a variable phase shift between the two principal linear polarization states and is usually fabricated from two plates of crystalline quartz whose optical axes are at right angles to each other and to the beam. One plate is made variable in its thickness by constructing it of two wedges whose acute angles are equal. The fixed plate cancels out the large $n \cdot 2\pi$ phase difference.

Since the characteristic time scale of the present experiments is 100 ps, a different method must clearly be used. Four independent parameters are required to specify the polarization state: the intensity, degree of polarization, the aspect ratio of the polarization ellipse, and the angle of the major axis. The sign of the aspect ratio gives the direction of rotation of the electric vector. Since all these measurements must be made simultaneously, the polarimeter is necessarily fairly complicated.

The Stokes parameters are a convenient set to measure. Let the electric field at a given position have the time dependence:

$$\vec{E} = a_1 \cos(\omega t + \delta_1) \hat{a}_x + a_2 \cos(\omega t + \delta_2) \hat{a}_y, \quad (18)$$

where $a_1, a_2, \delta_1, \delta_2$ are real quantities which depend on time. Then the Stokes parameters are the four quantities²⁹:

$$\begin{aligned} s_0 &= \langle a_1^2 \rangle + \langle a_2^2 \rangle \\ s_1 &= \langle a_1^2 \rangle - \langle a_2^2 \rangle \\ s_2 &= 2 \langle a_1 a_2 \cos \delta \rangle \\ s_3 &= 2 \langle a_1 a_2 \sin \delta \rangle \end{aligned} \quad (19)$$

where $\langle \rangle$ indicates an integration over time and $\delta = \delta_2 - \delta_1$. Thus, $s_0/2\eta$ is the energy density ($\eta = \sqrt{\mu_0/\epsilon_0}$ is the radiation resistance for free space) and s_1 is zero if the wave is linearly polarized. The expression $\sqrt{(s_1^2 + s_2^2 + s_3^2)}/s_0$ gives that fraction P of the light that is polarized. The direction (s_1, s_2, s_3) specifies a point on the surface of the Poincaré sphere Σ . Each point on Σ corresponds uniquely to one polarization state. The shape of the electric vector polarization ellipse is specified by the angles ψ and χ . The angle ψ is formed by the conjunction of the major axis with the x axis, where $0 \leq \psi < \pi$. This angle is measured from the positive x direction toward the positive y direction. The $\tan \chi = \pm b/a$ is the ratio of the minor axis length to the major axis length. The sign is positive if the electric vector rotates clockwise when viewed along the propagation direction (righthanded circular polarization). On the Poincaré sphere, 2χ is the elevation angle measured from the equatorial plane, while 2ψ is the azimuthal angle. Thus:

$$\begin{aligned} s_1/s_0 &= P \cos 2\chi \cos 2\psi \\ s_2/s_0 &= P \cos 2\chi \sin 2\psi \\ s_3/s_0 &= P \sin 2\chi \end{aligned} \quad (20)$$

The linear polarization states are positioned on the equator and the circular polarization states are at the poles. Any optical instrument measuring the fraction of light that is in a given polarization state A can be characterized by the Stokes matrix A , where $A_0 = I$ and (A_1, A_2, A_3) are the coordinates of A on the Poincaré sphere. The result of its measurement will be

$$I = \frac{1}{2} A^T s = \frac{I - P}{2} + P \cos^2 \left(\frac{\chi}{2} \right), \quad (21)$$

where T designates the matrix transpose operator on the column vector A and γ is the great circle distance between the points on the Poincaré sphere representing the polarization state A and the polarization state of the light.

Measurement of the six intensities $I(0^\circ)$, $I(90^\circ)$, $I(45^\circ)$, $I(135^\circ)$, I_{RH} , and I_{LH} suffices to determine the Stokes parameters, since

$$s_0 = I(0^\circ) + I(90^\circ)$$

$$s_1 = I(0^\circ) - I(90^\circ)$$

$$s_2 = I(45^\circ) - I(135^\circ)$$

$$s_3 = I_{RH} - I_{LH} \quad (22)$$

where I_{RH} and I_{LH} are the resultant intensities when the light is resolved into its right- and lefthand circularly polarized components, and $I(\theta)$ is the intensity of the linearly polarized component whose electric vector is in the direction $\cos \theta \hat{a}_x + \sin \theta \hat{a}_y$. The Stokes parameters are actually overdetermined since we have the constraints

$$I_{tot} = I_{RH} + I_{LH} = I(0^\circ) + I(90^\circ) = I(45^\circ) + I(135^\circ). \quad (23)$$

The ellipsometer consists of three of the analyzer prisms, such as are shown in Fig. 3-48. Ideally, each prism will measure one of the Stokes parameters (s_1/s_0 , s_2/s_0 , and s_3/s_0) by measuring one of the

Fig. 3-48. Exploded view of analyzer prism assembly. The light enters and exits normal to the oblique surfaces of the analyzer block. Successive analyzer blocks are connected by spoons. Photodiodes measure the amounts of light reflected from the two prism faces.

ratios $I(0^\circ)/I(90^\circ)$, $I(45^\circ)/I(135^\circ)$, or I_{RH}/I_{LH} , respectively. To measure either s_1/s_0 or s_2/s_0 , the principal axes of the prism must be properly oriented. But, to measure the amounts of light in the two circular polarizations, the two polarization states must first be transformed into orthogonal linear polarization states. This is achieved by introducing a 90° phase difference between any two orthogonal linear polarization states, labeled α_1 and α_2 . The analyzer prism that is to measure I_{RH} and I_{LH} follows this phase retardation element in the optical path and has its principal axes at 45° to α_1 and α_2 . Each analyzer prism has its end faces cut at Brewster's angle, but the planes of incidence associated with the reflection and refraction occurring at each face are orthogonal to each other. The linear polarization component that is incident upon the first face as a p wave strikes the second face as an s wave and vice versa. Each polarization component suffers the same reflection loss; hence, the prism does not alter the polarization of the light. Bandpass interference filters (as well as neutral density filters) were placed just ahead of the diodes, primarily to limit the angular acceptance to $\pm 5^\circ$. Without these interference filters, a significant amount of scattered light would shine on the diodes. The 90° phase retardation was achieved by a 45° - 90° - 45° light flint prism. The light is first incident upon the hypotenuse face, and, at each total internal reflection, the s and p waves see a phase shift of about 45° . The phase shift δ may be found from³⁰

$$\tan \frac{\delta}{2} = \frac{\cos \theta \sqrt{\sin^2 \theta - [n(\text{air})/n(\text{glass})]^2}}{\sin^2 \theta}, \quad (24)$$

where θ is the incidence angle measured from the normal and n is the refractive index.

Each prism assembly was carefully shimmed so that when the instrument was assembled, the total angular error would not be greater than several minutes of arc. Removable crosshairs at the entrance and exit make it possible to accurately align the ellipsometer. When it is aligned so that the crosshairs overlap and the incident light is collimated, each photodiode looks at the same region of light. The prism assemblies were stacked so as to minimize the clipping of the beam in the instrument.

The ellipsometer was calibrated by illuminating it with a collimated $1.064\text{-}\mu\text{m}$ beam of uniform inten-

sity. The beam was chopped at about 400 Hz by a mechanical chopper. A lock-in amplifier, externally synchronized by a signal derived from the chopper, measured the difference between the signal from one photodiode and a variable fraction of the signal from another with a precision ratioformer. Thus, the ratio of the signals could be measured by finding the fraction required to give a null. Although the ratioformer is accurate to $<1\%$, SCR switching noise radiated by the flashlamp cables for the cw laser limited the measurement precision to about 1% . We can assume that each analyzer prism measures the fraction of light linearly polarized along one of its principal axes. By varying the polarization of the incident light and measuring the ratio of the amounts of light reflected from the two prism faces, we can determine the Stokes parameters associated with each analyzer prism. When measuring the polarization of the scattered light, we must invert a 4×4 matrix, three of whose rows are the Stokes parameters associated with the three measurements made by the analyzer prisms. The matrix equation has the form

$$\frac{1}{2} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & A_1 & A_2 & A_3 \\ 1 & B_1 & B_2 & B_3 \\ 1 & C_1 & C_2 & C_3 \end{bmatrix} \begin{bmatrix} 1 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix} = \begin{bmatrix} 0.5 \\ I_A/I_{\text{tot}} \\ I_B/I_{\text{tot}} \\ I_C/I_{\text{tot}} \end{bmatrix} \quad (25)$$

where I_A , I_B , I_C are the amounts of light polarized in states A, B, C, respectively. Of course, I_A , I_B , I_C are very nearly $I(0^\circ)$, $I(45^\circ)$, and I_{RH} . The direction (s_1, s_2, s_3) specifies the state of the polarized fraction of the light and $\sqrt{(s_1^2 + s_2^2 + s_3^2)}$ gives the fraction which is polarized.

The ellipsometer has not been used in experiments that are covered in this report. However, the scattered light has been measured with a polarimeter that determines only the time-averaged degree of linear polarization along one axis. This is done by measuring the fraction of the light that is reflected from a glass plate at Brewster's angle to the scattered light. We do not worry about interference between the reflections from the front and

back surfaces because the plate is thick enough to ensure that the reflections are temporally incoherent. From this measurement, we can calculate the degree of linear polarization $p = (I_{\parallel} - I_{\perp}) / (I_{\parallel} + I_{\perp})$, where $I_{\parallel}$ and $I_{\perp}$ are the energy flux densities of the light polarized parallel to and perpendicular to the transmission axis of the Brewster window, respectively.

References

28. Max Born and Emil Wolf, *Principles of Optics* (Pergamon Press, Oxford, 1970), 4th ed., pp. 692-694.
29. *ibid.*, p. 30.
30. J. A. Stratton, *Electromagnetic Theory* (McGraw-Hill Book Co., New York, 1941), p. 500.

Author

D. W. Phillion

3-3.4 Scattered-Light Calorimeters

Volume absorbing calorimeters designed to measure the energy of 1.06- μm radiation continue to provide our basic standard for determining laser performance and the efficiency of energy coupling from laser pulse to target. A "box" calorimeter, model LC-16, for spatially integrating the scattered light from targets irradiated by two beams has been described previously.^{31,32} A larger version, LC-16D, has been built for use on Argus. Its construction is generally similar, but the ion-shield and absorber cubes have been enlarged to 102 and 70 mm on an edge, respectively, rather than 51 and 38 mm, to reduce the flux densities at the surfaces. In addition, an earlier version of the box calorimeter, LC-16B, has been modified with one new side for experiments with a single beam from an $f/10$ focusing lens on Janus.

Another type of calorimeter, model LC-21, was built to measure the intensity of scattered light at discrete positions about a target. It is basically similar to the model LC-15 particle calorimeter,^{31,33} but uses NG-1 or BG-18 glass as an absorber and has a surrounding jacket—features that give it some similarity to the LC-13 beam calorimeters.³⁴ Figure 3-49 is a cross section of the LC-21 calorimeter. These have been built with absorbers 12.7 and 19.0

Fig. 3-49. This LC-21 calorimeter is used to measure the intensity of scattered 1.06- μm light at discrete positions about a laser-irradiated target.

mm in diam. A glass ion shield is used over the absorber, and a selective light filter can also be used.

References

31. S. R. Gunn, *Calorimeters for Diagnosis of Laser-Fusion Experiments*, Lawrence Livermore Laboratory, Rept. UCID-17308 (1976).
32. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p. 404.
33. *ibid.*, p. 406.
34. S. R. Gunn, *Model LC-13 Laser Calorimeters Using Commercial Thermoelectric Module*, Lawrence Livermore Laboratory, Rept. UCID-16608 (1974).

Author

S. R. Gunn

3-3.5 Optical Streak Cameras

To meet the growing needs of our experimental program, we are building more LLL compact streak cameras of the type being used, which continue to provide reliable quantitative data. As described in

last year's annual report, there is a classic manufacturing problem with 40-mm microchannel plate intensifiers; however, there has been some easing of this problem, and we have begun receiving some good tubes from one manufacturer. We are still troubled by photocathode sensitivity slump at 1.06 μm in the S-1 image-converter streak tubes, although we have been able to get an adequate supply of acceptable tubes for present needs.

To document camera performance, improve our quantification of streak-tube performance, and evaluate tubes from several suppliers for our possible use, we have undertaken a comparative study of five types of tubes.³⁵ These are the RCA C73435 AG now used; a shortened version of the Instrument Technology (ITL) standard STM100 similar

Fig. 3-50. Image converter tubes: left to right—RCA C73435; ITL STM 100, shortened version; Hamamatsu N895X; ITT developmental.

to that in some commercial streak cameras; a developmental, magnetically focused tube designed jointly by LLL and IT&T; a Hamamatsu N895X tube operated in a camera built by the manufacturer; and an English Electric Valve (EEV) P855 tube operated in a Hadland 675 camera. Our main interest has been dynamic range because this is the chief concern in most of our applications, but the studies have included such parameters as deflection factors, operating voltages, and cathode active areas. Figure 3-50 shows four of the tubes. The fifth—the P855—is similar in appearance to the shortened STM100.

To make the measurements, we use Royal-X-Pan (RXP) film developed to an ASA rating of 2000. Film-response correction is made from exposure of

Fig. 3-51. Typical plot of film density vs log of exposure for Royal-X-Pan film. Usable dynamic range approaches 3.6 decades.

a calibrated step wedge on each piece of film during processing. Figure 3-51 shows a plot of film density vs log of exposure for one piece of this film. As shown, the usable RXP dynamic range approaches 3.6 decades. We correct all dynamic-range data presented for film response by means of this type of plot.

A densitometer presentation from the film of a streak record of the 100-ps etalon output from a single pulse looks similar to those shown in Fig. 3-52. The FWHM is measured for each reflected pulse. Pulse-width broadening is then used as the criterion for determining dynamic range. The lower limit of the dynamic range is established by the base noise level, in this case by the film fog level. The upper level is then determined by the peak amplitude

Fig. 3-52. Typical streak camera output using a 100-ps etalon with 93% coated surfaces. FWHM is in picoseconds.

of the pulse whose width at half-maximum exceeds that of lower amplitude pulses by some set amount. If the noise level of the system is low, this broadening limit can be set as low as 3 ps. However, an unexplained pulse-width jitter is often seen on some systems, even at low levels, so the broadening limit must occasionally be set as high as 10 to 12 ps. This contributes little to the error in determining dynamic range if "saturation" is abrupt but can cause an estimated twofold error or more if the onset of broadening is gradual.

We use streak cameras mainly for laser diagnostics where pulse lengths are generally 50 ps or greater. Therefore, dynamic-range testing is done using a 50-ps YAG at 1.06 μm for S-1 (RCA, IT&T, and EEV) tubes or a frequency-doubled YAG with

output at 532 nm for S-20 (ITL and Hamamatsu) tubes.

Figure 3-53(a) shows raw data points obtained from RXP film and from Kodak Type 4127 commercial film (daylight ASA 50) with the LLL camera using an RCA S-1 tube. We have used the same symbol for plotting the data from a single laser pulse. Figure 3-53(b) attempts to correct the data for variations in the laser pulse width from shot to shot. We believe that some of the noise and apparent pulse-width scatter is caused by the particular camera microchannel plate image intensifier that had become gassy. A dynamic range of 553 was found using RXP alone (limited by available step-edge calibration range), and the dynamic range was extended to above 5000 when data from 4127

Fig. 3-53. Dynamic range data for RCA tube from RXP and Type 4127 film. Part (a) is raw data, and part (b) is same data with some compensation made for input pulse-width variations. The value $10^{1.39} = 24.55$ is measured between 4127 film (◇) and RXP film (○) with 109 exposures of 2.42.

Fig. 3-54. Dynamic range data for ITL tube. Part (a) is raw data, and part (b) is same data compensated for input pulse-width variation. The symbols are the same as in Fig. 3-53.

film were added. The sensitivity ratio between RXP and 4127 was determined from step-wedge exposures to be 24.55, as shown in the figure.

The ITL and IT&T tubes were tested using a four-stage magnetically focused intensifier. The FWHM was plotted (Fig. 3-54) for the ITL tube against various input levels, and the ordinate was converted, as in Fig. 3-53, to dynamic range. An abrupt broadening of the curve was apparent at one point. Plots are shown for the raw data and again after compensation for input-pulse-width variations. Saturation was defined for 3-ps broadening, and this level above film fog was used to determine dynamic range. Also, to keep within the intensifier and film linear ranges, the gain of the intensifier was reduced for the higher-level inputs as required. For the ITL tube, the dynamic range was found to be 223. Similar data for the IT&T tube, the Hamamatsu N895X-S20, and the EEV P855 gave dynamic ranges of 239, 25, and 20, respectively, although pulse-width broadening on the last two was much more gradual, complicating the choice of a precise number.

Although the RCA tube appears to offer a clear dynamic-range advantage, at least three of the five tested seem suitable for our camera system and requirements. The remaining two also might be usable if a fiber-optic output were included on the N895X and if a later version of the P855, with a higher ex-

traction field and positive focus field, were substituted. Temporal-resolution testing must be done before final qualification can be given.

Interestingly, the dynamic range of some of these tubes is greater than previously believed for 50-ps pulses. The most likely reason, we believe, is that in many cases the dynamic ranges of the intensifier as well as the film were included in earlier figures.

We designed a high-speed optical deflection system for picosecond laser-pulse diagnostics.³⁶ Evaluations of a prototype system indicate that an ultracompact streak camera with picosecond resolution can be constructed from readily available components with relatively low cost. A Coherent Associates, model 12, electro-optic beam deflector with a 2-mm-aperture ADP crystal was used in the prototype. This unit deflects wavelengths from the visible to 1.06 μm . When high-power, single, picosecond pulses are used, previous limitations of electro-optic deflectors because of signal-beam absorption, internal heating, and mechanical shock waves are overcome. At 532 nm, a resolution of 18 spot diameters was obtained and the temporal resolution was 1.25 ns, whereas the dynamic range in excess of 200 was limited by the readout system. Using a crystal material with a much higher electro-optic coefficient produces a theoretical resolution comparable to that of electro-optic cameras. Also of interest is the availability of materials useful to wavelengths in excess of 10 μm (tellurium, for example). The high current required to drive the crystal presents some difficult electronics problems,

Fig. 3-55. Schematic diagram of prototype test assembly.

although solutions are available. Readout is done with film, a TV camera, or a linear diode array. Computer manipulation of the output data can be used to improve resolution and dynamic range.

Figure 3-55 shows the experimental apparatus for the prototype crystal streak camera. The laser beam first passes through an alignment and collimating aperture, next through a filter holder, and then into the deflector. For the required precision of alignment, the deflector was mounted in a micrometer adjustable mirror mount, and the deflection sweep circuit was attached to this mount. A 512-element, linear, self-scanned, silicon diode array made by Reticon Corporation was used as the detector. The deflector has a rated deflection coefficient of 1.36 mrad/kV and a maximum allowable deflection voltage of ± 2 kV, giving the deflection angle $\theta = 5.3$ mrad. The laser used for testing the system is an Nd:YAG that produces a 50-ps FWHM pulse. The laser-triggered, avalanche-transistor sweep circuit used in the prototype system has only an approximate 20-A capability and, thus, can only sweep the deflector in about 20 ns. This yields a sweep rate of 0.75 spot widths per nanosecond, hardly enough to measure the width of the 50-ps test pulse. However, mechanical shock wave or thermal-heating effects should be observable by careful comparison of the readout of a deflected and nondeflected beam. (An effort is now under way to develop an avalanche-transistor-triggered Krytron sweep that should achieve a twentyfold reduction in the sweep time.)

Figure 3-56 shows oscilloscope photographs from the Reticon array readout of sweeps of two single [(a) and (b)] and one double (c) switched-out 532-nm pulses, preceded by a double exposure of a single nonswept pulse, dc-positioned by +1500 V on the deflector. These and other data give a FWHM resolution of 20 spots for the full ± 2 kV. Analysis of these and many more similar recordings reveals no detectable anomalies attributable to shock wave or thermal-heating effects. The transmission at $1.06 \mu\text{m}$ was measured at 0.2% of the transmission at 532 nm for the prototype deflector. However, for full-scale output at $1.06 \mu\text{m}$ with a 50-ps pulse width, the system, including the Reticon array, has an input energy requirement of less than 1.5×10^{-7} J compared with the requirement at 532 nm of less than 1.6×10^{-10} J. Improving the system resolution by increasing the sweep rate will require a proportional increase in input energy. However, an increase in resolution of only about two orders of magnitude

Fig. 3-56. Photograph of the Reticon-array readout presentation. First pulse on the left in each photo is a static, nonswept single pulse with deflector biased at +1500 V. In (a) and (b), second pulse is swept. In (c), second and third pulses are two switched-out pulses separated by 10 ns.

would make this device practical; this presents no problem in terms of the input energy available in laser pulse applications. We are now making an effort to locate a suitable material that could make this type of deflector system practical for pico-second work.

References

35. S. W. Thomas and G. E. Phillips, "Comparison of Image Converter Tubes For Ultra High-Speed Streak Cameras," *Proc. 12th Intern. Congress on High Speed Photography* (Toronto, Ontario, August 1-7, 1976).
36. S. W. Thomas, "Crystal Streak Camera," *Proc. 12th Intern. Congress on High Speed Photography* (Toronto Ontario, August 1-7, 1976).

Authors

S. W. Thomas
G. E. Phillips

3-3.6 Ultrafast Framing Cameras

Since our last report, we have made significant progress on the LLL ultrafast framing tube (see Fig. 3-57). With the prototype tube, we have obtained framed images of 200-ps duration with a spatial

resolution of less than $100\text{ }\mu\text{m}$. This tube has an ultimate capability for framing images with frame times less than 100 ps.

The framing tube is based upon a new concept of image-line dissection and image restoration. With reference to Fig. 3-57, basically, an electron image is line-dissected at the slit-aperture plate (an intermediate-image plane). By using synchronized deflection in both the dissector and restorer sections of the tube, the sequentially time-developed line images obtained from a slit aperture are restored to an electron image at the phosphor screen.

Compensator plates, shown in the tube cross section of Fig. 3-58, minimize the electron-bundle height from all three slits within the restorer deflector. They also correct for the curvature defect in the restorer-electron lens, thus allowing for a flat-faced phosphor screen. Each slit aperture contributes to the formation of a stationary-image frame on the phosphor screen. Each spatially resolved line of the restored-image frame is well focused and has a temporal resolution similar to that found in a streak-camera tube. However, with the framing-camera tube, the image frame is scanned linearly in time. A

Fig. 3-57. Principles of operation for the framing camera tube. (Image inversion, lenses, and compensator plates are not shown for illustration clarity purposes.)

Fig. 3-58. Three-frame dissector framing camera tube.

delay, equal to the time required to sweep the electron image through the slit aperture, occurs between the first and the last lines of the frame. If necessary, computational techniques can be used to obtain single-timed frames from a multiple-slit tube.

The LLL prototype model of the framing tube is shown in Fig. 3-59. A modified RCA C73435 tube (the type used in our streak cameras) is used for the dissector section and a specially designed system is used for the restorer section. A further modification in the RCA tube was made by replacing the coarse parallel-wire extraction grid with a 394-mesh/cm screen spaced 0.2 cm from the cathode. With 600 V on the grid, the 3000-V/cm electric field at the cathode minimizes the transit-time dispersion to less than 10 ps in the cathode-grid region. To avoid problems involved in processing a cesiated photocathode, a thermionic cathode was selected initially for the prototype tube. An electron-image pattern as shown in Fig. 3-57 is generated from a 0.343-cm diameter dispenser cathode with a 25- μ m thick molybdenum stencil mask assembled onto the cathode surface.

Initial dynamic tests were performed with the sawtooth waveform from an oscilloscope to drive the framing tube as shown in Fig. 3-60. Using this technique, the fastest frame is 0.5 μ s for a 0.25-cm stencil pattern and a 44-mV/ μ m deflection factor for the dissector section. Three image frames are

shown in Fig. 3-57. Because of the limitation in the peak amplitude of this voltage-drive system, we have not yet performed a single sweep across all three slits. However, the image frame from each slit has been investigated by de-biasing the intermediate image at the appropriate slit position. The other tube operating potentials were maintained at constant values for this test.

Curvature defect of the restorer lens was corrected primarily by the compensator deflector control, thus permitting all three image frames to be simultaneously focused on a flat-face phosphor screen. Image frames were also investigated for a stencil pattern rotated 90° from the orientation as shown in Fig. 3-57. Image frames with dissection performed parallel and perpendicular to the line array pattern have similar imaging characteristics (Fig. 3-61). The spatial resolution (with respect to the object) of the image frame appears to be better than 65 μ m.

We investigated faster frames with the avalanche transistor driver system shown in Fig. 3-62. A 200-ps image frame is shown in Fig. 3-63. In these initial tests, considerable problems were experienced to obtain the best image frames because of driver-source jitter between the dissector and restorer deflectors and fine-control adjustment of the sweep-rate ratio for both deflectors. These problems are more serious for shorter-period image frames. The solutions to these problems will be addressed in the coming year.

Also, in 1977, we plan to perform tests on an S-20 photocathode version of the present three-frame

Fig. 3-59. Model of framing camera tube on vacuum station.

Fig. 3-60. Sawtooth driver for framing camera tube deflectors.

Fig. 3-61. Framed images ($0.5\text{-}\mu\text{s}$ duration) dissected parallel and perpendicular to the line slit.

Fig. 3-62. Avalanche driver system for framing camera tube deflectors.

Fig. 3-63. Framed image (200-ps duration).

prototype tube and on an x-ray photocathode version of the framing tube. Design studies are already being made for a five-frame tube; this design will be implemented into a prototype tube.

Author
R. Kalibjian

Major Contributor
J. P. Henz

3-3.7 Active Imaging

Many important diagnostic instruments for laser fusion use film as the recording medium. The intensity profiles of laser beams, for example, are detected electronically by streak cameras which then convert the data to photons recorded on film. Information retrieval from film is slow and arduous; the film

must be developed, scanned by a microdensitometer, digitized, corrected for D-log (E) non-linearity, and analyzed, usually by computer codes. In many instances it would help to have data such as the laser pulse FWHM available immediately for evaluating experiments or adjusting oscillators or other system components. The need for an automatic, fast-processing, active imaging system becomes even more evident when one considers the large number of images required for each laser-fusion target experiment, at, for example, the Argus or Shiva laser facilities.

Thus we need an effective system to replace film for our experiments. A suitable sensor must be found that is compatible with our computers and, ideally, with x-ray imaging and streak-camera readouts as well as 1.06- μm imaging. Required characteristics for the latter include high spatial resolution (at least 200×200 resolution elements), large dynamic range (500:1 or better), linear transfer function ($\gamma = 1$), good antiblooming properties, and minimal coherent interference effects from, for instance, multiple beam reflections within the sensor.

Fig. 3-64. General relationship of solid-state sensors. Manufacturer, sensor designation, and number of elements for each sensor are given as of December 1976. Sensors in brackets are planned but not yet available. Two companies, TI and Reticon, produce sensors that are either not commercially available (TI) or that are not applicable to high resolution area sensing (Reticon).

Fig. 3-65. Dynamic range and transfer function of three suitable sensors from Fairchild, RCA, and GE. These data were obtained using 0.53- μ m visible light.

As regards active streak-camera readouts, the requirements vary according to the sensor's location with respect to the streak tube. If it is outside the tube, the requirements are nearly the same as for 1.06- μ m imaging. The only additional needs are visible-light sensitivity and a length of at least 10 mm (because the output spatial resolution of the streak-camera phosphor is about 100 μ m, and at least 100 resolution elements are needed to define a temporal image).

On the other hand, if the sensor is within the tube, then high electron gain, resistance to radiation damage, and physical and chemical compatibility with the tube elements become important. Because the sensor is inside, all gains formerly obtained from the phosphor and image-intensifier combination must now be derived solely from the sensor itself.

We are studying candidate sensors, emphasizing solid-state devices rather than vidicons because of their superior dynamic range and their capacity to detect various types of radiation (visible light, near infrared, x rays, and electrons). Figure 3-64 shows

the general relationship among sensor types, which are broadly classified as discrete diode devices (DDD's), charge-coupled devices (CCD's), and charge-injection devices (CID's).

The two most important characteristics for all types of imaging applications are dynamic range and transfer property. We have measured these parameters to make a preliminary assessment of devices most useful for our purposes. Figure 3-65 shows some data on devices considered suitable. These measurements were made with incoherent 0.53- μ m visible radiation.

The best from our standpoint, the Fairchild 202 CCD, has a linear transfer function ($\gamma = 1$) and a dynamic range of more than 500:1 at room temperature. We have tested this device's dynamic range and γ value under incoherent 1.06- μ m radiation and at low temperatures. The results with 1.06- μ m light are the same as with 0.53- μ m light; the low-temperature tests indicate that the sensor's dynamic range can be extended to 1000:1 if operated near 250 K. Our conclusion is that the Fairchild 202 CCD

satisfies nearly all our criteria for 1.06- μm imaging. The only parameter not yet fully explored is its coherent interference characteristics.

To investigate the direct streak-camera readout aspect of active imaging, we have made a demountable x-ray streak tube with a Fairchild 202 CCD inside. The emphasis on an internal rather than an external sensor, such as the linear Reticon readout system now operating on a streak camera in the Argus facility, is to take advantage of the large electron gain realizable with an internal device. This allows full two-dimensional imaging without expensive external image intensifiers. Internal sensors, like those outside, produce near real-time readout,

hence bypassing film and its associated processing steps.

To facilitate our evaluation of the internal CCD readout, we have also equipped the streak tube with a conventional phosphor readout system. Data from the CCD are digitized and stored in the memory of an 8080 microcomputer. Corresponding phosphor images from the x-ray streak camera are intensified and photographed on hard film. This system is shown schematically in Fig. 3-66.

We have tested the active readout x-ray streak tube under near operating conditions. A 200-ps, 1-J pulse of 1.06- μm laser beam is focused onto an iron target. The resulting x rays are recorded by the x-ray

Fig. 3-66. General experimental setup for testing demountable x-ray streak camera system with both an internal CCD active readout and a phosphor output.

Fig. 3-67. Output data from x-ray streak camera equipped with XYZ monitor, phosphor/film, and CCD outputs.

streak camera (unstreaked mode) in both the CCD and phosphor/film output systems. Figure 3-67 shows typical output from the CCD, film, and general XY monitor. These data are now being evaluated.

Thus far, we are satisfied that solid-state sensors with a suitable dynamic range and linear transfer

function are available for our imaging applications. Such devices can operate within a streak tube and derive enough gain, under near operating conditions, to bypass the need for an image intensifier.

Author
J. Cheng

Major Contributor
G. R. Tripp

3-4 X-RAY DIAGNOSTICS

3-4.1 Time-Resolved X-Ray Spectral Data

In the 1975 Annual Report³⁷ we described how our 15-ps x-ray streak camera can be used to record the temporal signatures of laser-compressed targets over a dynamic range of 10^3 and in various x-ray

spectral bins from 1 to 10 keV. This work has now continued on a routine basis. In current experiments the x-ray streak camera's slit-shaped photocathode is covered with a series of K-edge absorption filters. When the target emission spectra and photocathode response are accounted for, the filters provide spectral windows about 1-keV wide. For instance, we previously showed that the response of our chlorine

(PVC) channel has a FWHM of 0.3 keV and a mean energy of 2.6 keV. Current experiments use a 10-channel filter pack extending from 1.0 to 17 keV. Multiple channels of aluminum, chlorine, titanium, iron, cobalt, zinc, and yttrium are used. Strong signals have been obtained in all channels. Typical results and analyses are described in Section 4 on exploding pusher targets irradiated on the Janus laser facility.

An interesting feature of x-ray streak camera applications has been observed on recent high optical intensity, high-Z target experiments with the Argus laser facility. In these experiments, the hard x-ray tail is sufficiently intense at energies in the 100-keV to 1-MeV range that without special precautions we obtain an unstreaked radiographic image of the streak tube, superimposed on the expected streak record. This is produced by unconverted hard x rays that pass through the entire front face of the streak tube and are then partially absorbed in the output phosphor. The resulting light emission is then image-intensified to produce a dc radiograph that clearly displays several features of streak tube components. Figure 3-68 shows an example of this "data" obtained without a streak record. Background film densities as high as 2.5 have been

Fig. 3-68. An example of an image obtained on the x-ray streak camera from a high-Z target experiment at Argus. The image is a flash radiograph of the streak camera made by high energy (100 keV to 1 MeV) x rays from the target. No streaked x-ray data is observable. Internal structure of the streak tube is clearly evident.

Fig. 3-69. A result similar to that shown in Fig. 3-69, except that shielding has been added to the x-ray streak camera and modifications have been made in mounting geometry and streak timing. Multichannel streaked x-ray spectral data (as identified in figure) are obtained in this case.

recorded. In follow-on work, the radiographic problem was reduced by the inclusion of lead shielding and special camera mounting procedures. A typical result is shown in Fig. 3-69, which shows the reduced radiographic image plus eight-channel streak record timed to be in a convenient place within the dc image. In other cases x-ray emission has been so intense that a 17-keV Yt channel saturated at early time in the streak.

Reference

37. *Laser Program Annual Report — 1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976) p. 418.

Authors

L. W. Coleman
D. T. Attwood

3-4.2 Time-Resolved X-Ray Images of Laser-Imploded Fusion Targets

In the 1975 annual report³⁸ we described development of a diagnostic allowing direct observation of

Fig. 3-70. Time-resolved x-ray pinhole photography.

target implosions by using our 15-ps resolution x-ray streak camera in conjunction with appropriate x-ray pinhole imaging. During the past year this diagnostic system has been implemented and these observations have been made, providing direct, quantitative data on the time-resolved implosion velocity and acceleration of laser fusion targets. The basic scheme is described in simplified form in Fig. 3-70. The 50X pinhole camera produces an image of the irradiated target in its own x-ray emission, which is aligned onto the slit photocathode of the x-ray streak camera. Accurate alignment is obtained by the use of special composite (or dichroic) pinholes, as described in the previous annual report. With 6- μm pinholes, we obtain simultaneous space-time resolutions of 6 μm and 15 ps.

The formation of the space-time streak records is described in Fig. 3-71. On the left an x-ray image is shown placed across the slit-shaped x-ray photocathode. Upon laser irradiation, the glass shell of the target is heated and strongly radiates x rays. It then explodes, causing the density in the shell to decrease, generally resulting in a decrease in x-ray emission, in some cases below the detection limits of the diagnostic system. As the imploding shell stagnates at the target center, the density again

achieves high values, producing a short burst of x rays before target disassembly. A simplified version of the resultant R,t streak record one expects from the process is seen in Fig. 3-71(b).

Figure 3-71(c) shows a color coded streak record from an actual target implosion experiment. The film isodensity contours have been color-coded to separate the low and high emission regions of the target. Note that the dashed lines follow peak x-ray emission. Since the slope of a line on an R,t plot represents a velocity, these streak records provide a velocity history of the implosion process. Acceleration values are obtained from the curvature of the lines. Typical observed velocity values are 3.4×10^7 cm/s, with measured accelerations of 3.4×10^{17} cm/s². Further results are described in Section 5; computerized data reduction is discussed in Section 2.

Reference

38. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p. 418.

Author

D. T. Attwood

Fig. 3-71. Space-time implosion diagram.

3-4.3 Critical Angle Reflection Spectroscopy

We are developing a technique for obtaining a time-integrated x-ray spectral measurement of intermediate resolution in the photon-energy range from 90 to 230 eV. A film-recording spectrograph has been built with three channels in this range, each approximately 50 eV wide. A thin carbon foil serves as a filter and is responsible for the low-energy cutoffs of the channels' energy response functions. The high-energy cutoffs are obtained by critical-angle reflection from carbon x-ray mirrors. Initial use of the spectrograph in laser fusion experiments has revealed that, for the technique to be successful, we must find a detector with a greater linear range than that of the presently used photographic film.

The efficiency of x-ray reflection from a flat mirror is a sensitive function of photon energy and mirror geometry. For a mirror set at a given angle with respect to the x-ray beam, there is a particular photon energy below which x rays will be reflected with high efficiency and above which, with low efficiency. Calculated reflection efficiencies of carbon mirrors set at 5, 7, 10, and 14° are shown in Fig. 3-72. In the spectrograph, mirrors at these angles were placed behind a 100- $\mu\text{g}/\text{cm}^2$ carbon foil, producing

the channel response functions shown in Fig. 3-73.

Unfortunately, the range over which the photographic film response is linear is not great enough in the soft x-ray region to allow reliable unfolding of spectral data taken with this spectrograph. Typical signals obtained on film for several laser fusion experiments are shown in Fig. 3-74. In addition, we are examining several active

Fig. 3-72. Calculated reflection efficiencies of vitreous carbon x-ray mirrors set at 5, 7, 10, and 14° grazing-angles of incidence.

Fig. 3-73. Calculated energy response functions of carbon mirrors filtered by $100\text{-}\mu\text{g}/\text{cm}^2$ carbon foil (a) and channel response functions formed by subtracting responses of adjacent mirrors (b).

Fig. 3-74. Typical experimental data from a shot at the Argus laser. The dispersion angle increases from right to left. A radiograph of a thin-film thermopile appears in the lower-right-hand corner.

the hydrogen-like neon x-ray line in super-liquid-density experiments (see Section 5). Original design specifications called for a resolution of 1 eV at 1 keV for a $10\text{-}\mu\text{m}$ source. The spectrometer was also to be placed about 12 cm from the target (see Fig. 3-75) to achieve high sensitivity, yet not significantly block laser light focused onto the target with the Janus 4π illumination system.

A high-resolution spectrograph must achieve sufficient x-ray dispersion so that the source dimension takes up only a small fraction of the film blackened by the x-ray line, Δs . The x-ray dispersion is given by differentiating the Bragg relationship

$$\Delta E = E \cot \theta (\Delta \theta) = E \cot \theta \frac{\Delta s}{\ell} \quad (26)$$

High dispersion can be achieved by choosing a crystal so that the Bragg angle, θ , for 1-keV x rays is large and by making the distance, ℓ , from the crystal to the film plane large. We chose a RAP crystal whose two-dimensional spacing is $26.12 \text{ \AA}$. Because of a physical constraint of fitting the spectrograph through the clamshell holder, ℓ was smaller than desired (3.4 cm); therefore, a 1-eV source energy width takes up

$$\Delta s = \frac{\Delta E \ell}{E \cot \theta} = \frac{(1 \text{ eV}) (3.4 \times 10^4 \text{ }\mu\text{m})}{(10^3 \text{ eV}) (1.9)} = 18 \text{ }\mu\text{m} \quad (27)$$

detectors to complement the spectrograph, including thin-film thermopiles and windowless fluorophotodiode detectors. In Fig. 3-74, a very hard suprathreshold x-ray component in the experiment produced a radiograph of a miniature thermopile that we had placed in the instrument for evaluation.

Author

L. N. Koppel

3-4.4 High-Resolution Spectrographs

We have designed and built a high-resolution crystal spectrograph to measure the energy width of

Fig. 3-75. High-resolution spectrograph located in the focusing optics.

Thus, a source dimension of $10\text{ }\mu\text{m}$ limits the resolution to $10/18\text{ eV}$. The resolution due to the crystal rocking curve is 0.83 eV at 1 keV .³⁹ The overall resolution is 1 eV if these two components are added in quadrature, 1.4 eV if they are added linearly. Thus the resolution should be between 1 and $1\frac{1}{2}$.

A picture of the spectrograph is shown in Fig. 3-76.

Reference

39. L. M. Richards and V. W. Slivinsky, *Resolution and Sensitivity of the Neon Emission Spectrograph*, Lawrence Livermore Laboratory, Internal Memo LPI-77-0147 (1976).

Author

V. W. Slivinsky

Fig. 3-76. High-resolution x-ray spectrograph. The front window was $8\text{-}\mu\text{m}$ beryllium; film was Kodak 101.

3-4.5 Spectrographs of Lead Myristate Crystals

Time-integrated x-ray spectral measurements of high resolution are obtained for photon energies ranging from 300 to 1000 eV with crystal-diffraction spectrographs that use curved lead myristate crystals. Lead myristate is a man-made crystal that strongly diffracts soft x rays with an effective interplanar (d) spacing of 40 Å. A special vacuum ultraviolet-sensitive photographic film and ultrathin foils to exclude light from the instrument complement the high resolution of the crystal.

Lead myristate crystals are constructed by laminating monomolecular films of the material onto smooth curved substrates. Professor B. Henke of the University of Hawaii built our crystals using substrates of machinable glass, hand-lapped to a fine polish.⁴⁰ The surface that received the crystal was a convex circular arc with a 3-in. radius of curvature.

Lead myristate has a reflecting power that is much greater than those of most solution-grown crystals (integrated efficiencies 4×10^{-4} rad, compared to 6×10^{-5} rad for potassium acid phthalate. However, the price of this high reflectivity is poor resolving power ($E/\Delta E \sim 200$) and relatively large second- and third-order reflecting powers ($\sim 20\%$). Figure 3-77 is a sketch of a spectrograph used in Janus and Cyclops laser-fusion experiments and the calculated sensitivity is depicted in Fig. 3-78. Measurements on the Argus laser were made with an instrument with essentially the same internal organization but contained in a different outer case.

Fig. 3-77. Lead myristate crystal spectrograph.

Fig. 3-78. Calculated sensitivity (photon/cm² at film per keV/keV sphere) of a spectrograph employing a curved lead myristate crystal and a 1500-Å parylene/1500-Å aluminum light-tight window. The drop in sensitivity at 0.5 keV results from anomalous dispersion of oxygen in the crystal.

Spectrographic data are recorded on Kodak type 101-01 film. A single layer of silver halide grains is laid down over clear gelatin. The film is not supercoated and therefore it is especially sensitive to soft radiation. In the spectrograph, the film is shielded from light by a 1500-Å barrier of aluminum, supported by 2500 Å of N-parylene. A sample spectrogram obtained from experiments on the Argus laser is shown in Fig. 3-79. Line spectra that were radiated by several constituents of a glass-microballoon target (irradiated with 153 J in 37 ps) are labeled.

References

40. B. L. Henke, "Single-Crystal Spectroscopy in the 0.1 to 1.0 X-Ray Region," presented at the APS Conference on Diagnostics of High Temperature Plasmas (Knoxville, Tennessee, Jan. 7-9, 1976).

Author
L. N. Koppel

Major Contributor
J. D. Eckels

Fig. 3-79. Spectrogram produced by the lead myristate crystal spectrograph on a glass-ball shot at the Argus laser. The fine radiations are labeled as to the ball constituents from which they originate.

3-4.6 Low-Resolution Subkilovolt X-Ray Detectors

The x-ray spectrum emitted by a laser fusion target provides valuable information about the

laser-plasma interaction. Therefore, this spectrum is measured absolutely from 1 to 100 keV for each laser plasma-interaction experiment.⁴¹ To provide data on energy balance, however, absolute measurement of the soft x rays down to 100 eV also is needed because typical targets emit about half their x-ray energy in the subkilovolt region.

Fig. 3-80. Radiation from typical laser experiment.

To measure the subkilovolt x-rays, thin-window detectors have been developed. But backgrounds from other radiation and high-energy particles transmitted through the thin windows can be significant. Figure 3-80 shows a typical energy balance from a laser experiment on a glass microsphere. The largest backgrounds for the x-ray measurements are from scattered laser light and from ions. Ions with energies in the MeV range have been observed and are assumed to be produced in the plasma corona. These backgrounds have to be minimized in the x-ray measurements.

We are now using three types of detectors to make subkilovolt x-ray measurements: a calorimeter with $70 \mu\text{g}/\text{cm}^2$ C window, a lead stearate bent-crystal spectrograph with an aluminized parylene window, and a silicon surface-barrier detector with a $40 \mu\text{g}/\text{cm}^2$ aluminum win-

dow. These detectors complement each other in characterizing the subkilovolt x-ray region.

Calorimeter

Figure 3-81 shows our calorimeter package. The calorimeter, built by Lockheed Missiles and Space Co., Palo Alto,⁴² consists of a $25\text{-}\mu\text{m}$ -thick tantalum disk with attached thermocouple. The x rays are absorbed in the tantalum; the thermocouple measures the temperature rise. The calorimeter's sensitivity, as measured by Lockheed with a proton beam, is $5 \text{ mV}/\text{J}/\text{cm}^2$. The output voltage is proportional to the energy deposited regardless of type or energy of the particle being measured.

In actual use, the detector is placed about 20 cm from the plasma source. To reduce $1.06\text{-}\mu\text{m}$ light and ions in the background signal, we put a nominal $70 \mu\text{g}/\text{cm}^2$ C light shield and 0.25-T magnet in front of the calorimeter (see Fig. 3-81). Also, the tantalum disks are coated with $0.2 \mu\text{m}$ of gold to reflect the $1.06\text{-}\mu\text{m}$ light. With this arrangement we have achieved 98% reflection.⁴³

Fig. 3-81. X-ray calorimeter.

Lead Stearate Bent-Crystal Spectrograph

The bent-crystal spectrograph (Fig. 3-82) has been described in detail elsewhere.⁴⁴ This detector uses a 75-layer lead stearate crystal bent to a 7.62-cm radius of curvature. A light-tight window of $44 \mu\text{g}/\text{cm}^2$ aluminum vapor deposited on $25\text{-}\mu\text{g}/\text{cm}^2$ N-parylene plastic foil serves as the entrance window. Recording is on type-101 film. This spectrograph is not sensitive to fast ions because the recording film is shielded from the target. In our experiments we have used the instrument to measure

Fig. 3-82. Lead stearate bent-crystal spectrograph.

x-ray spectral shape from 300 to 900 eV. It has also been used for absolute measurements in other experiments where the spatial distribution of the x-ray emitting source is known.

Silicon Surface-Barrier Detectors

McQuaid⁴⁵ has described the use of these detectors in the current mode to measure x rays. Their calibration as a function of photon energy, as reported by Gaines *et al.*,⁴⁶ is shown in Fig. 3-83. Note that the response drops off rapidly below 300 eV because of the aluminum window. These instruments have been shown to be light-tight by putting

Fig. 3-83. Gaines' calibration of a silicon surface-barrier detector.

two of them side-by-side with thick glass shielding one of the detectors. Magnets are placed upstream from the detectors to sweep out the ions.

Use of Detectors

We have used all three detectors in determining x-ray energy in the subkilovolt spectrum. The spectral shape from 300 to 900 eV is measured with the lead stearate bent-crystal spectrograph. Figure 3-84 shows one such measurement for a lead glass disk target. By using the spectral shape from the crystal spectrograph to calculate the x-ray energy loss in the aluminum window, the total x-ray energy greater than 300 eV can be calculated from the surface barrier signal. A similar correction must be made for the energy loss in the C filter of the calorimeter. However, in this case, a spectral shape from 100 to 300 eV has to be assumed since no measurement is available in this energy region.

Figure 3-85 shows a theoretical calculation of the emitted spectrum from the lead glass disk target, along with the transmission of the C filter. Good agreement exists between the predicted spectrum and the lead stearate results from 300 to 900 eV. An estimate of the x-ray energy less than 300 eV can be calculated by subtracting from the calorimeter signal that portion due to x rays with energies greater than 300 eV. Typically, for these experiments, this amounts to about half the total signal.

Fig. 3-84. X-ray spectral shape measured with bent-crystal spectrograph.

Fig. 3-85. Calculated x-ray spectrum from lead glass target. Calculated transmission through $70 \mu\text{g}/\text{cm}^2$ C foil.

References

41. V. W. Slivinsky, H. N. Kornblum, and H. D. Shay, *J. Appl. Phys.* **46**, 1975.
42. L. F. Chase, R. K. Bardin, T. R. Fisher, H. A. Grench, W. C. Jordan, D. A. Kohler, R. K. Landshoff, T. D. Miller, and J. G. Pronko, *X-ray Diagnostics for Laser Systems*, Defense Nuclear Agency, Rept. DNA-3404F (1974).
43. S. Gunn, Lawrence Livermore Laboratory, private communication, (1976).
44. L. Koppel, LLL Annual Report, p. 325, 1974.
45. J. H. McQuaid, C. E. Violet, and J. Petrucci, *Advances in X-Ray Analysis*, Vol. 18, p. 204 (Plenum Press, New York, N.Y.) 1974.
46. J. L. Gaines, R. W. Kuckuck, and R. D. Ernst, *X-ray Detector Calibrations in the 280-eV to 100-keV Energy Range*, Lawrence Livermore Laboratory, Rept. UCRL-78111 (1976).

Author

H. N. Kornblum

Major Contributors

V. W. Slivinsky

L. N. Koppel

3-4.7 Laser Fusion X-Ray Microscopy

Axisymmetric X-Ray Microscope Development

Efforts continued during 1976 to improve the spectral and spatial x-ray imaging diagnostic capability of the laser fusion program. The design of

Fig. 3-86. Hyperboloid/ellipsoid x-ray microscope resolution ($9\times$).

Kirkpatrick-Baez grazing incidence x-ray mirror pairs⁴⁷ was extended in an attempt to provide time-integrated micrographs of the subkilovolt (200-800 eV) and superkilovolt (4-6 keV) emission from laser fusion targets. The pursuit of submicron spatial resolution centered about the development of axisymmetric, grazing incidence x-ray microscope systems.⁴⁸

The axisymmetric x-ray mirror pair consists of confocal and coaxial hyperboloid/ellipsoid sections. The design of such a system, based upon the geometrical properties of these conic pairs, was evaluated using the optical design code, ACCOS V, modified to accommodate grazing incidence.⁴⁹ The x-ray mirror pair provides a $9\times$ magnification at an object distance of 300 mm and subtends a collecting solid angle of $4.2 \times 10^{-4} \text{ sr}$. X rays are incident upon the reflecting surfaces at 1° . This corresponds to a spectral range sensitivity of up to 3.5 keV for nickel reflectors. Figure 3-86 shows the ray tracing results for the off-axis resolution of this $9\times$ microscope design. The object-plane resolution is defined in terms of the rms diameter of the image plane blur circle divided by the system magnification. If we were to ideally figure these smooth surfaces, we would find that submicron resolution was implied over a field of view 500 μm in diameter. To realize this resolution, however, surface perturbations which introduce local slope deviations of approximately $2 \mu\text{rad}$ must be avoided. Based upon the scale length of the hyperboloid and ellipsoid sections, this slope tolerance corresponds to surface

figure deviations of, at most, several hundred angstroms.

In an attempt to approach these tolerances, we devised a mirror fabrication strategy based upon the unique capabilities of single-point diamond turning. Late in 1975, beryllium substrates, internally plated with copper, were first diamond turned and then coated with electroless nickel. We polished the nickel plated surfaces in an attempt to improve the local conic figures and to smooth surfaces to better than 50- $\text{\AA}$ rms. One of these mirror pairs, designated $9\times$ -30, was then mounted onto a d.c. x-ray source facility to determine its imaging characteristics.

The initial image characterization experiments consisted of focusing upon two superimposed 100 l.p.i. and 1000 l.p.i. electroformed nickel meshes, backlighted by a diffuse, copper Henke tube source drawing 60 mA at 5 kV. Preliminary alignment of the axisymmetric x-ray mirror pair was accomplished mechanically. The proper line of sight was established by symmetrizing the 6328- $\text{\AA}$ diffraction pattern generated by a He-Ne alignment beam incident upon the annular entrance aperture of the microscope. Axial adjustments in the location of both the mirror's principle and image planes were made to optimize resolution. Figure 3-87 reproduces the first known micrograph taken by an axisymmetric x-ray microscope designed for laser

Fig. 3-87. Hyperboloid/ellipsoid x-ray micrograph ($9\times$).

(a) X tilt

(b) No tilt

(c) Y tilt

Fig. 3-88. Misorientation of hyperboloid/ellipsoid mirror pair.

fusion research. The fine grid wires are about $8\ \mu\text{m}$ in diameter and $25\ \mu\text{m}$ apart. Spatial resolutions on the order of $10\ \mu\text{m}$ are indicated. The region of best focus falls within a radius of approximately $750\ \mu\text{m}$. For off-axis positions greater than $750\ \mu\text{m}$, the fine mesh image quality gradually degrades. A closer examination of this peripheral region reveals a preferential blurring, wherein, to first order, radial discrimination is maintained while "aximuthal" spatial resolution is lost. This preferential off-axis blurring is dramatically illustrated in Fig. 3-88, in which the hyperboloid/ellipsoid mirror pair has been pur-

posely misoriented in both orthogonal directions. This behavior is consistent with astigmatic aberrations of the mirror pair. The limited depth of field of these x-ray optics is suggested by the results pictured in Fig. 3-89.

Examination of the figure and roundness quality of mirror pair 9X-30 yielded data consistent with the observed $10\text{-}\mu\text{m}$ resolution and suggested revisions in the fabrication sequence which would better approach the theoretical submicron resolution of the instrument. We determined that the nickel

(a) $\Delta Z = 0$

(b) $\Delta Z = -75\ \mu\text{m}$

Fig. 3-89. Depth of field imaging results.

Fig. 3-80. Diamond turning the final reflecting hyperboloid/ellipsoid surfaces. Note the significant improvement in the roundness and azimuthal symmetry of axisymmetric x-ray mirrors.

Fig. 3-91. Numerically controlled corrections. Note the improved surface figure of diamond turned axisymmetric x-ray microscopes.

plating process introduced local azimuthal non-uniformities, which obviated the inherent roundness of the diamond turned copper surfaces ($0.2\text{ }\mu\text{m}$) and which could not be removed consistently with local polishing techniques. Furthermore, we noted that local surface figure deviations greater than several thousand angstroms were compounded by local polishing of the nonuniform surfaces.

These observations prompted two changes in the fabrication sequence. The second generation of 9X axisymmetric x-ray optics had their nickel reflecting surfaces directly diamond turned, thereby preserving the precise roundness capability of the diamond turning process. The improvement in the final roundness and local azimuthal symmetry of the conic reflectors due to this revision is evidenced in Fig. 3-90. In addition, we found that the surface figure cut by the diamond turning facility was reproducible to within about $250\text{ }\text{\AA}$ from run to run. Since the cutting tool movements are numerically controlled (N.C.), changes in the input N.C.

machine tape — taking into account the initial figure perturbations — should, in principle, allow us to machine generate the hyperboloid and ellipsoid surfaces to within the reproducibility of the diamond turning machine. Since the initial figure perturbations exhibited wavelengths on the order of 1 mm , passive feedback correction points were specified every $100\text{ }\mu\text{m}$ along the hyperboloid and ellipsoid surfaces. Using this technique, we produced surfaces within $250\text{--}500\text{ }\text{\AA}$ of the ideal surfaces over $15\text{--}mm$ lengths (Fig. 3-91). Several mirror pairs with these "corrected" contours were then polished and subjected to the same imaging experiments as the previous optics. Difficulties encountered in the final polishing phases introduced surface figure perturbations at the extremities and mid-section of the "corrected" mirror pair. In spite of this, the axisymmetric x-ray microscope resolution improved with the more accurate figuring and more precise roundness of the reflecting surfaces (Fig. 3-92).

Fig. 3-92. Axisymmetric x-ray microscope resolution. Note that the resolution improves with more accurate figuring of the hyperboloid/ellipsoid reflecting surfaces.

Future axisymmetric x-ray microscope efforts will be directed toward improving the hyperboloid and ellipsoid surface quality to further improve the spatial resolution. The "corrected" diamond turning fabrication technique will be applied to produce larger magnification systems that will interface with fast x-ray streak and framing cameras. More precise surface characterization and resolution measurements will be made using low-angle scattering techniques and intense, submicron x-ray point sources. Finally, we will attempt to extend the spectral range of a given microscope design by coating the high-precision diamond turned nickel surfaces with high-Z materials. The results of each of these efforts will be combined to provide the three high-

resolution x-ray imaging systems presently being designed for the Shiva laser target facility.

Four-Channel X-Ray Microscope Development

During 1976 four-channel x-ray microscopes continued to be the major x-ray imaging diagnostic for the laser fusion target experiments. The orthogonal, cylindrical mirror design reported before⁴⁷ continued to provide spatial resolution on the order of several microns. The design was used in the Janus, Janus clamshell, Cyclops and Argus target experiments. During 1976 preliminary attempts were made to more directly calibrate the spectral

Fig. 3-93. X-ray mirror imaging between 0.1 and 10 keV.

response functions of the microscopes and to extend the spectral response of our imaging capability into the subkilovolt and superkilovolt regimes.

Previous x-ray mirrors were calibrated by measuring the specular reflection from a single mirror surface as a function of incident photon energy. The spectral response functions for the instrument were then calculated from the experimental single-reflection data. Since the four-channel microscope consists of four mirrors aligned as a unit, it is more appropriate to calibrate the four-mirror combination directly rather than individually. Towards that end we designed an active calibration facility. The x-ray source was the line emission between 0.7 and 4.0 keV from various Henke tube anodes as seen through a pinhole aperture. Film in the image plane was replaced with an apertured proportional counter which monitored both the transmitted microscope intensity and the source intensity. In principle, the ratio of these two signals is proportional to the product of the double reflection efficiency and the collecting solid angle of each mirror pair. Absolute x-ray microscope calibration data are anticipated from this facility during the coming year.

Recent interest in subkilovolt x-ray emission and the desire to extend the x-ray spectral regime imaged by our grazing incidence microscopes resulted in the design and fabrication of orthogonal mirror pairs sensitive in the sub- and superkilovolt region. A four-channel system characterized by an object distance of 290 mm and a magnification of three used vitreous carbon- and gold-coated quartz reflectors. X-ray flux is incident upon the carbon mirrors at 2° and at 0.75°, with respect to the gold surfaces. The theoretical double reflection efficiencies (Fig. 3-93) suggest that we can, indeed, image below 800 eV and above 3.0 keV. These new mirror pairs are presently undergoing image evaluation experiments.

References

47. F. Seward, J. Dent, M. Boyle, L. Koppel, T. Harper, P. Stoering, and A. Toor, *Rev. Sci. Instrum.* **47**, 4 (1976).
48. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976).
49. ACCOS V-on-line Optics Design, Scientific Calculations, Inc., Rochester, N.Y. reprinted by National CSS, Norwalk, Connecticut, September 1973.

Author
M. J. Boyle

Major Contributors
J. B. Bryan
P. C. Baker
K. M. Brooks
T. L. Harper
H. G. Ahlstrom

3-4.8 X-Ray Microscopy of Laser Fusion Targets Using Coded Imaging Techniques

We have developed coded imaging techniques using a micro Fresnel zone plate as the coded aperture for x-ray (and particle) diagnostics of laser-fusion targets. The Zone Plate Coded Imaging (ZPCI) technique complements the capabilities of the grazing incidence reflection (GIR) x-ray microscope (see Table 3-5).

ZPCI is a two-step imaging technique (see Fig. 3-94). In the first step, the radiation source to be imaged casts a shadowgraph through a Fresnel zone plate (coded aperture) onto a photographic emulsion or other detector array. The shadowgraph is a coded image of the source-emission (time-integrated intensity) distribution. Image reconstruction or decoding is achieved with procedures similar to those used in holography. The shadowgraph transparency is illuminated with a coherent light source (λ). Downstream from the transparency, the Fresnel diffraction pattern of the transmitted light produces a three-dimensional reconstruction of the original source distribution. This image is inverted, reversed front to back, and magnified.

The physical processes underlying ZPCI are relatively simple. Figure 3-95 shows a source distribution of three separated points. Each source point maps into a zone plate shadow which, by its size and position in the shadowgraph plane, uniquely characterizes the position of its associated source point. Upon reconstruction, each zone plate shadow focuses the incident radiation to a diffraction-limited point, the image of its associated source point.* The three separated points in Fig. 3-95 represent a three-dimensional source distribution

* Only the first-order image is considered. A much more subtle and important assumption made here is that the overlapping zone plate shadows act independently of one another in the reconstruction. It can be shown that, as far as practical image reconstruction is concerned, this assumption is valid.

Table 3-5. Comparison of parameters for x-ray microscope and zone plate camera

Parameter	X-ray microscope	Zone-plate camera
Planar resolution limit	1 μm (surface smoothness limited)	5.3 μm ^a (limited by diffraction effects during shadow-graph recording)
Solid angle for radiation collection	5×10^{-4} sr	9×10^{-1} sr
Tomographic resolution	None	10 μm
Radiations imaged	X-rays $\lambda \geq 2 \text{ \AA}$	All radiations $\lambda \leq 2.5 \text{ \AA}$ ^b
Typical object distance	(30-50) cm	(1-2) cm

^aZPCI planar resolution limit depends on source spectrum. Specifically, $\delta \approx 3.3 \sqrt{\lambda_x S_1}$, where λ_x is the maximum wavelength of interest. The P.R.L. quoted corresponds to $S_1 = 1 \text{ cm}$, $\lambda_x = 2.5 \text{ \AA}$.

^bZPCI spectral range depends on minimum linewidth of coded aperture. Specifically, $\lambda_x < (\Delta r)^2 / 4 S_1$. The λ value quoted corresponds to $S_1 = 1 \text{ cm}$, $\Delta r \approx 3 \mu\text{m}$.

and the source is reconstructed with its three-dimensional detail preserved (i.e., the image is tomographic). The information contained in the three-dimensional image distribution is retrieved by viewing the image in "sections," i.e., in separate reconstruction planes. Ideally there is a one-to-one correspondence between each reconstruction plane

and each source plane. In this way a three-dimensional source distribution may be synthesized, plane by plane.

As a simple shadowcasting technique, ZPCI is achromatic. It places only weak constraints on the wavelength range of source radiations that can be imaged. The wavelengths must be short enough so

Fig. 3-94. Zone plate coded imaging technique.

Fig. 3-95. Zone plate coded imaging principles.

that ray optics are satisfied during image encoding (long-wavelength limit) and long enough for appreciable attenuation to occur in the "opaque" zones of the coded aperture (short-wavelength limit).

An important advantage of ZPCI over competing imaging diagnostics is its large radiation-collection efficiency. A zone plate camera may typically possess a radiation-collection solid angle that is four to six orders of magnitude greater than that of a pinhole camera of equivalent resolution. This, in turn, may provide a significant (S/N) advantage for the zone plate camera. On the other hand, all coded-imaging techniques suffer a (S/N) decrease as the source size increases. A quantitative analysis of these factors reveals that coded imaging of laboratory plasmas will be most successful for source distributions with an active area much smaller than that of the coded aperture. Thus, we conclude that ZPCI is well suited for diagnosing our laser-fusion target experiments.

Fig. 3-96. Micro-Fresnel gold zone plate, 7 μm thick, having 100 zones and a minimum zone width of 5.3 μm .

(a)

(b)

(c)

Fig. 3-57 Free-standing Fresnel zone plate. In (a), the zone plate is mounted for use in the zone-plate camera, and (b) and (c) are views with increased magnifications.

The planar and tomographic resolution capabilities of the ZPCI technique depend on the parameters of the micro Fresnel zone plates that serve as coded apertures. Quantitative expressions for the planar and tomographic resolution limits are presented in Eqs. (28) and (29), respectively:

$$\delta = 1.64 \left(\frac{S_1 + S_2}{S_2} \right) \Delta r, \quad (28)$$

$$\Delta = \frac{0.75}{N} \frac{S_1}{S_2} (S_1 + S_2). \quad (29)$$

In these equations, δ is the planar two-dimensional resolution limit, Δ is the tomographic (depth) resolution limit, N is the total number of zones in the coded aperture, Δr is the width of the narrowest (i.e., outermost) zone of the coded aperture, and S_1 and S_2 are the source to zone plate and zone plate to shadowgraph distances, respectively.

Free-standing, Fresnel zone plates of high-Z material (e.g., gold), large zone number ($100 \leq N \leq 240$), microscopic minimum linewidth ($2.6 \mu\text{m} \leq \Delta r \leq 10.2 \mu\text{m}$), and appreciable material thickness ($1 \mu\text{m}$ to $7 \mu\text{m}$) have been fabricated for coded imaging applications. Figure 3-96 illustrates a gold zone plate where $N = 100$, $\Delta r = 5.3 \mu\text{m}$, material thickness = $7 \mu\text{m}$. Figure 3-97 illustrates a similar free-standing zone plate mounted in a holder used with the zone plate camera.

Experimental investigations in the past year have accomplished the following:

- Verified the theoretical planar-resolution limit of ZPCI on a $10 \mu\text{m}$ scale.
- Demonstrated the applicability of ZPCI to charged-particle imaging.
- Produced the first successful high-resolution, tomographic x-ray images of laser-produced plasmas.

- Spatially resolved the alpha-particle emission from laser-compressed, DT-filled microshells.

Results from the first three areas are presented in the following paragraphs; the experimental investigations associated with the last achievement are discussed elsewhere in this report.

We conducted experiments to verify the ZPCI resolution with a zone plate camera that possessed a nominal resolution of $10 \mu\text{m}$. A simulated point source ($\approx 5\text{-}\mu\text{m}$ diameter electron source) was imaged. The reconstructed-image data are presented in

Fig. 3-98. ZPCI "point" response function.

Fig. 3-98, which compares the measured image density, D , with the calculated image intensity, I . Density and intensity are plotted vs radial distance; the

scale is in image dimensions with a magnification factor of 4.6. A meaningful test of the agreement between calculated and measured data in Fig. 3-98 can be made by comparing the positions of the first minimum and secondary maximum of the Airy patterns because these positions will not be affected by film nonlinearity. The agreement indicates that a resolution of $10\text{ }\mu\text{m}$ can indeed be achieved for ZPCI of small laboratory source.

Examples of zone plate camera x-ray imaging results for laser-irradiated, DT-filled microshell targets are shown in Figs. 3-99 and 3-100. In these figures, the coded image of the x-ray source distribution is presented in (a), a two-dimensional, isodensity contour map of the image reconstructed from (a) is given in (b), and (c) is a quasi three-dimensional representation of the microdensitometer data of (b). The figures are scaled in

Fig. 3-99. ZPCI data for target compression.

Fig. 3-100. ZPCI data for no target compression.

object-plane dimensions. In the Fig. 3-99 experiment, the laser energy on target was 33 J in a pulse of 46 ps (FWHM); significant target compression was achieved, as evidenced by the sharp central spike of x-ray emission. There is excellent agreement between Fig. 3-99 and the GIR x-ray microscope images of the same shot.

Figure 3-100 shows image data for a low-energy laser shot (5 J in 53 ps) in which no target compression occurred. Only x rays from the heated regions of the target wall in its initial position are observed. The x-ray flux from this poorly irradiated target was insufficient to yield GIR x-ray microscope images. Thus, this figure is a direct illustration of the (S/N) and sensitivity advantages offered by the zone plate camera with its large solid angle for radiation collection. Nominal zone plate camera resolution for these images is 9 μm .

Tomographic data from the low-energy (no-compression) shot of Fig. 3-100 are presented in Fig. 3-101. Isodensity contour maps for reconstructed images are viewed in three separate reconstruction planes. Figure 3-101(a) shows the source plane at the geometrical center of the plasma shell; Figs. 3-101(b) and (c) show the source planes at 37 and 74 μm behind the central plane, respectively, as viewed from the zone plate camera. Nominal tomographic resolution for this shot was 74 μm .

A careful analysis of the images in Fig. 3-101 supports the contention that true tomographic information is represented. Most convincing is the migration of the region of peak density in the contour pattern on the left. In Fig. 3-101(a), the peak density region is approximately 23 μm above the equatorial plane of the plasma shell (perhaps the laser beam hit high on the target). This region migrates down toward the equatorial plane as we view rear sections of the plasma shell until, in Fig. 3-101(c), it is only 4 μm above the equatorial plane. This migration is to be expected from the spheroidal curvature of the source distribution.

Work continues to extend the imaging capabilities of the ZPCI technique. Zone plate cameras employing gold zone plates, 5 to 10 μm thick, are being used to image the suprathermal x-ray emission from laser fusion targets. Also, techniques are being developed for the fabrication of free-standing Fresnel zone plates with submicron outermost-zone widths. A zone plate camera using such a coded aperture would possess a 1- to 2- μm planar resolution capability. A new zone plate

Fig. 3-101. ZPCI tomographic data.

camera with a nominal tomographic resolution of about 38 μm ($N = 240$ zones) already has been built and soon will be used to image the x-ray emission from laser-irradiated targets. Work is also under way on a zone plate camera with a nominal

tomographic resolution of approximately 10 to 15 μm ($N = 1000$ zones).

Author
N. M. Ceglie

3-4.9 X-Ray Image Detection with Charge-Coupled Devices

We have used a solid state television sensor, a charge-coupled device (CCD), to directly detect the patterns of soft x rays. The spectral sensitivity and response characteristics of an RCA sensor also have been measured.⁵⁰

The art of constructing metal-oxide semiconductors for solid state sensors for use in television systems has received a great deal of attention in the last few years. One of the most sophisticated products of this work is the RCA SID 51232 sensor. This sensor incorporates an array of 256×320 image cells on a single chip of silicon (each cell measures $30 \times 30 \mu\text{m}$). The photoelectric responses of the cells are read out by CCD shift registers. The cells are sensitive to light; they are also sensitive to

Fig. 3-102. Spectral sensitivity of the SID detector for soft x rays. The points are measured and the curve is a fit derived from a simple photocharge collection model.

Fig. 3-103. Characteristic response curve of the SID detector for 8-keV x rays. Each of the two segments of the curve are linear to within experimental accuracy.

soft x-rays when the x-ray attenuating glass protective shield over the sensor is removed.

We tested a complete closed-circuit TV camera including the SID sensor in an x-ray-machine calibration facility. Figure 3-102 shows the measured and calculated spectral sensitivity of the camera and a response-characteristics curve is given in Fig. 3-103. The change in slope of this curve is a result of the signal processing that is done in the camera by a gamma-correction circuit. The dynamic range of the camera for x rays is approximately 50 to 1. Nonfatal radiation damage to the shift registers, of no consequence for pulse detection by the camera, was also observed.

We plan in the near future to couple this camera to one of our axisymmetric x-ray microscopes (see § 3-4.7) to obtain real-time, two-dimensional x-ray images of laser fusion targets.

Reference

50. L. N. Koppel, *Direct Soft X-Ray Response of a Charge-Coupled Image Sensor*, Lawrence Livermore Laboratory, Rept. UCRL-78856 (1976).

Author
L. N. Koppel

3 - 4.10 Applications Prospects of Fast Scintillator Evaluations

Plastic scintillators are widely used as x-ray and neutron detectors but have been limited primarily to time-integrated measurements in their applications to laser fusion diagnostics because of their fairly long (~ 1 -2 ns) response times. Recent experiments⁵¹ evaluating commercial plastic scintillators that are doped with various concentrations of several quenching materials have shown subnanosecond response times. We have evaluated samples of ZnO:Ga, Ne-111 plastic scintillators doped with varied amounts of acetophenone, benzophenone, and Butyl-PBD [2 phenyl-5 (4-biphenyl) -1,3,4-(oxiadazole)] in PVT (polyvinyl toluene). Increased doping showed a decrease in scintillator response time when excited with a short pulse of ~ 1 keV x rays. Subnanosecond scintillators used for x-ray and neutron detectors can be used with ultrafast streak cameras for timing and imaging.

A series of NE-111 plastic scintillators with varied amounts of quenching have been evaluated for efficiency and decay constant using short pulses of x rays. Figure 3-104 shows the experimental setup. A $1.06\text{-}\mu\text{m}$, 150-ps, 1-J, Nd:YAG laser pulse

is focused onto an iron target. The x rays generated from the plasma are ~ 1 keV and 200 ps in duration with actual temporal shape being measured by an ultrafast x-ray sensitive streak camera.⁵² The spectral shape of the plasma x-ray emission is measured using a seven-channel PIN diode array with appropriate K-edge filters.⁵³ Three plastic scintillator samples are irradiated simultaneously by the x rays, and the light emitted is coupled to an ultrafast S-20 photocathode streak camera by means of a three-channel vacuum light pipe. This three-sample method allows us to determine relative efficiencies of the samples accurately.

The experimental results are tabulated in Table 3-6. Account has been taken of nonlinearities in the ultrafast streak camera and transit time dispersion of the vacuum light pipe. The long and short decay time constants are obtained by fitting two straight lines to a log intensity vs time plot of the deconvoluted experimental data. The first group of samples shown in Table 3-6 indicate the time response to various concentrations of Butyl-PBD in PVT. Only a slight decrease in FWHM value was observed although the starting FWHM is already extremely short. The second and third group of samples were designed to investigate the response times of the fastest commercially available plastic scintillator NE-111 as a function of acetophenone and benzophenone quencher concentration. The best

Fig. 3-104. Experimental arrangement used to study scintillator temporal response.

FWHM for both types of quenched NE-111 scintillators is about 200 ps with an efficiency of 6% relative to unquenched NE-111. Increased doping up to the 15% level made the NE-111 so soft at room temperature that cooling was required to allow the samples to be machined to the correct sizes. Fluctuations from 1.33 ns to 500 ps FWHM were observed in the unquenched samples. The reason for this change is unknown, but may be due to contamination of the control sample by quenched samples being stored in the same container. The fourth sample, a Zn:O phosphor showed a response time that did not depend as much on the Ga concentration as upon the manufacture of the phosphor sample. One phosphor sample yielded a long FWHM larger than 2 ns, and the other sample showed a 250-ps FWHM.

In one application, time-resolved imaging, a fluor can be used as an image plane, which is closely coupled to a fiber-optic image dissector to encode the two-dimensional image into a one-dimensional

line suitable for ultrafast streak camera input. The streak data may be dissected line by line perpendicular to the streak; each encoded line that is decoded produces a time sequential segment of a frame. A specific adaptation of this scheme under consideration is a higher resolution technique to measure the Doppler-broadened 14-MeV neutron spectrum from laser-irradiated DT targets. This scheme entails a series of sandwiched fast scintillators whose individual outputs are coupled with a fiber-optics dissector to a streak camera, as shown in Fig. 3-105. Fast scintillators enable direct measurements of the number of neutrons arriving per nanosecond rather than absorbed neutron energy. A light pulse in the scintillator is transmitted down the light pipe in the image dissector onto the photocathode of an ultrafast streak camera. The number of scintillations per unit time can then be counted in the streak record to determine the spectrum of neutron arrival time. The statistics associated with spectral data measured this way

Table 3-6. Summary of the scintillator's temporal responses to pulsed soft x-ray radiation

Sample	Rise time (ps)	FWHM (ps)	Decay constant (short)	Decay constant (long)	Light output ^a
PVT, Butyl-PBD (50 g/l)	100 ± 25	300 ± 25	470 ± 25	2.6 ± 0.5 ns	(100)
PVT, Butyl-PBD (75 g/l)	140 ± 50	300 ± 50	400 ± 100	—	32
PVT, Butyl-PBD (125 g/l)	90 ± 25	280 ± 25	250 ± 50	1.2 ± 1.0 ns	69
PVT, Butyl-PBD (150 g/l)	100 ± 25	280 ± 50	290 ± 100	4.0 ± 1.0 ns	27
PVT, Butyl-PBD (175 g/l)	140 ± 50	260 ± 50	200 ± 50	—	—
PVT, Butyl-PBD (200 g/l)	130 ± 50	270 ± 50	350 ± 50	4.0 ± 1.0 ns	56
NE111	100 ± 25	500 ± 50	630 ± 50	1.7 ± 0.5 ns	(100)
NE111 + 5% Acetophenone	100 ± 25	230 ± 25	200 ± 50	1.0 ± 0.5 ns	2
NE111 + 15% Acetophenone	100 ± 25	200 ± 25	210 ± 25	—	9
NE111 (control)	100 ± 25	500 ± 25	730 ± 50	1.7 ± 0.5 ns	(100)
NE111 + 5% Benzophenone	100 ± 25	300 ± 50	—	—	6
NE111 + 10% Benzophenone	100 ± 50	200 ± 25	140 ± 25	1.9 ± 0.5 ns	6
NE111 + 15% Benzophenone	100 ± 50	200 ± 50	220 ± 50	—	4
ZnO: Ga	100 ± 25	250 ± 25	260 ± 25	1.0 ± 0.5 ns	—

^aLight output relative to first sample of the group.

Fig. 3-105. Application of fast scintillators in neutron time-of-flight detector.

would be about two times better than those measured with our present scintillator-photomultiplier system (§ 3-5.4) and will provide more precise spectral shape and temperature information.

References

51. P. B. Lyons, S. E. Caldwell, L. P. Hocker, D. G. Crandall, P. A. Zagarino, L. Franks, J. Cheng, G. Tirsell, and C. R.

Hurlbut, *Sub-Nanosecond Plastic Scintillators*, submitted to the 1976 IEEE Nuclear Science Symposium.

52. S. W. Thomas, J. W. Houghton, G. R. Tripp, and L. W. Coleman, in *Proc. 11th Int. Congress on High Speed Photography*, 1974, p. 101.
53. R. A. Lerche, *Laser Program Annual Report 1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1974).

Author
G. R. Tripp

Major Contributor
J. Cheng

3-5 PARTICLE DIAGNOSTICS

3-5.1 Particle Calorimeters

An important technique we use to determine the fraction of the laser energy absorbed by a target is to directly measure, by calorimetry, the energy of the products of the laser-target interaction — ions, electrons, and x rays. For this purpose a number of specialized calorimeters have to be built and adapted to particular experimental requirements.

A differential-ring-and-disk ion calorimeter, model LC-17, has been previously described.^{34,55} In this design, two receivers are used, one shielded

against x rays and particles so that compensation is provided for signals generated by $1.06\text{-}\mu\text{m}$ radiation scattered by the target. A new model, LC-18, has now been built for laser-target diagnostic applications in locations where less space is available—such as holes in the equatorial support ring of the Janus clamshell focusing system. This new calorimeter is illustrated in Fig. 3-106. The three receivers are 12.7 mm in diam. The thermoelectric modules of the end units are compensated with a resistor network to match their sensitivity to that of the center module, and they are

Fig. 3-106. LC-18 three-disk ion calorimeter is designed to fit into small spaces.

connected in parallel and opposed to the central module to compensate for scattered radiation.

A glass-disk particle calorimeter, model LC-19, which is transparent to $1.06\text{-}\mu\text{m}$ radiation, has also been previously described.^{54,55} Another version of this calorimeter, model LC-25, has now been developed. It uses a Pyrex 7740 disk, 6.0 mm in diam and 1.0 mm thick, with the thermocouple junctions cemented to the edge of the disk rather than to a face. The disks are designed to be mounted behind the 5.0-mm holes in the Janus clamshells, so that the thermojunctions are not irradiated.

A significant problem in the calorimetric measurement of particle fluxes is insufficient knowledge of the efficiency of absorption of the incident energy; some energy is lost by sputtering and other mechanisms. On the basis of a literature search we have chosen aluminum as the most promising absorbing surface, but the literature is far

from definitive for multiply charged heavy ions. To investigate the losses due to energy that is not absorbed, we have developed model LC-26, shown in Fig. 3-107. The two receiving disks are similar to those of LC-18 described above but are somewhat larger, 15.9 mm in diam. The apertures, 11.15 mm in diam, are 36 mm from the receivers and 155 mm from the target in the Argus system; thus a circle 13.7 mm in diam on the receivers is irradiated. The cylinders are aluminum, 19.0 mm in diam, 22.2 mm long, and 0.30 mm thick, subtending 91.6% of 2π steradians about the center of the receiver. The temperature difference of the two cylinders is measured by a wire thermopile with eight junctions uniformly distributed on each cylinder. Simultaneous measurements of the energy absorbed by the disk and by the cylinder give an approximate measure of the efficiency of energy absorption by the aluminum surface of the disk.

Another approach to the energy loss problem is to compare the energy absorbed by two different surfaces. For this purpose, model LC-24 has been built.⁵⁴ This calorimeter is essentially three model LC-18's fastened side by side. The six receivers on the side groups have aluminum surfaces and the three on the central group have the surface being compared, such as gold. The ratio of the energy absorbed by the central group to the average of that absorbed by the two side groups is therefore the ratio of the efficiencies of energy absorption by the two surfaces. Figure 3-108 shows the layout of the system.

The reflectivity at $1.06\text{ }\mu\text{m}$ of the household aluminum foil used on the particle calorimeters has been measured calorimetrically.⁵⁴ Several spots on different calorimeters gave values ranging from 91.8 to 93.5%.

References

54. S. R. Gunn, *Calorimeters for Diagnosis of Laser Fusion Experiments*, Lawrence Livermore Laboratory, Rept. UCID-17308 (1976).
55. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p. 406.

Author
S. R. Gunn

Fig. 3-107. Model LC-26 calorimeter uses a cylinder covering 91.6% of 2π steradians about the center of the absorber disk to measure the energy of particles that escape being absorbed by the disk.

Fig. 3-108. LC-24 nine-disk ion calorimeter—essentially three LC-18 calorimeters arranged side by side—is used to measure energy-absorbing efficiencies of various materials relative to aluminum.

3-5.2 Ion Spectrometers

To investigate the charge state and energy distribution of high-energy ions expanding from laser fusion targets, we have added two magnetic spectrometers⁵⁶ (Fig. 3-109) to the arrays of Argus particle diagnostics. Charge collectors are still being used to monitor the ion time of flight at several positions within the target chamber, but they have inherently poor resolution for the fastest ions. In addition, the measured signal of such detectors is proportional to the ion charge and number flux. The number flux of the "fast ions," which come from the high-energy tail of the distribution, is low. Also, the detectors must be placed far from the target to increase the time-of-flight resolution at high energy. This further reduces the flux into the detector.

Thus, energy-sensitive rather than charge-sensitive detectors — fluor-photomultipliers, PIN diodes, silicon surface barrier detectors, etc. — are ideally suited to investigate these “fast ions.” Most of these energy-sensitive detectors are sensitive also to light and x rays, so special precautions must be taken to ensure their recovery from the radiation response before arrival of the ions (long time of flight).

The spectrometers now installed on the Argus target chamber use fluor-photomultipliers as detectors and are basically identical to the instruments developed for α -particle detection.⁵⁷ A new design, being fabricated, uses several detectors, PIN diodes, and SiSB detectors for the high-energy (above 500 keV) end of the spectrum and fluor-photomultipliers for the low range (110 to 500 keV).

Figure 3-110 shows the particle trajectories in the spectrometers. For a uniform field, the basic equation governing these trajectories is $BR \propto (A/Z)v$, where B is the magnetic field, R is the radius of curvature of the trajectory in the field's region of influence, v is the particle velocity at the instrument entrance, and A and Z are the mass and charge of the particles, respectively. By varying the size and location of the output aperture in the detector plane, we can detect variable ranges of $(A/Z)v$. The present system aperture corresponds to a span of 0.9 keV (for Si^{1+}) to 21-MeV (for Si^{14+}). The detection range is limited because of the scintillator's degraded response to heavy low-energy ions, as discussed below.

Fig. 3-109. Wide band spectrometer. Note the micrometers used to align the input slit.

Fig. 3-110. Operation of a magnetic spectrometer. For a given species the radius of curvature of the particle trajectories increases as the energy increases or the charge state decreases.

Operating Modes

The spectrometers have been used in two basic modes:

- **Wide-band mode.** Here, the output aperture is fully open so that, for each type of particle, a wide energy range is detected. Since the time of flight provides the energy per amu and the detector response is proportional to the total energy flux, we can determine the total energy carried by the “fast ions” to within the uncertainty in $\bar{A}$. For glass microspheres, whose ions are mostly silicon and oxygen, the choice $\bar{A} = 20$ produces errors of the order of 30%, whereas data gathered from charge collectors in this energy range can easily have 100% error.

- **Narrow-band mode.** In this case, the output slit is so narrow that overlap does not occur between the accepted energy bands of (some of the) species. In particular, protons with $A/Z = 1$ are uniquely identifiable.

Figure 3-111, which compares data from these two modes, shows that the fastest ions ($v \approx 10^9$ cm/s) are protons. Since the two shots from which these data were obtained were similar, the comparison also indicates that, in the range 4×10^8 to 10^9 cm/s, a large fraction of the particles are not hydrogen- or helium-like ions but particles of lesser charge states.

Figure 3-112 is a schematic diagram of the apparatus, which comprises a collimator section (mounted on the target chamber), a deflection section, and a detector package. The entrance aperture,

Fig. 3-11 i. Windows for various species are indicated for the narrow or wide band mode of operation. Comparing both figures, we see a first proton peak (around 600 eV on the narrow-band configuration, extending to several MeV in the wide-band mode) followed by a second peak at several MeV containing all charge states of oxygen and silicon ions (compare windows on both figures). Data were obtained on similar tests.

Fig. 3-112. Spectrometer design showing the collimation, deflection and detector sections. Compare with Fig. 3-109.

located at the end of the collimator tube, is a 1- × 14-mm slit surrounded by a lead shield. For alignment purposes, the slit can be translated in two directions normal to the tube axis. A 1-mm-wide slit can be placed normal to the basic aperture to provide a 1-mm² acceptance area. Alternately, pinholes of various sizes can be placed in front of the slit to limit the particle flux into the detector.

The deflection section is baffled to further decrease the scattered light into the detector. The magnetic field is generated by two magnetized pieces of strontium ferrite in a rubber matrix linked by a steel plate. Slots in the steel plate permit adjustment of the path length between poles and, hence, the field strength. The drift region between the end of the magnet and the detector minimizes the effect of the magnetic field on the photomultiplier tube and also increases the distance between the direct line of sight to the target (which must be shielded from the radiation) and the position where the fastest ions are detected.

The 38- × 14-mm output slit is located at the end of the drift tube. At the very high energy end of the slit, a lead trap is provided for x rays. A narrow slit — 2 × 14 mm — can be positioned within the output aperture, at any distance from the lead trap for the narrow band mode of operation.

The detector consists of a bare 250-μm-thick NE-111 fluor bonded to a thicker filter glass and a photomultiplier tube. The thin fluor transmits most of the high-energy x rays, which are absorbed in the filter material without producing fluorescence. The filter also selectively transmits in the 4000-Å region, matching the light emitted by the fluor.

Calibration

We calibrate the fluor-photomultiplier tube with a 5.8-MeV α-particle source (²⁴⁴Cm), resulting in 0.28 V-ns. The detector response is better than 5 ns. For a 1550-mm total flight path from target to detector, the useful portion of the ion-spectra data typically comes from flight times of 70 to 800 ns.

As discussed by Birks,⁵⁸ the response of organic scintillators to heavy particles is approximately proportional to range, but the proportionality constant depends on the atomic number of the incident

particle. Beketti *et al.*⁵⁹ have studied plastic scintillators' response to high-energy particles. For our data reduction, we have used their parametric representation of light output as a function of range and particle atomic number, normalized to the calibrated value for 5.8 MeV α-particles. Where most of the collected ions are oxygen and silicon (characteristic of experiments with glass microspheres), the response has been obtained for $\bar{Z} = 10$ and the range vs energy values of neon.⁶⁰ In the range 1 to 10 MeV, the same parametric representation is also valid for protons with $\bar{Z} = 1$ and the appropriate range vs energy curve, and has been used where the narrow-band mode of spectrometer operation identifies the collected ions as H¹⁺.

In the lower energy range (10 to several hundred keV/amu), no calibration data are available, so the spectrometer can only indicate the presence of certain ion species as an aid to interpreting the charge-collector data. Strictly in this context, the scintillator response in this energy band is still taken as proportional to range.

The magnetic field within the deflection region has been mapped to determine the particle trajectories. As shown in Fig. 3-113, the field is uniform over most of the length of the poles, decreasing rapidly outside them. The equivalent field strength over the pole length (152.9 mm) is 3.77×10^{-2} T. Similar scans at different lateral positions between the poles provide identical curves, thereby ensuring lateral uniformity of the field.

Since the solid angle subtended by a 1-mm² entrance aperture is 6×10^{-7} , the ion current into the deflection region is about 10^{-9} A at velocities of 10^8 cm/s, based on charge-collector data. Hence, space-charge effects are negligible in the spectrometer.⁶¹

Now being investigated are methods for calibrating the scintillator response to heavy particles (silicon, oxygen, and carbon) in the 100-keV range.

Our future plans include using the spectrometers to investigate the "fast ions" produced from planar targets of low-Z materials. (It is easier to identify species emitted from such targets.) We will also determine the fraction of absorbed energy lost to "fast ions" as a function of total absorbed energy for variable incidence of 1.06-μm radiation onto these targets. After calibration, the multidetector spectrometer will also be used to identify and obtain spectra on each charge-state ion.

Fig. 3-113. Magnetic field within the deflection region. The magnetic field is uniform over most of the pole length. Lateral scans within the deflection region show identical curves.

References

56. S. S. Glaros, K. G. Tirsell, V. C. Rupert, H. C. Catron, and V. W. Slivinsky, *Measurement of High Energy Ions*, Lawrence Livermore Laboratory, Rept. UCRL-78427 Rev. 1 (1976).
57. V. W. Slivinsky, K. G. Tirsell, S. S. Glaros, D. E. Campbell, and H. Catron, UCRL-50021-75, pp. 409-410 (1975); V. W. Slivinsky, H. G. Ahlstrom, H. G. Tirsell, S. S. Glaros, G. B. Zimmerman, and H. D. Shay, *Phys. Rev. Lett.* **35**, 1083 (1975).
58. J. B. Birks, *The Theory and Practice of Scintillation Counting* (Pergamon Press, New York, 1964), p. 187.
59. F. D. Beckett, C. E. Thorn, and M. J. LeVine, *Nucl. Instr. and Meth.* **6** (1976).
60. L. C. Northcliffe and R. T. Schilling, *Nuclear Data Tables* (Academic Press, New York, 1970).
61. P. Grivet, *Electron Optics* (Pergamon Press, Oxford, England, 1965).

Author

V. C. Rupert

3-5.3 Infrared Imaging of Plasma Energy Distribution

In exploding-pusher-type targets, about 80 to 90% of the plasma energy is contained in the ions. Depending on the type of laser plasma interaction

process, the ion distribution may have a highly complex spatial structure. There has been considerable interest in mapping this spatial plasma energy distribution for implosion experiments with a detector that would have a large spatial coverage and good spatial resolution. It is quite obvious that discrete ion detectors cannot satisfy this requirement. An alternative is to use the infrared imaging technique.

The infrared imaging technique surrounds the target with a thin receiver material that is transparent to 1.06- μ m light, but stops the ions (as well as the low energy electrons and thermal x rays). The stopped ions then heat the receiver material and raise its temperature locally; thus an infrared image of the heated material provides a spatial distribution of the plasma energy.

Figure 3-114 shows a schematic of the infrared imaging system. The receiver may be a bubble enclosing the whole target or, depending on the experimental configuration, a flat plate intercepting the solid angle of interest. An infrared transmitting lens system focuses the spatial thermal distribution produced by the plasma energy distribution onto the pyroelectric element of the TV camera; the infrared image is then recorded on a video disk. The image obtained at this stage is only raw data since the true infrared image of energy distribution is convoluted with the specific receiver geometry and the infrared lens system characteristics. Therefore, to facilitate the data processing, the video signal is digitized. A PDP-11/10 computer is linked to the digitizer for averaging out the noise introduced by the video disk and digitizer. The "clean" digitized signal is then recorded on a floppy disk. A magnetic tape interfaces this data onto the Octopus system where the final data processing (unfolding, etc.) is performed. (The Octopus is the Livermore timesharing computer system.) This gives us the true spatial map of relative energy.

One great advantage of the infrared imaging scheme, besides large spatial coverage, is that plasma energy (i.e., ions) in the direction of the incident beam could also be imaged. This is a capability that discrete ion detectors such as Faraday cups or plasma calorimeters do not possess.

For the effective operation of the infrared imaging system, there are several requirements imposed on the receiver material. First, it must be highly transparent to 1.06- μ m light. Second, the material should have either a low density (ρ), a low specific heat (c_p), or be made very thin so that for a given

Fig. 3-114. Infrared imaging system for spatial plasma energy distribution measurements.

amount of energy impinging on a spot of the receiver, a maximum temperature rise consistent with structural integrity should occur. Third, the material should have a high emittance.

Since the pyroelectric detector in the infrared TV camera is sensitive only to changes in the temperature of the radiating object (i.e., the receiver material), a shutter has to be used for the infrared imaging of plasma energy in implosion experiments. The trigger delay for opening the shutter and shutter speed can be estimated by considering the following.

From the heat conduction equation

$$\frac{\partial T}{\partial t} = \nu_T \nabla^2 T, \quad (30)$$

where

$$\nu_T = \frac{k}{\rho c_p}$$

is the thermometric diffusivity (k is the heat conductivity, ρ the density, and c_p the specific heat). The

characteristic time for heat conduction is

$$\tau_c \sim \frac{L^2}{\nu_T}, \quad (31)$$

Fig. 3-115. IR image of ceramic resistors at different temperatures. (a) left to right 24, 27, and 33.5°C. (b) temperature profile scan through A — A.

where L is some characteristic length scale. For Pyrex glass ($\nu_T = 5.62 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$), the characteristic time for a 20- μm -thick receiver to be heated up by the stopped ions is $\tau_c \sim 7 \times 10^{-4} \text{ s}$. On the other hand, the characteristic time for smearing a 1-mm "thermal spot" on the receiver due to heat conduction in the plane of the receiver is $\tau_c \sim 1.78 \text{ s}$. The above example indicates that a trigger delay of say, 100 ms, and a shutter speed of 1/2 s or less would be very adequate. Incidentally, cooling off of the thermal spot by radiation is of no concern since the characteristic time for radiation cooling is quite large compared to the conduction times. This can be estimated by equating the change in energy in unit volume (of receiver material) per unit time per unit radiating area to the Stefan-Boltzmann law of radiation; this results in

$$\rho c_p d \frac{\partial T}{\partial t} = \epsilon \sigma (T^4 - T_0^4), \quad (32)$$

where d is the thickness of the receiver, ϵ is the emittance, $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ is the Stefan-Boltzmann constant, and T_0 is the ambient temperature, assuming that the shutter is at ambient temperature and that the shutter has the same emittance as the receiver. Otherwise T_0^4 is replaced by

$$\frac{\epsilon_s}{\epsilon} T_0^4, \quad (33)$$

where ϵ_s is the emittance of the shutter. Depending on the geometry of the receiver, $I = 1$ for a bubble and $I = 2$ for a flat plate. The characteristic radiation cooling time is therefore scaled by

$$\tau_H \sim \frac{\rho c_p d}{4 T^3 \epsilon \sigma}. \quad (34)$$

For Pyrex glass at room temperature and $d = 20 \mu\text{m}$, this gives $\tau_H \sim 6.87 \text{ s}$.

Other candidates besides glass (e.g., thin Mylar sheets) are also being considered as receiver material. It appears that uniform thickness of the receiver is a very stringent requirement.

For the infrared lens system design, the relationship between the variation in the radiance (ΔR) of the receiver and the irradiance (ΔE) of the

Fig. 3-117. Sensitivity calibration curve obtained by using glazed ceramic resistors ($\epsilon \approx 0.92$) and blackened shutter ($\epsilon \approx 0.94$).

Fig. 3-116. IR image of "Vector-Bord." Hole diameters of 1.1 mm on material are clearly resolved.

TV tube face plate has to be taken into account. This is given by

$$\Delta E = \frac{T_0 \Delta R A}{4f^2(1+m)^2} \quad (35)$$

where T_0 is the transmittance of the lens systems, f is the lens f number, and m is the magnification. ΔR is given by the Stefan-Boltzmann law, and A is the fraction of the total radiance transmitted between the transparency window limits. A is given by

$$A = \frac{\int_{\lambda_1}^{\lambda_2} I(\lambda, T) d\lambda}{\int_0^{\infty} I(\lambda, T) d\lambda} \quad (36)$$

where $I(\lambda, T)$ is Planck blackbody radiation function. The requirements on the lens system are therefore: (1) high infrared transmittance, (2) small f number (i.e., fast lens system), and (3) low magnification.

The preliminary systems calibration has been performed by using a simple $f/0.833$ infrared transmitting lens. The temperature resolution is $T_{res} = 2^\circ\text{C}$. The radiating objects used were glass bubbles and ceramic resistors with an emittance of $\epsilon \approx 0.92$. A typical example showing the temperature resolution is given in Figs. 3-115(a) and (b). The spatial resolution is better than 1 mm, provided that the condition $\Delta T \geq \Delta T_{res}$ is satisfied. Figure 3-116 shows an example of the spatial resolution of the camera system. The output sensitivity of the camera system is of order of $2 \text{ mV}/^\circ\text{C}$. A typical sensitivity calibration curve is shown in Fig. 3-117. At present, the digitizer and PDP-11/10 computer have been interfaced to the infrared imaging system.

The infrared imaging system will be ready for use on implosion experiments after full system calibrations (including digitizer) are completed.

Author
P. H. Lee

Major Contributors
V. C. Rupert
J. R. Severyn
S. S. Glaros
C. E. Thompson

3-5.4 Argus Neutron Time-of-Flight System

When a fusion target is irradiated and compressed by a laser pulse, the target emits neutrons. By measuring the neutron yield and energy distribution, we can acquire knowledge of the target's density and fuel ion temperature, as well as gain insight into the mechanism of the reactions.⁶² X-ray emission from the fuel, which in principle might provide data about the reactants, is masked in these experiments by radiation from the surrounding higher- Z shell. Furthermore, unlike the α -particle distribution,⁶³ the neutron energy distribution is virtually unperturbed by neutron passage through the compressed fuel and target wall. For these reasons the neutron energy distribution measurement is an important and valuable tool for studying target performance.

The neutron time-of-flight (TOF) spectrometer, whose design was discussed in last year's Annual Report,⁶⁴ has been built, calibrated, and used to measure DT neutron energy spectra in Argus experiments. Fuel ion temperatures have been determined from these data.⁶⁵ As shown in Fig. 3-118, a schematic of the TOF facility, the spectrometer has two separate 44.5-m flight paths (41.5 m in vacuum) between the center of the Argus target chamber and the detectors. The transmission for 14-MeV neutrons is about 95%. Each detector consists of a large, fast, plastic scintillator coupled to a fast photomultiplier whose output is recorded on 500-MHz oscilloscopes. Each detector system time response—typically about 3.5 ns FWHM—is carefully characterized using signals induced by cosmic rays. The sensitivity of each detector is determined by calibration against a laser-induced neutron yield measured by a calibrated copper activation neutron monitor (see § 3-5.5) and also by direct exposure to DT neutrons from a pulsed neutron generator.

The photomultiplier output is split between several oscilloscopes and transient digitizers so that different time intervals after the DT burn may be investigated using optimized sweep rates. Figure 3-119 shows traces from one experiment. The x-ray burst arrives at the detector 148.6 ns after the DT burn. Timing marks are added to each trace so that any point on the neutron trace can be timed, relative to the x-ray-induced pulse, with an accuracy of ± 3

Fig. 3-118. Argus neutron time-of-flight spectrometer.

ns. The average neutron energy can thus be determined to ± 100 keV. To date, the recorded signals show no evidence of scattered events entering the detectors, which has confirmed the effectiveness of our shielding and collimation design.

A computer code that uses an iterative procedure was developed for unfolding the neutron-induced signal. Because of the relatively low number of neutrons interacting in the detector and the poor single-event pulse-height distribution of the detector, response to individual neutron interactions is often noticed. Interpretation of the data is enhanced by plotting the results as discrete data points and assigning error bars consistent with the detector statistics. The nature of the unfold problem makes it difficult to separate impulse functions spaced closer than about half the FWHM of the detector system response. Energy bins of 50 keV are used; this is equivalent to about half the FWHM of the system response.

An example of an unfolded energy spectrum measured on a shot is shown in Fig. 3-120. It clearly

Fig. 3-119. Oscilloscope traces of typical experimental signals. (a) X-ray-induced pulse caused by burst of x rays which arrive at the detector 148.6 ns after the DT burn, followed by a timing mark. Sensitivities are 500 mV/div and 10 ns/div. (b) Neutron-induced pulse followed by timing mark. The time interval between timing marks is 713 ns. Sensitivities are 500 mV/div and 5 ns/div.

shows that there is energy broadening about the mean DT neutron energy. The spectral shape is consistent with a Maxwell-Boltzmann ion velocity distribution. However, the target yields are not yet great enough to determine the spectral shape conclusively on a single-shot basis. Clearly evident are the statistical variations due to the low number of neutrons detected.

A Monte Carlo simulation of the TOF experiment was done to study the statistics associated with an individual shot. A series of shots was simulated with the neutron arrival times randomly generated from a 14-ns FWHM Gaussian time distribution. We modeled the detector using its pulse-height distribution to 14-MeV neutrons. The results show

that for experiments at current neutron yields, the FWHM cannot be read directly from an unfolded distribution because of the statistical fluctuations. However, the study also showed that if the spectrum were assumed to be Gaussian, the FWHM could be determined by calculating the standard deviation of the unfolded distribution and scaling it by a constant factor (2.35). The error σ (FWHM) when the FWHM is estimated this way is

$$\sigma(\text{FWHM}) = (1.25 \times \text{FWHM}) / \sqrt{N} \quad (37)$$

where N is the number of neutrons interacting in the detector.

Fig. 3-120. Neutron energy distribution for one shot. DT neutron yield was 6.7×10^8 . The average neutron energy is 13.94 ± 0.10 MeV.

Table 3-7. Sample of neutron TOF measurements and calculated ion temperature.

The result for each shot is the average for two detectors

Shot	Yield, 10 ⁸ neutrons	Neutrons detected	Average neutron energy, MeV	Energy width, keV	Ion temperature, keV
36092905	4.2 ± 1.0	250	13.97	456	6.6 ± 1.4
36093003	6.0 ± 1.0	360	13.97	428	5.8 ± 1.3
36100812	6.7 ± 0.9	410	13.97	463	6.8 ± 1.4
36101202	3.3 ± 0.5	200	14.00	382	4.7 ± 1.1
36101203	4.4 ± 0.6	270	14.00	430	5.9 ± 1.3

Table 3-7 shows the results of five shots that had similar laser and target characteristics. The measured average neutron energy for these experiments agrees with the expected 14.05-MeV value that is calculated from nuclear mass data.⁶⁶ The expected value includes a small shift caused by the ion temperature. The ion temperature, θ_i , is determined from Brysk's analytical expression: $\Delta E = 177 \sqrt{\theta_i}$, which assumes that the ion velocity distribution is Maxwell-Boltzmann. The temperatures determined by neutron TOF techniques are in general agreement with the 5-keV temperature values predicted for these targets by the two-dimensional Lagrangian magnetohydrodynamic code LASNEX. They are also in agreement with the temperature values determined from α -particle measurements on similar targets.

3-5.5 Neutron Yield by Copper Activation

To improve our accuracy in measuring DT neutron yields, we have developed a neutron activation detector system and added it to our target diagnostics at the Argus facility. The 14-MeV fusion neutrons produce $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ reactions in a copper disk placed at the target chamber. The target yield is determined by coincidence-counting the annihilation γ rays from the 9.8-min half-life positron decay of ^{62}Cu . The system is useful for target yields exceeding about 3×10^8 neutrons, and it has several advantages over other yield monitors. The technique is immune, for instance, to x rays and low-energy scattered neutrons because the neutron reaction cross section has a threshold at 11 MeV and a low value below 13 MeV. Coincidence counting substantially reduces background counts. Also, the technique is directly amenable to automatic operation from computer-interfaced data systems.

Figure 3-121 is a block diagram of the system we have assembled to count ^{62}Cu disintegrations. The irradiated copper disk is inserted between two 3-in.-diam, 3-in.-thick NaI(Tl) detectors and then counted. The window of each single-channel analyzer (SCA) is set so that detected 511-keV γ rays generate standard 1- μs output pulses. Figure 3-122 is a pulse-height spectrum showing the 511-keV x-ray peak and the setting of the SCA window. When suitable signals occur in the two detectors within the system resolving time of 2 μs , a coincidence pulse is

References

62. H. Brysk, *Plasma Phys.* **15**, 611 (1973).
63. V. W. Slivinsky, H. G. Ahlstrom, K. G. Tirsell, J. Larsen, S. Glaros, G. Zimmerman, and H. Shay, *Phys. Rev. Lett.* **35**, 1083 (1975).
64. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976).
65. R. A. Lerche, L. W. Coleman, J. W. Houghton, D. R. Speck, and E. Storm, "DT Ion Temperatures Determined from the Neutron Energy Spectrum of Laser Fusion Targets," Lawrence Livermore Laboratory, Rept. UCRL-78430 (1976).
66. J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, *Nucl. Phys.* **67**, 1 (1964).

Author
R. A. Lerche

Major Contributors
L. W. Coleman
J. W. Houghton
W. R. McLerran
W. G. Holloway

generated and counted with a scaler. Two additional scalers that count events from the SCA's provide the needed information to correct for accidental coincidence counts. A timer which starts running at irradiation time controls a printer that records the number of scaler counts at the end of preset time intervals.

The coincidence count rate $R(t)$ for ^{62}Cu disintegrations from a disk irradiated at time $t = 0$ by a

temporal and spatial point source of N_0 neutrons at distance D is given by

$$R(t) = \frac{a N_0 \lambda}{D^2} \exp(-\lambda t) \quad (38)$$

where a is a constant that includes the neutron reaction cross section and detection system efficiency

Fig. 3-121. Block diagram of coincidence system.

Fig. 3-122. Pulse-height spectrum for copper disk after irradiation by 14-MeV neutrons. Lower-level and upper-level discriminators of the SCA's are set at 430 and 600 keV, respectively, so that events within the window about the 511-keV photoppeak generate a SCA pulse.

and λ is the decay constant of ^{62}Cu . The number of disintegrations, C_n , counted between $(n-1)\Delta t$ and $n\Delta t$ is given by

$$C_n = \left\{ \frac{aN_0}{D^2} [\exp(\lambda\Delta t) - 1] \right\} \exp(-\lambda n\Delta t), \quad (39)$$

where n is an integer and Δt is the counting time interval. The intercept from the semilog plot of C_n vs n readily yields C_0 , as shown in Fig. 3-123. On a calibration shot, the value of a is determined from Eq. (39) by using measured values of C_0 , N_0 , λ , and the system parameters D and Δt . On a laser shot, the neutron yield N_0 is determined from Eq. (39) by using the measured values of C_0 , λ , D , Δt , and the a value determined on a calibration run.

Fig. 3-123. Copper disk decay curve, C_n vs n . Initially, decay of the 9.8-min half-life ^{62}Cu atoms dominates the curve. After an hour, decay of the ^{64}Cu isotope (12.8-h half-life) is noticeable. These data were taken on a calibration run for which $N_0 = 9.75 \times 10^{12}$, $\lambda = 7.87 \times 10^{-2} \text{ min}^{-1}$, $D = 220 \text{ cm}$, and $\Delta t = 1 \text{ min}$. The calibration constant a determined from this curve is 2.37×10^{-3} ; it includes a 0.91 cross-section correction factor.

Fig. 3-124. Copper disk decay curve, C_n vs n . Data taken on laser shot with $a = 2.45 \times 10^{-3}$, $\lambda = 7.07 \times 10^{-3}$ min, $D = 41$ cm, and $\Delta t = 1$ min. The neutron yield value determined by the integral method (Eq. 3) is $1.76 \pm 0.20 \times 10^9$. The solid line represents this neutron yield.

Calibration neutron irradiations performed in the cw mode at the LLL Rotating Target Neutron Source (RTNS) facility⁶⁷ were typically 30 s long. Corrections were made for the beam "on time." The equivalent isotropic source strength N_0 seen by the copper disk was measured to $\pm 5\%$ using two proton-recoil counters (PRC's). The relative positions of the target foil, beam, and copper disk were such that the irradiations were done with 14.8-MeV neutrons. Correction was made for the slight change in reaction cross section from the value at 14.1 MeV.

For a 10^9 neutron yield and a separation distance (D) of 41 cm between the target and the copper disk, the initial count rate is 100 per min, as shown in Fig. 3-124. Because of the large statistical error associated with each point, accurate yield values cannot be determined directly from a simple curve fit as in the case of the calibration runs, which had initial count rates of 40,000 per min. However, a weighted least-squares fit will work. An alternate approach—now in use—is to sum the number of detected disintegrations, C_{12} , between the measured times t_1 and t_2 . Since

$$C_{12} = \frac{aN_0}{D^2} [\exp(-\lambda t_1) - \exp(-\lambda t_2)] , \quad (40)$$

the value of N_0 can be readily determined.

In the laboratory, the measured number of coincident events includes a background component that is not associated with the ^{62}Cu decay. Before each shot, the disk's background level is counted for 10 min to permit a background correction. The PRC calibration and cross-section ratio limit the absolute accuracy of the determination of a and the value of N_0 to about $\pm 7\%$. Under current operating conditions and yields above 10^9 , the total error is approximately $\pm 10\%$. The system has been successfully implemented and is providing neutron yields values on Argus experiments.

Reference

67. H. H. Barschall, R. Booth, and C. Wong, *Neutron Flux Measurements at RTNS Facility*, Lawrence Livermore Laboratory, Rept. UCID-17206 (1976).

Author
R. A. Lerche

Major Contributors
W. R. McLerran
G. R. Tripp

3-5.6 Radiochemistry of Target Debris

Articles elsewhere in this report describe the diagnostics systems for determining the Doppler-broadened energy spectra of the fusion-reaction products (i.e., neutrons, alpha particles, protons) emitted from laser-compressed fusion targets. These measurements are made with targets that achieve moderate compressions and average pusher-density-thickness products, $(\rho R)_p$, on the order of 10^{-4} to 10^{-3} g/cm². In this case, the charged particles (α and p) pass out of the target and can be diagnosed. The fusion yields are sufficiently high because the moderately high ion temperature ensures that there are enough neutrons with which to make time-of-flight spectral measurements. As we progress to higher-laser powers and to targets designed to compress to higher density, we enter a

regime where $(\rho R)_p$ is high enough so that spectroscopy is not possible; the charged particles do not escape the target and the thermonuclear yields initially are too low for neutron time-of-flight diagnostics.

To obtain information concerning the compressed state of the target under these conditions, we are developing the application of nuclear reaction and activation techniques. In particular, we are implementing a scheme using a neutron-induced reaction in ^{28}Si (the 92% naturally abundant isotope of silicon) which is a plentiful constituent in the glass-walled microsphere targets.⁶⁸ At the instant of thermonuclear burn, 14-MeV neutrons emitted by the compressed DT gas in the target center pass through the glass pusher wall and react with ^{28}Si nuclei forming ^{28}Al via the reaction, $^{28}\text{Si}(n,p)^{28}\text{Al}$. The ^{28}Al then decays (2.2-min half-life) by β^- emission (2.9 MeV) to an excited state of ^{28}Si which, in turn, decays to its ground state by emission of a 1.8-MeV γ ray. By collecting and accurately counting the target debris, the number of ^{28}Al nuclei can be determined. The neutron yield is independently measured and thus $(\rho R)_p$ of the compressed pusher can be determined because the number of activated nuclei is proportional to the product of neutron yield and $(\rho R)_p$.

We have tested a special detector system designed to detect and count coincidences between the β^- and γ rays emitted during this decay. With this technique, the background level and efficiency of the detector system are such that it is possible to detect 150 atoms of ^{28}Al . This means that our present targets, which produce about 5×10^8 neutrons with a $(\rho R)_p$ of approximately 2×10^{-4} gm/cm², are at the limit of detectability.

This activation technique depends, of course, on the ability to collect, retrieve, and begin counting the pusher debris in a short time. The time constraint is imposed by the 2.2-min half-life of the ^{28}Al . We plan to collect the debris on a plastic balloon "catcher" surrounding the target.⁶⁸ This catcher will then be removed from the target chamber through a vacuum-lock, inserted into the counting system, and counted.

We are continuing to evaluate and calibrate our counting system for this application. Engineering studies and designs for the target-debris collection and retrieval are under way for implementation of this technique at the Argus laser facility.

Reference

68. F. J. Mayer and W. B. Rensel, "Plastic bubbles and tamper $\langle \rho R \rangle$ measurements for laser-driven fusion experiments," *J. Appl. Phys.* 47, 1491 (1976).

Author

L. W. Coleman

Major Contributors

H. G. Hicks

F. Rienecker

3-5.7 14.7-MeV Proton Detector

To measure protons in the D, ^3He experiment, we have built a high-gain, large-area detector (Fig. 3-125) consisting of an Amperex XP 2041 photomultiplier tube mated to Pyrex glass and 3-mm-thick Corning 7-54 glass. The scintillator material — 0.25-mm-thick NE-111 — is glued to the front face of the filter glass. The active-area fluor material is 110 mm in diameter. A transition fixture has been built to hold the x-ray absorber foil and to mount the entire assembly light-tight to the target chamber.

We calibrated the detector with protons in the energy range 2.3 to 7 MeV at the LLL cyclograph facility. Results are shown in Fig. 3-126. Protons from the cyclograph were scattered from a carbon target in the center of a scattering chamber to the detector, located at 135° with respect to the beam. The vacuum interface was made at the fluor, so there was no window between the fluor and the scatterer. However, 0.043-mm-thick aluminum foil was put in front of the fluor to reduce the signal from x rays emitted by the scatterer. This required a correction for proton energy loss in the foil, found to be only 70 keV for 5-MeV protons. The photomultiplier was run at high gain (-2900 V) so we could count individual protons. The FWHM of a proton pulse was 5 ns.

For the D, ^3He experiments, as many as 50 protons per pulse were measured. The photomultiplier was used at -2500 V. Gain measurements had to be taken to correct the data for this difference in tube voltage. These measurements were made using x rays from a commercial x-ray tube and monitoring the current from the

Fig. 3-125. 14.7-MeV proton detector.

Fig. 3-126. Calibration of 14.7-MeV proton detector. The response rolls off at higher energies because the fluor is thin to high-energy protons.

Fig. 3-127. Gain calibration of 14.7-MeV proton detector obtained from D, ³He experiments.

photomultiplier as its voltage changed. These results are shown in Fig. 3-127.

Author
V. W. Slivinsky

Major Contributor
G. R. Liepelt

3-5.8 Pinhole Imaging of 3.52-MeV Alpha Particles

Alpha particles that are generated in laser fusion experiments lose energy when they escape from the target.⁶⁹ By imaging the particles with a pinhole

camera⁷⁰ (Fig. 3-128), we can empirically confirm the thesis that observed 3.52 MeV particles are generated in the compressed D-T fuel.

The camera used in the experiment has pinholes that are 10 and 25 μm in diameter. Kodak Pathe LR-115 cellulose nitrate is used as a detector. The necessary particle discrimination is provided by an $8 \times 10^{-3} \text{ g/cm}^2$ tantalum filter. Figure 3-129 illustrates the response of this filter-detector system. As can be seen, neither the filter nor the detector absorb a significant amount of the energy released in high-energy neutrons, protons, tritons or deuterons.⁷¹ Low-energy electrons and x rays are absorbed in the filter. Higher energy x rays and electrons pass through the filter but are not imaged in the pinhole and deposit very little energy in the

Fig. 3-128. Pinhole camera.

plastic detector. For a typical Argus microsphere target, a total of only 1.2×10^{-7} J of energy is absorbed in the detector. This energy contributes only to the bulk etch rate of the plastic. Essentially all ions

other than the α particles are stopped in the tantalum filter. Initial 3.52 MeV alpha particles are reduced to approximately 3.27 MeV in escaping through the target plasma.⁶⁹ Their energy is further

Fig. 3-129. Filter-detector response to Argus exploding pusher emissions.

Fig. 3-130. Alpha imaging geometry.

reduced to about 0.9 MeV in passing through the tantalum filter. These alpha particles then produce characteristic damage sites in the plastic which can be seen by etching in six-normal sodium hydroxide for 2 to 4 h at 40°C.⁷¹

Image resolution is poor because of the large size of the pinhole in comparison with the expected object size. Therefore, rather than classical pinhole resolution, it is more appropriate to consider the

spread over which a point source on the object can illuminate the detector. Figure 3-130 shows that this spread is approximately

$$S = 2 R_{ph} (b + a)/a. \quad (41)$$

*See Fig. 3-130 for explanation of symbols.

Further, the object size is found to be

$$R_0 = \left(\frac{a}{b}\right) \left[R_P - R_{Ph} \left(\frac{b+a}{a} \right) \right]. \quad (42)$$

With 10- μm pinholes placed 1 cm from the target and a camera magnification of four, the expected spread is 100 μm . This is comparable to the expected image size of 120 to 130 μm . Equation (42) will allow us to determine a maximum size for the burning gas.

When the camera is placed in close proximity to the target <1 mm, scattered laser energy ionizes the pinhole approximately 100 ps before passage of the alpha particles. This allows the pinhole to partially close, reducing its effective size. The two pinhole sizes incorporated in the same camera provide data that enable us to determine the effective pinhole size at alpha passage:

$$R_{P_1} - R_{P_2} = (b+a)(R_{Ph_1} - R_{Ph_2})/a, \quad (43)$$

$$\left(R_{Ph_1} / R_{Ph_2} \right)^2 = (\text{alpha density}_1 / \text{alpha density}_2). \quad (44)$$

Three targets have been imaged using this system. These results are analyzed in Section 5.

References

69. V. W. Slivinsky, H. G. Ahlstrom, K. G. Tirsell, J. T. Larsen, S. S. Glaros, G. B. Zimmerman, and H. D. Shay, *Phys. Rev. Lett* 35, 1083 (1975).
70. R. W. Bauer, and R. C. Weingart, *A Time-Resolved Fast-Neutron Pinhole Camera for Studying Thermonuclear Plasmas*, Lawrence Livermore Laboratory, Rept. UCR1-77527 (1976).
71. R. L. Fleischer, P. B. Price, and R. M. Walker, *Nuclear Tracks in Solids*, (University of California Press, Berkeley, 1975).

Author
K. M. Brooks

Major Contributors
V. W. Slivinsky
H. G. Ahlstrom

Fig. 3-131. Experimental arrangement for recording the alpha-particle coded image.

(a) Mx

(b) ~4 Mx

(c) ~20 Mx

Fig. 3-132. Optical micrographs illustrating the pinhole distribution in the coded alpha image: (a) central zone = 1.35 mm, (b) 4X, and (c) 20X.

3-5.9 Zone Plate Coded Imaging of Alpha Particle Emission from Laser Fusion Targets

Coded-imaging techniques, discussed earlier in connection with x-ray microscopy, have also been used to produce high-resolution ($\sim 10 \mu\text{m}$) images of the thermonuclear burn region within laser fusion targets. Specifically, the alpha particle emission from laser-compressed, DT-filled microshells has been imaged using the Zone Plate Coded Imaging (ZPCI) technique.

The alpha-imaging experiments reported here were conducted with the Argus laser target irradiation facility. The targets were compressed by

simultaneous, two-sided irradiation with an intense neodymium laser pulse. A zone plate camera viewed the target in a plane normal to the directions of the two-sided laser irradiation. A diagram of the arrangement for coded-image recording is provided in Fig. 3-131. A free-standing Fresnel zone plate structure with 100 zones was used in these alpha imaging experiments. It subtended a solid angle for radiation collection of approximately 2×10^{-2} sr. The zone plate material was gold, $\lesssim 5 \mu\text{m}$ thick; the width of the narrowest zone was $5.3 \mu\text{m}$.

Radiation discrimination poses the greatest problem in such an alpha imaging experiment. A submillijoule alpha-signal must be recorded out of a multijoule background of electron, ion, and x radiation. We were able to achieve appropriate radiation discrimination with a 0.3-mil beryllium foil that filtered the heavy-ion emission and a thin polymer

Region A

Region B

Fig. 3-133. Results of radiation-discrimination experiments confirming the assumption that only alpha particles produce pinholes through the cellulose nitrate. In region A, the cellulose nitrate was covered with the 0.3-mil beryllium foil; in region B, the beryllium foil was 1.3 mil thick.

film, ion-track detector that recorded the coded alpha image. The polymer film is a threshold-type, ion-track detector that is unaffected by radiation species with an energy-deposition rate (dE/dx) below a threshold value characteristic of the particular polymer. A wide variety of polymer track detectors exist and are commonly used in heavy-particle radiography and alpha autoradiography. In this experiment, we used 6- μm -thick cellulose nitrate that was dyed red to enhance image contrast. Alpha particles incident on the cellulose nitrate produce ionization tracks passing all the way through the 6- μm layer, whereas radiation species of lower dE/dx (e.g., x-rays, electrons, hydrogenic ions) do not produce such tracks. On the other hand, heavy-ion species (silicon, oxygen, carbon) do not reach the polymer but are blocked by the 0.3-mil beryllium foil in front of and in intimate contact with the cellulose-nitrate layer. After exposure to

Fig. 3-134. Alpha-imaging results showing the (a) microshell target, (b) the coded image from the laser-compressed target, and (c) the reconstructed alpha image. The reconstructed image is presented as an isoemission-contour map. Each contour represents a locus of constant alpha-emission density and the incremental change in alpha emission is constant between successive contours.

Table 3-8. Logic for radiation discrimination in alpha-imaging experiments

- (1) Data appear as pinholes in the cellulose nitrate caused by radiations producing an ionization track completely through the cellulose-nitrate layer.
- (2) X rays do not produce tracks.
- (3) Electrons do not produce tracks.
- (4) Heavy ions are stopped by the beryllium foil.
- (5) Protons, deuterons, and tritons produce tracks only at low energy (0.5, 1.0, and 1.5 MeV, respectively). At these energies, they have a range in the cellulose nitrate that is significantly less than its 6- μ m thickness.
- (6) Alpha particles emerging from the beryllium foil have appropriate energy to produce ionization tracks completely through the cellulose nitrate.

the alpha flux, the cellulose nitrate is "developed" in a NaOH etching solution that preferentially attacks the ionization channels formed by the alpha particles. Thus each alpha track is etched to form a small (1- to 2- μ m-diam) pinhole through the red polymer. The recorded shadowgraph is therefore a coded array of pinholes through the red polymer film, each pinhole being produced by an alpha track.

Figure 3-132 shows a series of three optical micrographs of a coded alpha image at three different magnifications. [The central dark zone in Fig. 3-132(a) has a 1.36-mm diameter. This dimension can be used to determine the appropriate value for the magnification factor, M .] The zone plate coded image in Fig. 3-132(a) can, in fact, be seen to be comprised of many microscopic pinholes as the image magnification is increased.

A series of discrimination experiments, in which beryllium-filter foils of varying thickness were used to test the effects of the various radiation species on the cellulose nitrate, explicitly confirmed that the recorded coded images indeed were produced by alpha particles and not by other radiation species. The results of one such discrimination experiment are shown in Fig. 3-133. An optical micrograph, at high magnification, of a cellulose-nitrate layer exposed to radiation from a laser-fusion target is shown (no zone plate aperture was used). In region A, the cellulose nitrate was protected by the standard 0.3-mil beryllium foil; note the many particle tracks. In region B, the cellulose nitrate was protec-

ted by a 1.3-mil-thick beryllium foil. This foil was thick enough to stop alpha particles while allowing energetic light ions (protons > 1.6 MeV; deuterons > 3.2 MeV; tritons > 4.8 MeV), electrons ($\leq$ 64 keV) and x rays ($\leq$ 1.8 keV) emitted from the source to reach the polymer. No track information was recorded in region B.

Table 3-8 provides a brief summary of the operation of the beryllium foil, cellulose nitrate pair as an alpha-particle detector capable of discriminating against other radiation species.

Image reconstruction from the coded array of pinholes (i.e., the coded image in cellulose nitrate) was optimized by using contrast enhancement techniques. (In short, the coded image, when viewed through appropriate blue-green filters, appears as an array of blue-green pinholes on a black background.) The coded image was vacuum-contact printed from the cellulose nitrate onto a Kodak high-resolution plate (HRP) which is blue-green sensitive and red blind. The pinhole-density distribution in the cellulose nitrate, which is proportional to the alpha-particle flux, is thus mapped into an exposure distribution on the HRP. This HRP shadowgraph was then used as the coded-image transparency and an image of the source distribution was optically reconstructed on Agfa-Gevaert Scienta plates. Standard calculational methods for two-step imaging techniques were used (with minor modifications) to convert the calibrated photographic density in the reconstructed image to the relative alpha-emission density at the source.

Table 3-9. Parameters and data from a representative alpha-imaging experiment

Parameter	Data
Target diameter (μm)	88
Target wall thickness (μm)	0.88
DT fill (mg/cm^3)	3.10
Laser power (W)	3.9×10^{12}
FWHM pulsedwidth (ps)	27
Neutron yield	$8 \pm 1 \times 10^8$
Burn-region dimensions (μm) (vertical, horizontal)	26, 22
FWHM burn region (μm) (vertical, horizontal)	18, 15

Alpha images were recorded for a number of imploded microshell targets. Data from a representative experiment are listed in Table 3-9, which also presents information about the target, laser performance, thermonuclear yield, and burn-region dimensions. Figure 3-134 shows coded and reconstructed alpha images for that same experiment. The coded image is an array of 1.3×10^6 pinholes (typically 1 to 2 μm in diam) through the cellulose nitrate layer. We found the pinhole density in the coded image to be in excellent agreement with the density estimated from the alpha yield and the solid angle subtended by the coded aperture. Additional alpha-imaging data derived by the ZPCI technique are provided in Section 5 of this report.

Thus, the viability of the ZPCI technique for high-resolution alpha imaging of laser fusion targets has been successfully demonstrated and the size and shape of the DT-burn region of laser-compressed microshells has been accurately measured.

Author
N. M. Cepilo

Major Contributor
L. W. Coleman

3-5.10 Quadrupole Triplet Time-of-Flight Spectrometer

The Argus quadrupole triplet time-of-flight (TOF) system has been designed to focus DD protons and DT alpha particles produced by laser fusion onto a detector several meters from the source. In addition to increasing the energy resolution by a factor of three over that of our other systems, the quadrupole triplet accepts a relatively large solid angle of emission from the target.

In principle, a sequence of quadrupole fields of opposite sign is required to achieve net overall focusing in both axial components. We have chosen a triplet consisting of three quadrupoles of equal strength, with the central one having a reversed field and an effective length twice as long as the other elements. The triplet focusing properties as a function of charged particle energy have been investigated using the SPEAM beam envelope code developed by Joho and Kost.⁷² The code was modified to generate and display charged particle trajectories on the initially converging and initially diverging axes, respectively.⁷³

Two focusing configurations were considered with flight paths of 4.0 and 7.5 m, respectively. Figure 3-135 shows the 7.5-m TOF arrangement. Protons and alpha particles emitted from the source into the solid angle defined by an elliptical aperture at the entrance to the magnet are focused by the system of quadrupoles onto a detector at the end of the evacuated flight tube. This detector consists of an NE-111 scintillator coupled to a photomultiplier tube. A shadow shield can be used to prevent photons from going directly to the detector. For the proton experiments, in particular, this shield may not be necessary since the scintillator will be covered with a lighttight, metallic, heavy ion filter foil. At 4 m the image is small enough so that the 2.6- to 4.0-MeV α -particle energy range can be spanned with the standard 42-mm-diam Amperex 2106 photomultiplier tube. The 7.6-m flight path requires using an Amperex XP 2041 photomultiplier tube with a 110-mm-diam cathode.

The calculated dependence of the system acceptance solid angle on charged particle energy is shown for three different experimental arrangements in Fig. 3-136. Field values were chosen to

Fig. 3-135. Schematic drawing of a 7.5-m-charged-particle time-of-flight system using a quadrupole triplet focusing magnet.

Fig. 3-136. Calculated dependence of system acceptance solid angle on charged particle energy.

Table 3-10. Comparison of time-of-flight system resolution parameters

	Permanent magnet	Triplet A	Triplet B
Flight distance (cm)	222	400	760
α resolution at 3.2 MeV (keV/ns)	36	20	10
p resolution at 2.9 MeV (keV/ns)	61	34	18
α energy loss uncertainty (%)	14	8	4
(energy loss = 250 keV)			
p energy loss uncertainty (%)	61	34	18
(energy loss = 100 keV)			
FWHM (α peak) ^a	2.5	4.4	8.8
FWHM (system)			
FWHM (p peak) ^a	1.25	1.6	2.7
FWHM (system)			
$t_{\alpha} - t_{\text{hydrogen}}$ (1.5 MeV) ^b (ns)	48	86	164

^aWe assume a temperature (θ) value of 5 keV yielding FWHM (α peak) = $177 \theta^{1/2} = 400$ keV and FWHM (p peak) = $177/2 \theta^{1/2} = 200$ keV.

^bDifference in flight time between a 3.2-MeV α particle and a 1.5-MeV background hydrogen ion.

minimize the image size of a point source of 2.9-MeV protons on a 110-mm-diam detector. Note that a large solid angle covering a very wide energy range can be obtained using the 4-m flight path and no shadow shield. Moving the detector to 7.6 m does not significantly affect the acceptance solid angle at the design energy. The effective energy range is considerably reduced, but the detection efficiency is still good from 2.3 to 3.8 MeV.

The configuration with the full shadow shield is more suitable for alpha particle experiments. The elliptical entrance aperture has been adjusted for uniform detection efficiency from 2.3 to 4 MeV. Even with the full shadow shield the acceptance solid angle is 14 times greater than that of the permanent magnet time-of-flight spectrometer shown for comparison. The sharply rising leading edge of the triplet response vs energy curve provides an advantage for alpha particle measurements in the presence of hydrogen ion backgrounds.

Table 3-10 summarizes the capabilities of three time-of-flight systems. The table shows that the 222-cm time-of-flight system is just adequate for measuring alpha particle energy loss but rather poor

for measuring that of protons. The 760-cm system is required to measure the proton energy loss to better than 40%.

Details of any spectral distribution can be more accurately determined (i.e., results are less sensitive to the deconvolution procedure) as the width of the recorded distribution increases relative to the fixed width of the detector-oscilloscope system time response, typically 4.5 ns. A measure of the quality of energy distributions can thus be obtained by comparing the FWHM of a standard alpha or proton distribution with that of the system time response. From the tabulated values we note that the permanent magnet system is just adequate for obtaining alpha energy distributions but inadequate for good proton energy measurements.

An additional advantage of the triplet system in measuring alpha distributions is the increased oscilloscope recovery time from a large hydrogen ion precursor.

In summary, a quadrupole triplet focusing system has been designed to provide an increase in acceptance solid angle 10 to 20 times that of existing uniform field deflection time-of-flight spectrometers.

Triplet focusing permits the use of flight paths up to three times longer than those previously employed. The corresponding improvements in energy resolution are significant for alpha energy measurements and necessary for the more demanding proton energy measurements. One triplet configuration has been found to be particularly suitable for alpha particle measurements in the presence of a low energy hydrogen ion background.

References

72. W. Joho and C. Kost, University of British Columbia, Vancouver, B.C., Triumf Design Note No. TR1-DN73-11 (March 19, 1973).
73. The SPEAM code was modified by E. M. Lent, Lawrence Livermore Laboratory, 1975.

Author

K. G. Tirsell

3-5.11 Permanent-Magnet Alpha Time-of-Flight Spectrometer

We have developed a more compact, economical, alpha-particle time-of-flight (TOF) spectrometer using a permanent magnet for deflection. Significant improvements in our technique have resulted in more accurate measurements of the number and energy distribution of fusion-produced alpha particles. Using several of these spectrometers to view the fusion target, we can make an interesting comparison of alpha energy loss and energy broadening as a function of angle.

The experimental setup for the permanent-magnet time-of-flight system is shown in Fig. 3-137. Alpha particles emitted from the source into a small solid angle, accurately defined by an aperture at the end of the evacuated TOF tube, are deflected into

Fig. 3-137. Schematic drawing of the compact alpha time-of-flight spectrometer using a uniform-field permanent magnet.

the detector. Alpha particles from 2.6 to 3.9 MeV are detected with a NE-111 scintillator coupled to an Amperex 2106 photomultiplier tube. The deflection arrangement, including baffles and light trap, was designed to permit the use of a bare scintillator. An average deflection angle of 12° , rather less than that of 17° for the electromagnetic system, was obtained for the compact system using a 3.4-kG Armco-8, uniform-field, permanent magnet with a 51.4-kG-cm field product. The permanent magnet does not require a power supply and has the advantages of decreased size, weight, and cost.

Smaller deflection angles result in a significant increase in the background signal due to the x rays and scattered light which are first to reach the bare scintillator after the laser light strikes the target. Thus, we made the following changes to reduce the background to acceptable levels. First, we reduced the edges of the blackened tantalum defining collimator to 0.15 mm to decrease light scattering. Second, we added a similarly thin (although not defining) collimator near the chamber flange. Third, we reduced the scintillator thickness to 0.25 mm and coupled it to the photomultiplier cathode with a 3-mm-thick Corning CS7-54 glass filter. This greatly reduced the detector sensitivity to background photons with wavelengths greater than 450 nm.

In later experiments at higher input laser power, the energetic ions from the target produced a serious background problem. To alleviate this, we covered the scintillator with a 3 mg/cm²-nickel filter. The detector sensitivity to 3-MeV α particles was reduced to 35% of its former value; however, the heavy ion background was removed.

We fed detector anode output pulses to a recording system consisting of one to three oscilloscopes by means of a 50- Ω air dielectric coaxial cable and a matched splitter. Figure 3-138 shows an alpha distribution recorded near the display center of a Tektronics 7844 oscilloscope. The delayed, attenuated, and inverted scattered laser light pulse provides a good time reference. Timing accuracies better than ± 2 ns were achieved by triggering both traces simultaneously, using the delayed output from a fast laser-triggered photodiode.

Various delays are taken into account to reference the alpha oscilloscope trace to a start time at the center of the target chamber. This signal and the measured time response of the detector oscilloscope system are then used to obtain the alpha TOF distribution by deconvolution. For the 220-cm

Fig. 3-138. An alpha-TOF detector pulse recorded on an oscilloscope. The lower trace is the delayed inverted x-ray precursor used as a time reference. The same delayed trigger is used for both traces.

flight distance used in these experiments, the ± 2 ns timing uncertainty corresponds to an energy uncertainty of 60 keV.

The important parameters determined from the alpha energy distribution include the average alpha particle energy loss and the FWHM from which we derive an upper limit to the plasma ion temperature. In addition, by calibrating the detector with a ²⁴⁴Cm alpha source and accounting for the measured detector response at lower energies compared to the response to 5.8-MeV alpha particles emitted by ²⁴⁴Cm, we determine the number of alpha particles incident on the spectrometer aperture to better than $\pm 15\%$. This number can be referred to the target rather accurately since the solid angle subtended by the aperture is well known. Measured alpha yield values have generally been in good agreement with 14-MeV neutron yield obtained using the copper activation technique. (see § 3-5.5). For example, the value for the average of α/n yield ratios for the period between June 15 and October 15, 1976, is 1.01 ± 0.06 . Fusion yield values have thus been confirmed using two entirely independent techniques.

Author
K. G. Tirsell

3-6 REAL-TIME DATA AND CONTROL SYSTEMS

3-6.1 Target Data Acquisition and Analysis System

An extensive computer-interfaced system has been implemented for the acquisition and analysis of target-diagnostic data at the Argus laser facility. The system is based on a Digital Equipment Corporation PDP-11/40 and distributed CAMAC serial highway interfaces. A modular software system has also been implemented to allow dynamic definition of the experimental environment, automatic data acquisition, and real-time data processing. The system is operator-controlled through an interactive command language called CAMEL (*CAMAC Experimental Language*) which is implemented in BASIC.

The design goals of the Argus Data Acquisition System (ADAS) are to provide:

- Real-time data acquisition from laser-fusion diagnostics.
- Capability for real-time analysis and evaluation of data immediately after a target shot.
- Data recording and short-term archives.
- Experimental verification of the diagnostics and calibrations.
- Capability to conduct experiments that are almost impossible to do with conventional instrumentation.

ADAS has been designed as a modular-distributed system in both hardware and software. Here, we elaborate on the software aspects of the system (the hardware is described in detail in the next subsection).

The ADAS software is based on CAMEL with which an operator can communicate with the computer. This language allows the operator to define the experimental configuration, test and reset interfaces, and enable the system for data acquisition. When the laser is fired, the system automatically collects and records all interfaced data without operator intervention. The data are recorded either on disk or magnetic tape and a summary of the raw data is listed. After the shot, some of the data are

processed under operator command and graphical output is produced in the analysis room. The data are also made available to experimenters for additional or specialized processing.

The operator command language allows experimental-interface-definitions statements such as

ADD; 3, 5, BIATOD, 96

which is interpreted to mean: "Add to the logical system a Bi-Ra A/D (BIATOD) residing in crate 3, slot 5, and acquire 96 data values when the laser fires." Similarly, the statement

SCALE; 3, 5, 33, 1.7E5

means: "Set the calibration factor for data-point 33 of the module in crate 3, slot 5, to 1.7E5." If no module was added to crate 3, slot 5, then appropriate error messages are sent to the operator.

Commands exist to add, delete, and calibrate modules, as well as to initiate various actions such as test and reset sequences and the processing of acquired data. With these commands, the operator can dynamically change the experimental configuration as seen by the computer without reprogramming. Under normal operating conditions, it is not necessary for the operator to be knowledgeable in the use of standard programming languages (e.g., BASIC, FORTRAN). Abnormal conditions such as improper commands or hardware malfunctions cause error messages to be typed. The operator responds with the appropriate commands to correct the error. At no time does the system abort the program, as happens for normal FORTRAN programs.

A scenario for a typical target shot and data acquisition with ADAS begins as the operator builds the logical experimental configuration, either via commands or by reading from disk. The configuration is modified and calibrated for the particular target parameters and test sequences are performed. The system is initialized. It waits for the external laser trigger, at which time the rapid-response-time data is acquired. After all the time-critical data is taken, the computer then acquires the remaining data held in latches and local memories throughout the CAMAC system. The data is recorded on disk and summary information is printed. This process is diagrammed in Fig. 3-139.

Fig. 3-139. Shot preparation and data-acquisition sequence with ADAS.

Fig. 3-140. Organization of the ADAS code.

Data processing is performed under operator command. Currently, the K-edge-filter x-ray spectrum, the electron-energy spectrum, and all transient digitizer waveforms are plotted after the shot. The calorimeter data are fitted to exponential curves and energy is calculated. An optional plot of any calorimeter trace is also available. The neutron time-of-flight and α -spectrometer data taken on transient digitizers are collected with the ADAS system. An unfolding code for the neutron spectrum has been written and tested recently on the PDP-11/40 and will soon be incorporated into the system.

The ADAS software is written primarily in BASIC with some assembly-language CAMAC handlers. It is designed to be operating-system and machine independent. The organization of ADAS is shown in Fig. 3-140. The code runs either under the

REBEL/BASIC operating system or under RSX-11M. Data have been taken both with the PDP-11/40 and with an LSI-11 using the same ADAS software. This capability to take data on a laser experiment with an LSI-11 means that a back-up to the PDP-11/40 is available at all times. This is also the data-acquisition-system design planned for the Shiva laser system.

Work is in progress to expand the data processing and analysis capabilities of the ADAS system. User-oriented plotting packages and multishot archival of data within the PDP-11/40 are just coming online. General graphics packages and mathematics libraries will be incorporated so that most of the data from a target shot can be analyzed immediately. Permanent archival of all data within the Octopus system will continue by transferring data by using magnetic tape from the PDP-11/40. In

general, the ADAS system is planned to fully use the hardware capabilities in 1977 and to be 100% transferable to the Shiva system.

Author
J. R. Greenwood

Major Contributors
D. E. Campbell
J. R. Severyn
C. E. Frerking
J. E. Pollack

3-6.2 Target Diagnostics Electronics for Argus Laser Irradiation Facility and Proposed System for Shiva

The Argus target diagnostics instrumentation system consists of two independent recording installations. Although these two are adjacent and connected to the same isolated power source, trigger system and instrumentation ground, the philosophy of each differs greatly. One system uses conventional oscilloscope/film recording techniques and

the other uses a CAMACTM-based digital data acquisition system on a PDP-11/40.

Conventional System on Argus

The conventional oscilloscope/film recording system is contained in three double equipment racks (Fig. 3-141). The far left bay is the system trigger electronics and the far right is the AC power control and DC power supplies for detector bias. The entire rack system is a cooling plenum with cold air piped in between chassis sides and exited out the bottom of the far right power bay. The warm air exits into the facility basement. This cooling system keeps equipment maintenance to a minimum. High-level trigger signals prevent spurious traces on the oscilloscopes. All signal cables are either double shielded or solid outer jacketed, and all cables are routed to the target chamber experiments via an enclosed steel wireway. The majority of the oscilloscopes are Tektronix R7903's or 7904's, with some 556's used for recording slower signals.

Digital Data Acquisition System. Two CAMAC crates are in the diagnostics room and are shown in the small table racks of Fig. 3-142. The crate on the right houses the initiator module used for notifying the computer that a shot has occurred. An A/D converter module is contained here also and receives analog signals on twisted pair cable via the

Fig. 3-141. Conventional oscilloscope/film recording system for Argus.

Fig. 3-142. CAMAC-based digital data acquisition system for Argus.

same enclosed steel wireway as the oscilloscope signals. Both crates contain controller modules that are connected to the PDP-11/40 unibus. The unibus is connected to the PDP-11/40 through its own enclosed steel wireway. The crate on the left is the mother crate for the fiber optics serial highway.⁷⁵ It contains the serial highway driver, U-port adapter, and fiber-optic driver modules. The fiber-optics serial highway connects in a daisy chain fashion to three additional crates, as shown in Fig. 3-143. The crate farthest from the mother crate is located at the neutron time-of-flight (NTOF) station. The other two are located adjacent to the target chamber, the first in one of the clean instrumentation racks and the second in a utility rack. The fiber-optics link permits a mixture of various diagnostic instrumentation functions without concern for electrical interaction through communication link wiring. The present Argus optical link is 250 m long. The optical signal is regenerated at each crate. Present on-line CAMAC instrumentation modules at the Argus facility consists of the following:

- BiRa A/D converters to digitize time integrated x-ray, electron, and 1.06- μ m signals.
- Tektronix R7912 controller module connected to R7912's, which provide data on α , ion, and neutron signals.
- A LLL-designed calorimeter scanner to digitize calorimeter signals. (See also § 3-6.3.)
- A LRS 2249 charge digitizer to digitize neutron signals.

- Various utility modules such as dataway readers, word generators, trigger initiator, and baseline pulser.

The CAMAC serial system is very reliable, and we are planning to implement an expanded version on Shiva.

Trigger System. Both digital and conventional systems receive their front-end trigger signals by a laser-trigger-beam source derived from the incident laser beam pulse. This laser trigger beam is distributed to various photodiode sensors throughout the facility as shown in Fig. 3-144. At the trigger photodiode arrays of the main diagnostics system, a position sensor checks trigger-beam alignment, and fiber-optic light pipes (exiting a portion of this array) transmit a fraction of the 1.06- μ m beam to an avalanche-transistor, electrical pulse generator used for streak-camera triggering. These optical fibers provide electrical isolation from the potentially noisy optical diagnostic tables where the streak cameras are mounted.

Alignment Console. In the Argus target chamber room, a console⁷⁶ provides a central location for final beam and target alignment (Fig. 3-145). The following functions are controlled or monitored from this console:

- Turning mirror position by stepping motors.
- Beam blocks through hydraulic actuators.
- Cross hairs through hydraulic actuators.
- Neutral density filters through hydraulic actuators.

- Television monitoring of alignment cameras.
- Video switching of various monitors to various cameras.
- Video recording on disk (analog).
- Video waveform monitoring.
- Alignment laser control.
- Remote laser firing through the rod amplifier.
- Target manipulator positioning via stepping motors.

- Readout of linear variable differential transformers indicating relative positions to $1\text{ }\mu\text{m}$.
- Five-degree-of-freedom lens positioners.

This console is the center of activity during final target alignment.

Computer Hardware. At present, the peripherals on the Argus PDP-11/40 include a high speed printer, remote terminal, two disks, a dual floppy disk, and a standard teletypewriter. A backup system

Fig. 3-143. Argus CAMAC fiber-optics serial highway.

Fig. 3-144. Path of trigger beam through Argus laser target diagnostics.

consisting of an LSI-11 connected to a teletypewriter, and a dual floppy disk provides emergency raw data output if the main system is down. This backup system resides in the small desk top rack below the CAMAC crates.

Target Diagnostics on Shiva

We plan to implement a slightly larger data acquisition system on Shiva than that on Argus. We will begin with a six-crate CAMAC system on a

Fig. 3-145. Alignment console at Argus.

Fig. 3-146. Target diagnostics instrumentation system proposed for Shiva CAMAC serial highway.

serial fiber-optics link as shown in Fig. 3-146. In addition to a small conventional oscilloscope/film system located in the target chamber room, instrumentation packages will be installed throughout the target chamber space frame. Although the majority of these instrumentation housings will contain CAMAC crates and associated equipment, others may contain more conventional analog recording equipment as necessary. Data output for the Shiva target diagnostics data acquisition system will initially be on floppy disk through a LSI-11 minicomputer. These floppy disks can then be processed, and the data reduced on the Argus PDP-11/40 or on the Shiva PDP-11/34 assigned to target diagnostics. Eventually a fiber-optics communication link will tie the LSI-11 directly to the PDP-11/34 for more efficient data transfer. Control func-

tions on Shiva will be done using CAMAC interfacing. For instance, streak camera shutters and calorimeter shutters will be controlled through a fiber-optics link from a CAMAC module to a camera control chassis. This will guarantee electrical isolation from potential sources of noise while providing control functions over the CAMAC highway. Similarly, we can monitor the vacuum and other systems by running the fiber-optics path in the opposite direction (i.e., into a CAMAC module to detect a closure). The trigger fanout system will be much more complex on Shiva as streak cameras and instrumentation packages need to be serviced in many varied locations. A laser trigger beam will be provided from the switched-out pulse at the oscillator end and will be distributed widely throughout the target chamber room.

References

74. U. S. AEC NIM Committee, U. S. AEC Rept. TID 25875, *CAMAC A Modular Instrumentation System for Data Handling*, (1972).
75. J. Severyn, *Serial Fiber Optic Link*, Lawrence Livermore Laboratory, Rept. UCRL-79279 (1977).
76. T. Stewart, *Argus Glass Laser Target Alignment System*, Lawrence Livermore Laboratory, Rept. to be published.

Authors

D. E. Campbell
J. R. Severyn

Major Contributors

D. L. Holeman
T. C. Stewart
E. J. Powell

3-6.3 Digital Acquisition Modules and Systems

Computer analysis of experimental data requires that the data be changed from an analog to a digital format. To date, we have developed two CAMAC diagnostic modules — for calorimetric data and for a photodiode-array streak camera readout — and have implemented a system for digital acquisition of two-dimensional video images.

CAMAC Data-Acquisition Modules

Our design needs for these modules are as follows:

- To make them independent of computer control while they are performing their functions, thus eliminating program-timing restraints imposed by computer-module interaction at zero time.
- To incorporate local memory into each module so that data can be taken and stored for future access through the acquisition system (an outgrowth of the above).
- Otherwise, to incorporate as much computer control as possible.

These unique needs have been impossible to meet with standard commercial equipment. Typically,

calorimetric data are acquired using strip-chart recorders; available commercial analog-to-digital (A/D) modules require computer control to initiate point-by-point conversion, channel selection, and data acquisition, and they do not have local memory. On the other hand, readout of a Reticon photodiode array requires a special sequence of control signals unique to the specific array hardware and to our application.

We have now completed designs for both modules and intend to implement them soon in our online data systems.

Calorimeter Module. This module (Fig. 3-147) contains a 12-bit A/D converter, a 16-channel analog multiplexer, and a 16×1024 semiconductor memory. Data channel selection is extremely flexible, allowing the choice for signal acquisition of all 16 channels, any single channel among the 16, or several sequential channels anywhere among the 16. The channel number is stored in memory with each data point for easy identification of data by channel. In operation, the module is initialized, then data acquisition starts and continues until receipt of a trigger that causes the module to take a predetermined operator-selected number of samples before stopping. This sequence permits sampling both before and after a shot. Computed curves fitted to the pre and postshot data can then be extrapolated to zero time and an accurate energy calculated.

Photodiode-Array Readout Module. This module (Fig. 3-148) works with and controls standard Reticon circuitry. Such arrays are now being used to record streak-camera data for display in analog form on an oscilloscope. We expect to increase our use of Reticon arrays for acquiring one-dimensional, spatially separated data; hence, we want to interface the arrays directly to our computer data acquisition systems. The array and drive electronics, along with minimum interface circuitry, are incorporated in the diode array, with differential digital control lines to the readout module.

Complete control of the array is generated in the module for 256, 512, or 1024 element arrays. A pretrigger about 6 ms before zero time initiates a sequence comprising array reset, background data acquisition, and signal data acquisition. Zero time occurs during the 500 μ s between background and signal readout. Ten-bit converted data are stored in two 10×1024 semiconductor memories. Data correction for background will be handled by software.

Fig. 3-147. Calorimeter CAMAC module.

Fig. 3-148. Reticon-array CAMAC module.

Fig. 3-149. Video digitizer.

Video Image Data-Acquisition System

In our first attempt at digital analysis of two-dimensional video images, we relied on commercially available equipment. We assembled an infrared vidicon-TV digitizer system (Fig. 3-149) and have demonstrated data acquisition through storage onto a floppy disk. The process starts at zero time with the storage of a vidicon scene on the video disk. On computer command and with 8-bit resolution, the video digitizer converts selected points or areas of the stored image and writes the data on the floppy disk. Several steps of media and format processing are then required to transform the data into Octopus files for reduction.

This system, also, will soon be operational in our online data system.

Author
C. E. Thompson

Major Contributors
W. R. McLerran
J. R. Severyn
J. R. Greenwood

3-6.4 Systems Software Development

Because of the complexity and rapid evolution of our laser experimental programs, we have had to devise multiple-use systems software — data-base management utilities, graphics support packages, and interprocessor communications — to serve a wide range of similar but varying experimental

needs plus many discrete hardware and software interfaces. The goals are programming quality, uniformity of documentation, and widest possible applicability. For efficiency, we have put the development of these system tools in the hands of our systems group.

In the area of laser experimental data acquisition, we have progressed rapidly from our first limited data-acquisition system (serving Janus and Cyclops) to the complex systems now under development for Shiva. That first system, for target-interaction experiments at Janus and Cyclops, was XLASE, written in machine language and run on a small PDP-11/10 computer. XLASE acquired only a few fixed, essential experimental parameters and provided only raw data.

Argus required a more comprehensive system. As a basis for this and later software, we chose REBEL/BASIC, a proved basic-language system developed at the University of Wisconsin and improved at LLL for laser-system control applications. Using REBEL/BASIC we developed ADAS 2, a combination that allows rapid, flexible modification of experimental scenarios in response to experimenters' needs. These systems, XLASE and REBEL/BASIC with ADAS 2, have met most of our general needs although several specific changes have been made during the past year. For example, we have incorporated new experimental hardware and upgraded to a small disk for storage to replace the slower paper tape. Small LSI-11 microprocessor systems have allowed us to customize REBEL/BASIC systems as tools to other developmental laboratories within the laser program.

We use a PDP-11/40 as our diagnostic development computer system to maintain REBEL/BASIC, write new analytical and systems-support computer codes, and test new hardware interfaces. The PDP-11/40 is interfaced with various computer hardware, comprising a comprehensive hardware and software testbed. This ensures complete checkout before any hardware or software goes on-line, permitting ongoing development independent of Argus production schedules.

During the past year, increasing experimental demands have shown us that the REBEL/BASIC system alone will not suffice for our forthcoming Argus and Shiva experiments. We have standardized on PDP-11/LSI-11 architecture for Shiva and, based on this decision, have chosen the RSX-

11M operating system as a foundation for future systems. RSX-11M, supplied by Digital Equipment Corporation, is a multiuser system that allows simultaneous data acquisition, hardware control, and data analysis. In various configurations it drives from the largest to the smallest of the PDP-11 computers, thus suiting it particularly well to our array of processors from the PDP-11/70 to the LSI-11. We find that RSX-11M is a strong base for future software tools.

Besides RSX-11M, we have begun buying and developing utility software to handle some of the anticipated problems for Shiva. For example, we are acquiring software to provide the basis for a data-management system to manipulate and recall data generated by laser experiments. Computer acquisition of two-dimensional experimental images will produce so much data that a management system is necessary. We are now developing a comprehensive graphics-display software package to facilitate access by Argus and Shiva applications programmers to the various plotting and display options available with PDP-11 equipment.

Much of our effort has gone into hardware and real-time software development for Argus and Shiva, which requires considerable lead time. The anticipated results are versatile, modular, systems-software tools to support our on-line data acquisition and analysis. The success and acceptance of this software to date verifies the effectiveness of our approach.

Author
J. E. Pollack

Major Contributors
J. R. Greenwood
F. W. Holloway

3-6.5 Computer Networking

With the operation of multiple target irradiation facilities and many minicomputer systems within the laser program, the need for intercomputer communication increases. The addition of the multiprocessor Shiva control and analysis system has necessitated a unified approach to computer network software and hardware. Two classes of networks are applicable to our program:

- An intrafacility system network such as the Shiva hierarchical computer system. In this system the computers are closely coupled within the facility and are managed as an entity.

- An interfacility network in which the processors are remote (but still within the Laboratory) and are connected either by telephone or dedicated lines.

A third class of network, which we do not yet envision for the laser program, is the interlaboratory network. This would link the laboratories much like the ARPA or MFE networks.

Each class of network requires different design choices in hardware and software, but they all have much in common. The laser fusion program's needs for network capabilities cover a broad range of applications. For example:

- Data file transfers between
 - Development facilities
 - Shiva/Shiva
 - Argus/Octopus
 - Shiva/Octopus
- Distributed control capability within the Shiva control system
- Remote interactive processing and analysis between
 - User/Shiva
 - Shiva/Octopus
 - User/other facilities

Both the speed of communication and the amount of data transferred will cover a wide range in these networks. For example, the Shiva control systems will send small packets of information for control and status, as well as large (1 million bytes) data blocks between systems. Hardware interfaces being obtained for the Shiva system range from serial lines with a 300 baud (bit/s) transfer rate capability to parallel links with up to 1.6 megabaud transfer rate. The intercomputer links shown in Fig. 3-150 are capable of transferring files over serial links at 1200 baud.

We are currently testing the network software for a preliminary version of the DECNET network package purchased from Digital Equipment Corporation. The package, which will be ready in the fall of 1977, has been designed to handle 60% of our needs. The remaining 40% will be handled by a small software package implemented in-house. This time frame is consistent with the evolution of the Shiva system as well as the installation of intercomputer hardware links.

Fig. 3-150. Planned interfacility network.

The eventual connection of the Shiva system to the LLL Octopus system is planned for 1978. This connection will be through a new Octoport capability being designed by the LLL Computations Department for Laboratory-wide use. During 1977 we will consider hardware and software designs for this link. We will also consider a way to support DECNET over this link.

Author
J. R. Greenwood

Major Contributors
J. E. Pollack
F. W. Holloway
P. R. Rupert

3-6.6 Photographic Image Processing

Image recording on photographic emulsion remains the most accurate high-resolution method of data acquisition, especially where the data is of a three- or four-dimensional nature. When more than 10^3 data points are to be recorded by a single detector, it still is too expensive to electronically record

data on a real-time basis. Photographic-data recording is a well-proven and relatively well-understood method by which very large amounts of data are taken and stored for later evaluation. The most undesirable feature of this type of data acquisition is the relatively long delay-time between the acquisition of the data and its reduction to a usable digital form. Considerable effort has been directed toward reducing this delay time and, at the same time, toward improving the quantity and quality of information gleaned from the computerized evaluation of photographic images. This effort has resulted in the following software improvements.

The first step in the reduction of data recorded as a photographic image is to read the densities of the photograph with a photomicrodensitometer, producing a magnetic tape with readings that correspond to the density and position on the film. The information on the tape is then transferred to the disk of a CDC 7600. It is put into photostores for archival storage and, at the same time, it is processed by programs that extract the information required to evaluate the experiment.

We have written software programs that allow us to do the above transfer and manipulation of data with minimum interaction between the operator and the computer, thus reducing the time delay between data acquisition and reduction. To extract the

required data, we have expanded MATHSY (Math system), a program which is described in Section 2 of this report.

MATHSY is an interpreter program that is controlled either by direct command from TTY (sets of micron commands) or by file-stored lists. We have written several such lists for photographic-image processing that use film-calibration curves. Some examples of these lists are described below.

POWER is a program (List) that takes the digitized file, produced by the PDS from the photographic image of the streak cameras, and converts the density measurements to light intensity. POWER then does a spatial integration on the file and displays the spatially integrated intensity vs time, thus producing a temporal profile of the beam that was focused on the streak camera. In this way, we characterize the power of the Laser beam as shown in Fig. 3-151.

The program (List) FILLFACTOR uses a file that is the averaged-radial energy profile from the array camera, as described in last year's Annual Report.⁷⁷ FILLFACTOR uses this profile with normalization in conjunction with the known allowed beam radius to calculate the percentage of amplifier cross-sectional area that is used by the measured beam. An example of this is shown in Fig. 3-152.

MSMIES is an extension of the MISF code⁷⁸ and the SWELL code⁷⁹ written for MATHSY. We use

Fig. 3-151. Power curve produced by POWER list.

Fig. 3-152. FILLfactor curve produced by FILLFACTOR list.

361208 D-5-4
 KEV PHOTON ENERGY: 4.000
 KEV CHANNEL ENERGY WIDTH: 3.000
 TOTAL FILTER TRANSMISSION: 1.000
 LENS 2-MIRROR EFF. FRACTION: 0.160
 MICROSCOPE MAGNIFICATION: 3.000
 GEOM FRAC OF SPHERE SEEN 2-MIRR: 6.8500E-09
 FILM DENSITY BACKGROUND: 1.0710E-01
 NUMBER OF ROWS: 64.
 NUMBER OF COLUMNS: 64.

NO	ERGS/CM/SQ/KEV	SQ MICRONS	ERGS/KEV	SOURCE EMISSION
				KEV/KEV
1.	-4.1845E+08	1.1044E+04	-4.6212E+04	8.6681E+14
2.	1.7927E+08	4.8213E+03	8.6430E+03	8.9566E+14
3.	7.7698E+08	2.5458E+03	1.0780E+04	8.9026E+14
4.	1.3747E+09	1.2587E+03	1.7303E+04	8.7791E+14
5.	1.8624E+09	7.6900E+02	1.5148E+04	8.8711E+14
6.	2.5701E+09	4.8933E+02	1.2062E+04	8.5766E+14
7.	3.1678E+09	3.6267E+02	1.1489E+04	8.5013E+14
8.	3.7666E+09	3.3422E+02	1.2585E+04	8.4298E+14
9.	4.3633E+09	2.7733E+02	1.2101E+04	8.3510E+14
10.	4.9610E+09	1.9200E+02	9.5261E+03	8.2785E+14
11.	5.5587E+09	2.2786E+02	1.2689E+04	8.2160E+14
12.	6.1564E+09	1.4933E+02	9.1936E+03	8.1371E+14
13.	6.7541E+09	1.7778E+02	1.2007E+04	8.0787E+14
14.	7.3519E+09	1.6356E+02	1.2024E+04	8.0047E+14
15.	7.9496E+09	2.1332E+02	1.6959E+04	7.9297E+14

Fig. 3-153. Computer plots for x-ray microscope data evaluation produced by MSMIES list.

the methods from MISE to unfold the x-ray intensity and then to plot the output as with SWELL. This is shown in Fig. 3-153.

References

77. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p.380.

78. *ibid.*, p. 444.
79. *ibid.*, p. 435.

Authors

K. J. Pettipiece
 G. G. Peterson
 D. R. MacQuigg
 T. Harper
 M. J. Boyle

3-6.7 Film Calibration Method for Analysis of Laser Light Energy Distributions

To analyze laser energy distributions photographically, we need to understand the non-linear response function of the film. We have developed a simple method which requires only two images with known exposure ratios and produces accurate calibration curves with excellent immunity to noise and localized defects in the images. The method is especially useful on images whose fine structure makes calibration difficult.

A series of images with accurately known exposure ratios is recorded on film using a pair of beamsplitters.⁸⁰ These images are scanned with a microdensitometer, and the data is computer-processed to convert photographic density to energy density. Figure 3-154 shows a display of a typical laser focal spot after computer processing.

Alternative methods^{81,82} for determining the non-linear calibration curve include 1) using a standard predetermined curve, 2) fitting a curve to a density level plot measured from identical features in each image, and 3) using a separate calibration exposure. None of these seemed appropriate for routine

Fig. 3-154. Computer display of a typical laser energy distribution incident on a laser-fusion target.

analysis of the energy distributions incident on laser fusion targets.⁸³ Shot-to-shot variations in the pulse duration and the processing of the film⁸⁴ (1Z spectroscopic plates) require a separate curve for each shot. Locating identical features in a series of images is too time-consuming for routine work, especially for images with fine structure. Separate

Fig. 3-155. Cumulative distribution functions for the density levels in two identical images with 2:1 exposure ratios.

Fig. 3-156. Integration of the density differences with a known exposure ratio gives the desired D -log(E) curve.

calibration exposures require extra beamsplitters in an already crowded diagnostic package. Our new method analyzes the cumulative distribution functions (CDF) of the density distributions in two images. CDF's for two adjacent images from a multiple-image camera are shown in Fig. 3-155. These plots show the total image points at or below a given density level.

In a pair of images differing only by a known exposure ratio, the N most dense points in one image will be nearly the same set of points as the N most dense points in the second image, even though the density levels are different. Thus, by choosing a number N , we can find a density difference ΔD . Then knowing the exposure ratio R , we can find the slope at that particular point on the D -log(E) curve. Varying the value of N will allow us to fill in the curve over the entire density range. Figure 3-156 illustrates this process.

Localized image defects and grain noise have only a small effect on the CDF's. Thus, we can expect excellent noise immunity in curves generated by this method.

Figure 3-157 shows the results of this analysis for a pair of images of a typical laser focal energy distribution. The hand-plotted points were determined from line scans across a series of images with known intensity ratios. The scans were located very carefully to cross the same features in each of the

several images. To obtain a smooth curve, we had to make the width of the scan a little larger than the smallest features in the images. This results in some averaging of the density data in each image, lowering of the density differences between images, and

Fig. 3-157. Comparison of the computer-generated D -log(E) curve with hand-plotted points for a pair of images with complicated structure. The circles and squares represent density levels from two features tracked through four identical images with equal increments in exposure.

hence a reduction of the slope of the curve ($\gamma = 3.9$) as compared to the more exact computer-generated curve ($\gamma = 4.8$). A similar comparison for a series of images with no fine structure shows the hand-plotted gamma matching the computer-generated curve within 5%.

This film calibration method has been implemented as a FORTRAN subroutine and incorporated into a program which performs the conversions and generates the displays of which Fig. 3-154 is an example. Automatic generation of calibration curves has allowed us to reduce large amounts of photographic data to accurate quantitative information on the incident light energy distributions in laser-fusion experiments. A description of the code is given in Section 2.

References

80. D. C. Burnham, "Laser Beam Photography by a Multiple Beam Technique," *Appl. Opt.* 9, 1482 (1970).
81. I. M. Winer, "A Self-Calibrating Technique Measuring Laser Beam Intensity Distributions," *Appl. Opt.* 9, 1437 (1966).
82. H. J. Weaver, G. E. Sommargren, and E. S. Bliss, "Self Calibration and Analysis of Image Formation in the Sub-Nanosecond Domain," *Proc. SPIE* 48, 63 (1974).
83. D. R. MacQuigg and D. R. Speck, *Beam Diagnostics on Argus*, Lawrence Livermore Laboratory, Rept. UCRL-78447 (1976).
84. C. H. Dittmore and H. Joosur, *Characteristics of Photographic Plates at 1060 nm*, Lawrence Livermore Laboratory, Rept. UCRL-75047 (1973).

Author

D. R. MacQuigg

Major Contributors

G. G. Peterson

C. A. Wilgus

FUSION EXPERIMENTS PROGRAM

Hal Ahlstrom - Program Leader

Shirley Lewis - Secretary

Laser Plasma Interaction Group

Hal Ahlstrom - Group Leader

Erik Storm - Assistant Group Leader - Argus experiments

Ken Manes - Assistant Group Leader - Janus experiments

Kathy McCollum - Secretary

Ralph Speck - Chief Physicist - Argus operations

Frank Rainer - Physicist - Argus

Charlie Swift - Physicist - Argus

Jim Swain - Chief Physicist - Janus Operations

Roger Haas - Shot Physicist

Mike Boyle - Shot Physicist; x-ray microscopes

Viviane Rupert - Shot Physicist; particle diagnostics

Don Phillion - Shot Physicist; scattered light

Kenn Brooks - Shot Physicist; alpha imaging

Jerry Auerbach - Shot Physicist

Bill Slivinsky - X-ray and particle diagnostics

Harry Kornblum - X-ray and particle diagnostics

Lou Koppel - X-ray spectrum and alpha imaging

Glenn Tirsell - Particle diagnostics

Peter Lee - Shot Physicist and plasma energy distributions

Dave MacQuigg - Optical diagnostics

Bob Price - X-ray microscopes

Ken Pettipiece - Data management and analysis

Hal Eddleman - Data management and analysis

Fred Rienicker - Lead Mechanical Engineer

Stan Glaros - Mechanical Engineer

Marion Kobierecki - Mechanical Engineer

Don Hughes - Mechanical Coordinator

Bill Laird - Mechanical Designer

Ray Bantz - Mechanical Designer

Dick Dunham - Mechanical Technician

Del Eckels - Mechanical Technician

Don Campbell - Lead Electronics Engineer

John Severyn - Electronics Engineer

Sharon Lacy - Electronics Engineer

Gail Anderson - Secretary

Ted Stewart - Electronics Technician

Tom Ellis - Electronics Technician

George Leipelt - Facilities supervisor

Argus Technicians

Bob Baltzer
Steve Mayo
Keith Bratcher
Jerry Reay
Mike Nichols
Bill DeCroix
Winston Wong

George Hermes

Greg Brown
Ev Powell
Jim Stewart
Steve Evans
Bob Read

Janus Technicians:

Billy Radke
Ken Andrus
Ron Bolt
Terry Schwinn

Diagnostics Development Group

Lamar Coleman - Group Leader

Elizabeth Garrett - Secretary

Dave Attwood - Physicist - Interferometry, x-ray streak data

Nat Ceglie - Physicist - Zone plate imaging, x-ray streak tubes

Jack Cheng - Physicist - Active imaging arrays, x-ray streak tubes

Jim Greenwood - Physicist - Software systems development, Argus/Shiva

Stu Gunn - Chemist - Calorimeter development/applications

Erik Frerking - Physicist - Software development, Argus

Eric Pollack - Math Programmer - Systems/support software

Ralph Kalibjian - Electronics Engineer - Framing camera development

Dick Lerche - Electronics Engineer-Neutron diagnostics, data analysis, instrumentation

Stan Thomas - Electronics Engineer - Streak cameras, image tubes

Joe Cathey - Electronics Coordinator

Cal Thompson - Electronics Coordination - Digital hardware, interfaces, applications

Gary Tripp - Electronics Technician - Active imaging arrays, digital/analog circuits

Joe Henz - Electronics Technician - Framing camera development

Wayne McLerran - Electronics Technician - Neutron diagnostics, digital circuits

Glen Phillips - Electronics Technician - Streak camera, image tubes

John Houghton - Mechanical Engineer-Time-of-flight facilities, streak cameras, systems design/implementation

Bill Holloway - Mechanical design, fabrication, coordination

Sam Nakano - Mechanical design/drafting

Bill Long - Mechanical design - test chambers, Reticon systems, fabrication

Ed Pierce - Mechanical Technician - Interferometry, optical support

Section 4

FUSION TARGETS

Contents

Section 4 — FUSION TARGETS	4-5	Theoretical Estimates for Mode Conversion	4-62
4-1 Laser Target Design and Analysis	4-6	Computer Simulations of Mode Conversion	4-63
4-1.1 Exploding Pusher Target Parameter Study	4-6	Second-Harmonic Generation	4-65
4-1.2 Exploding Pusher Targets	4-10	Summary	4-67
General Considerations	4-10	4-5.2 $J_L \times B_L$ Plasma Heating by Very Intense Laser Light	4-67
Scaling	4-13	4-5.3 Interaction of Focused Laser Beams with Nonspherical Targets	4-70
4-1.3 Intermediate-Density Targets: LASNEX Calculations	4-22	4-5.4 Relativistic Effects in Laser Plasma Interactions at High Intensities	4-71
4-1.4 Intermediate-Density Targets: Design Constraints and Physics	4-25	Modal Instabilities Due to Weak Relativistic Mass Corrections	4-72
Implosion History	4-25	Stimulated Scattering in the Underdense Plasma at Relativistic Electron Temperatures	4-73
Target Performance Constraints	4-27	4-5.5 Brillouin Side Scattering of Laser Light	4-74
Diagnostic Techniques	4-28	4-5.6 Stimulated Brillouin Scatter and Density Profile Studies	4-76
Conclusions	4-29	Distance and Time Scales	4-76
4-1.5 High-Gain Targets	4-29	Short Time-Scale Reflection Effects	4-78
4-1.6 High-Gain Targets: Symmetry	4-30	Long Time-Scale Reflection Effects	4-81
4-1.7 High-Gain Targets: Effects of Density-Gradient Modification on Fluid Instabilities in Thermonuclear Micro-Implosions	4-36	4-6 Theory and Simulation: Heated Electron Energies	4-83
4-2 Electron and Ion Beam Target Design and Analysis	4-44	4-6.1 Heated Electron Energies from Resonance Absorption	4-83
4-2.1 Ion Beam Targets	4-44	4-6.2 Wave-Breaking Amplitudes in Warm Inhomogeneous Plasmas	4-87
4-2.2 Electron and Ion Beam Targets	4-46	4-7 Theory and Simulation: Heat Transport	4-90
One-Dimensional Computer Study	4-46	4-7.1 Polarization-Dependent Thermal Energy Transport	4-90
Generation of Magnetic Field and Preheat	4-47	Resonance Absorption Magnetic Fields	4-90
Conclusions	4-48	Flux Limitation by Ion Acoustic Turbulence	4-91
4-2.3 Heavy Ion Target Technical Summary	4-49	Ponderomotive Potential at Critical Density	4-91
Target Design	4-49	4-7.2 Effect of Transport Inhibition on Ablation in a Spherical Laser Target	4-92
Target Fabrication	4-51	4-7.3 Energy Flux Limitation by Ion Turbulence	4-96
4-3 LASNEX: Overview	4-51	Formulation of a Model	4-96
4-3.1 Matrix Inversion Techniques	4-52	Anomalous Transport Coefficients	4-98
4-3.2 A New Method for Numerically Solving the Transport Equation	4-56	Incorporation into a Fluid Code	4-100
4-3.3 Ion Beam Deposition Physics	4-57	4-7.4 Growth of Current Filaments in Laser Fusion Plasmas	4-101
4-3.4 LASNEX Line Postprocessor	4-58		
4-3.5 Theoretical X-Ray Streak Pictures	4-59		
4-4 Laser Plasma Theory and Simulation	4-59		
4-5 Theory and Simulation: Laser Light Absorption	4-61		
4-5.1 Absorption and Harmonic Generation Due to Self-Generated Magnetic Fields	4-61		

Dispersion Relation	4-103	Physical Vapor Deposition	4-147
Solution	4-105	Electron Beam Vapor Deposition	4-147
Conclusions	4-109	Ion Beam Milling/Deposition	4-147
4-7.5 Effect of Laser Electric Fields on Plasma Transport Coefficients	4-109	4-9.6 Electron Microscopy Applications to Laser Fusion	4-147
4-8 Theory and Simulation: Other Studies	4-110	Conventional Transmission Electron Microscope (CTEM)	4-148
4-8.1 Mechanisms of the Plasma Spatial Filter for High-Power Lasers	4-110	Scanning Electron Microscope (SEM)	4-148
4-8.2 Plasma Profile Steepening Due to Normal Incidence of Strong Microwaves	4-114	Scanning Electron Microscope (SEM)	4-148
4-8.3 Experimental Observations of Finite- Bandwidth Effects on Parametric Instabilities Near the Critical Density	4-115	Scanning Transmission Electron Microscope (STEM)	4-153
4-8.4 Effect of Instability of the Critical Surface on Laser Absorption	4-117	Sample Preparation	4-154
4-8.5 Suprathermal Electron Production During Resonant Absorption	4-118	Conclusions	4-154
4-8.6 Absorption of a Focused Laser Beam by a Nonspherical Plasma	4-120	4-9.7 Techniques, Tools, and Methods of Target Part Handling	4-155
4-8.7 Anomalous DC Resistivity	4-120	Vacuum Chuck	4-155
4-9 Target Fabrication: Overview	4-122	Cement Application	4-156
4-9.1 Droplet Generation	4-126	Micromanipulators	4-156
Basic Procedure	4-126	Optical Equipment	4-157
Collisional Interaction of Liquid Drops	4-128	Storage and Transport	4-157
Copper Particle Generation	4-128	Fabrication Techniques	4-158
Droplet Generator	4-131	Conclusions	4-159
Drying-Firing Oven	4-133	4-9.8 Cryogenics	4-160
Glass Solution	4-134	4-9.9 Target Characterization	4-161
4-9.3 Grinding and Lapping Glass Microspheres	4-136	Present Characterization Techniques	4-161
Single-Sphere Method	4-136	Advanced Target Characterization	4-168
Batch-Sphere Method	4-138	Conclusions	4-174
Conclusions	4-139	4-9.10 DT Loading	4-174
4-9.4 Laser Machining of Parts	4-139	Precrush	4-174
Laser Machining Arrangement	4-140	DT Loading System	4-175
Results	4-140	Analysis of Loading Conditions	4-175
4-9.5 Thin Films	4-142	4-9.11 Target Assembly	4-178
Radiofrequency Plasma Coaters	4-142	4-9.12 Automation of Microsphere Characterization	4-179
Parylene Coating	4-143	4-9.13 Levitation	4-181
Direct Current Sputtering	4-144	4-9.14 Sieving Commercial Hollow Glass Microspheres	4-185
		4-9.15 Special Target Parts Handling and Production	4-187
		Fabricating Hollow Microspheres	4-187
		Large Spherical Targets	4-188
		Multiple-Mandrel Forming of Disk Targets	4-189

Section 4

FUSION TARGETS

The principal functions of the target program are the design and fabrication of targets and the computer simulation of laser fusion experiments.

In 1976, important advances were made in exploding pusher (Hyperion) targets, intermediate-density targets, and high-density, high-gain targets.

In Argus experiments, Hyperion targets achieved record-breaking thermonuclear conditions. DT gains of 10^{-2} were achieved for the first time in laboratory fusion experiments. Diagnostic measurements are in excellent agreement with predictions of the LASNEX magnetohydrodynamic fusion computer program. These Hyperion experiments are discussed in the next section, "Progress Toward Laser Fusion."

Intermediate-density targets were designed that are capable of compressing DT to 100 times liquid density with the Argus laser. This target design uses a two-step pulse shape and incorporates solutions to the critical problems of efficient laser light absorption, preheat, symmetry, and fluid instabilities. These targets will be tested in 1977.

High-density targets were designed to compress DT to 1,000 to 10,000 times liquid density in Shiva experiments. These targets use a multistep pulse shape and may be capable of approaching scientific breakeven with Shiva and gains of 10 to 100 with Shiva Nova.

Development of the high-density target design is a major breakthrough that greatly relaxes the laser and target fabrication requirements for power reactors. These requirements for a 1-GWe reactor are:

Laser efficiency	1-3%
Wavelength	$\leq 1.2 \mu\text{m}$
Energy	400-1000 KJ
Peak power	400 TW
Average power	3-10 MW
Pulse rate	10/s
Target surface finish	1000 Å
Cost	10¢

Target designs with similar energy and power requirements have also been developed for

relativistic-electron-beam machines and heavy-ion accelerators.

LASNEX's demonstrated capability to predict accurately the results of fusion experiments—a capability that is unprecedented in controlled fusion research—has been vigorously exploited to accelerate the rate of progress of the laser fusion program. Extensive simulations of possible experiments have been used to determine which advanced laser facilities to construct, the optimum set of experiments to perform, and the laser, target fabrication, and diagnostic requirements. Based on these calculations, we have determined program milestones and realistic schedules for their achievement. Target designs have been optimized to reduce the risk of failure as well as minimize the laser, target-fabrication, target-design, and diagnostic requirements. Post-shot simulations have been used to obtain maximum information from the results of each experiment. The development and application of LASNEX is a major breakthrough in the inertial fusion program, potentially as decisive as the development and use of the ULTRA machine to decipher secret codes in World War II.

LASNEX's success in predicting the results of our experiments is due partly to the successful development of approximations to nonlinear plasma phenomena derived from plasma simulation calculations with particle codes. The particle plasma simulation codes have predicted these complex plasma processes with remarkable accuracy.

The success of the laser fusion program depends critically on our ability to fabricate these computer-optimized targets. In 1976, we constructed hundreds of Hyperion and other low-density targets of unequalled complexity and precision, and demonstrated remarkable flexibility and rapid response to design changes.

These target and simulation functions are performed by an organization consisting of two main components: Design and Fabrication. Design includes three groups: Plasma Theory/Simulation, LASNEX, and Target Design/Simulation.

Fig. 4-1. Target performance is optimal for a specific diameter (at a given shell thickness) that varies as a function of laser power and pulse width. Correctly timed (sized) target for 20-TW peak power and a 30-ps pulse has a diameter of 100 μm . All data shown here assume a 0.7- μm shell and 2 mg/cm^3 DT.

LASNEX, which includes plasma approximations developed by the Plasma/Simulation Group, is used by the Design/Simulation Group to design targets and simulate experiments. Progress made by each of these groups is described in the following articles.

Author
J. H. Nuckolls

4-1 LASER TARGET DESIGN AND ANALYSIS

4-1.1 Exploding Pusher Target Parameter Study

During the past two years, we have been performing laser fusion experiments on exploding pusher targets. Several hundred DT-filled glass microspheres have been irradiated to investigate the dependence of fusion yield on target and laser parameters. Prior to these experiments, many numerical simulations were performed with the

LASNEX computer code to determine which experiments to perform and the probable results.

To establish the optimum combinations of target and laser-pulse parameters, we have undertaken a multidimensional parameter study using LASNEX. Target parameters varied in this study have been the diameter, the shell thickness, and, to a limited extent, the initial density of the DT gas. Laser pulse parameters have been confined to simple Gaussian temporal profiles of a specified peak power and FWHM. The calculations reported here were

Fig. 4-2. Optimal diameter for a properly timed target at a given gas density (2 mg/cm^3) depends on the laser pulse characteristics. These curves are for different wall thicknesses, as indicated. High-power lasers are less sensitive to mistiming for large diameters than low-peak-power lasers for small diameters.

Fig. 4-3. Variation of wall thickness can affect target performance, as shown by these curves for 30- and 100-ps pulse widths at 2.0-TW peak power.

Fig. 4-4. Output is moderately sensitive to the initial quantity of DT gas. This target—diameter $80\text{ }\mu\text{m}$, wall thickness $0.7\text{ }\mu\text{m}$ —was irradiated at 2 TW, pulse width 30 ps. All targets of the exploding pusher type have a maximum performance near 2 mg/cm^3 .

Fig. 4-5. Timing of the capsule to the laser pulse can also be viewed with respect to the laser. This capsule is $80\text{ }\mu\text{m}$ in diameter with a $0.7\text{-}\mu\text{m}$ wall. There are many similar curves for different target dimensions.

Fig. 4-6. Optimization curves for 20-TW peak power and 50% absorption at 65- and 130-ps pulse widths, respectively, for different shell thicknesses.

spherically symmetric. Because of various asymmetric illumination systems (f/l lenses, etc.), many two-dimensional (axisymmetric) calculations have also been made to establish corrections to these spherically symmetric results. Certain assumptions have been made in these calculations: 20% absorption of the laser light through resonance and instability processes at the critical density (plus a few percent by inverse bremsstrahlung), heating of a multigroup distribution of suprathermal electrons by the collective laser absorption mechanism with $\alpha = 9$, and inhibition of thermal electron transport by the Fried-Gould approximation to the electron-ion two-stream instability.

For the several thousand calculations performed, Fig. 4-1 shows one portion of the parameter space investigated wherein the diameter of the target is varied for a constant wall thickness and initial DT gas density. The curves show different peak laser

powers for pulses of 30 and 100 ps, respectively. The effect of "timing" the target size (diameter) to the laser pulse is vividly demonstrated in that diameters too small or too large can degrade the performance by several orders of magnitude. There are many families of similar curves. Since one is most often concerned about the optimal target, Fig. 4-2 shows the optimal diameter for targets with 0.4-, 0.7-, and 1- μm walls, respectively, for several laser conditions.

Variation of the shell thickness can significantly affect the target performance. Figure 4-3 demonstrates the calculated performance for a laser peak power of 2 TW at 30 and 100 ps, respectively. The wall thickness at the small diameters has a small effect; at large diameters, thickness degrades the yield because the increase in shell mass reduces the implosion velocity for the same absorbed energy.

Table 4-1. LASNEX calculations of important implosion — fusion parameters

Peak input power, TW	Gaussian (FWHM), ps	Target diameter, μm	Shell thickness, μm	Peak absorbed power, TW	Maximum interface velocity, $\mu\text{m/ps}$	Maximum fuel density, g/cm^3	Peak fuel ion temperature, keV	DT reactions
0.5	30	60	0.4	0.12	0.56	0.21	7.9	3.2×10^8
0.5	65	100	0.4	0.15	0.36	0.13	3.4	1.2×10^8
0.5	100	120	0.4	0.17	0.36	0.13	2.8	1.2×10^8
1	30	80	0.4	0.24	0.62	0.18	9.7	1.2×10^9
1	65	140	0.4	0.28	0.40	0.09	4.0	5.4×10^8
1	100	160	0.4	0.33	0.42	0.11	3.9	8.8×10^8
2	30	100	0.7	0.47	0.58	0.18	9.6	3.7×10^9
2	65	140	0.7	0.54	0.46	0.14	5.6	3.1×10^9
2	100	160	0.7	0.61	0.42	0.16	4.3	2.1×10^9
5	30	140	0.7	1.15	0.64	0.16	10.7	1.5×10^{10}
5	65	200	0.7	1.31	0.56	0.11	8.1	2.2×10^{10}
5	100	240	0.7	1.47	0.53	0.10	6.3	2.3×10^{10}
20	30	300	1.0	10.7	0.80	0.13	11.9	3.7×10^{11}
20	65	350	1.5	11.1	0.76	0.13	14.6	1.2×10^{12}
20	100	375	2.0	11.4	0.76	0.15	15.0	1.9×10^{12}
20	130	450	1.5	11.7	0.76	0.10	13.2	2.0×10^{12}
20	165	525	1.5	12.0	0.70	0.10	10.1	2.0×10^{12}

Figure 4-4 shows the typical dependence of yield on initial DT gas density. All reasonable exploding pushers have this unique characteristic of maximum performance at fuel densities of about 2 mg/cm^3 regardless of laser power, pulse width, or other target parameters.

Another way to slice the parameter space is shown in Fig. 4-5. For a given target (e.g., $80\text{-}\mu\text{m}$ diameter, $0.7\text{-}\mu\text{m}$ wall thickness, 2 mg/cm^3 DT), the yield is only slightly sensitive to pulse width at the lower laser powers but becomes significant at the multiterawatt level.

Since these calculations assumed spherical symmetry, correction factors must be applied for non-spherical illumination. This correction factor varies from a fewfold to more than tenfold for two f/l lenses, depending on the laser and target parameters.

With the expected completion of the Shiva laser facility in late 1977, 20-TW peak power will be available for target experiments. LASNEX simulation studies have also been done at this level but with an assumed 50% absorption. We predict absorption in the range 35 to 50% for Shiva because each beam has a different polarization and is focused to a separate spot on the target. For each beam, resonance absorption is optimized by proper choice of the angle of incidence in conjunction with the direction of the polarization vector. The pattern of 20 beams is chosen to give good implosion symmetry. Figure 4-6 shows the dependence of DT reactions on the target diameter for several shell thicknesses at two pulse widths. For these exploding pusher targets, gains of 10^{-3} to 10^{-2} of scientific breakeven are predicted.

Finally, Table 4-1 shows LASNEX calculations of various important implosion-fusion parameters for the best performing targets at each laser power. An important advantage of these calculations is the great wealth of detailed data generated for each simulation run. Almost all significant physics variables are calculated, highly resolved in space, time, and energy. Note that all the implosions are roughly to liquid density and that the ion temperature increases with the square of the peak implosion velocity.

Author
J. T. Larsen

4-1.2 Exploding Pusher Targets

Laser-fusion exploding pusher targets were invented at Livermore in 1970 and have since been the subject of many basic experiments.¹ We have named this type of target Hyperion. The simplest version consists of a spherical hollow glass microsphere, filled with low-density DT gas and mounted on a stalk. Typical microsphere parameters are $80\text{-}\mu\text{m}$ diameter, $1\text{-}\mu\text{m}$ wall thickness, and 2-mg/cm^3 DT density. Many variations of Hyperion have been developed, including those in which the microsphere fusion capsule is enclosed in foam or mounted on a glass or plastic sheet. A D₂-filled glass microsphere target was first fabricated at LLL in 1970. An LLL aluminum-coated LiD solid-fuel target was imploded in 1971 with the Nd laser at Sandia, Albuquerque. No neutrons were detected. The simple glass microsphere version first yielded DT neutrons in tests at KMSF in May 1974.² A two-beam confocal ellipse illumination system was used in these experiments. Advanced Hyperions first generated detectable neutrons in single-beam Janus laser experiments performed at LLL in December 1974.³ The first experimental demonstration of TN fusion in a laser implosion was achieved with advanced two-beam Hyperion targets at LLL in May 1975.⁴ An f/l lens illumination system was used in these experiments. In September 1976 Argus two-beam experiments using advanced Hyperions achieved record breaking thermonuclear conditions, including 8-keV ion temperatures, $10^{12} \text{ cm}^{-3} \cdot \text{s}$ Lawson numbers, and 10^{-2} DT gains (fusion energy/DT thermal energy).⁵ (See Fig. 4-7.)

General Considerations

Hyperion targets are particularly well suited to early laser implosion experiments. Because the pusher (glass shell) is suddenly heated and exploded by a short duration ($\leq 100 \text{ ps}$) high power laser pulse, the implosion is relatively insensitive to preheat by superthermal electrons and x-rays, and fluid instabilities grow relatively slowly. Figure 4-8 shows the characteristic decrease of the exploding pusher density during implosion. The laser temporal pulse shape may be Gaussian, and the illumination may be relatively asymmetric (with

some degradation in neutron yield). A variety of emissions from the imploding target make detailed diagnostics possible, including x-rays, neutrons, alpha particles, ions, and scattered light.

The Hyperion target may be imploded to thermonuclear conditions with lasers having energies as small as a few joules. With such small energies, targets weighing only a few ng can be heated to keV temperatures at which observable fusion occurs.

The Hyperion target is designed to drive ng masses to multi-keV ion temperatures. Laser light primarily heats electrons, whereas it is the heated DT ions which generate fusion reactions. Since the ion-electron coupling time in ng masses of liquid

density DT at keV temperatures is much larger than the hydrodynamic disassembly time, simple homogeneous DT pellets are poorly suited to early experiments with small lasers. For example, 10 ng of liquid density DT may be heated to 10 keV electron temperature with 4 J absorbed energy. Then about 100 ps is required for the electrons to heat the ions to 2 keV, whereas the hydrodynamic disassembly time is about 10 ps.

The Hyperion target design overcomes this ion heating difficulty by enclosing low density DT gas (2 mg/cm^3) in a much higher density glass microsphere. This glass and the DT gas are suddenly heated to 0.1 to 1 keV electron temperatures

Fig. 4-7. DT ion temperatures, Lawson numbers, and DT gains achieved in LLL laser fusion experiments with Hyperion targets. The Lawson number is the product of the electron density and confinement time, and the DT gain is the ratio of the fusion energy generated to the thermal energy in the DT ions and electrons. The performance of various magnetic fusion machines is also shown.

Fig. 4-8. Maximum density in Hyperion glass microspheres vs radius/initial radius. Explosion of glass to lower density drives the implosion of the DT fuel. Also shown is the projected performance of intermediate-density and high-density targets.

by laser-heated electrons. The laser-heated electron spectrum has a strong superthermal component to more than 10 keV because of resonance absorption and plasma instabilities. The high thermal electron pressure in the glass causes it to explode inward and outward at high velocities (10^7 to 10^8 cm/s). The imploding glass ions collide with the DT ions giving the DT ions average energies ranging from several hundred electron volts to several keV.

In most experiments that have been conducted so far, the range of these DT ions is much less than the capsule radius in the early stages of the implosion. Consequently, ion-ion collisions in the DT generate an inward moving ion shock. Behind this shock the inward moving glass continues to be heated by laser-driven electrons and accelerates to high velocities, further compressing and heating the DT ions. This post shock compression/heating of the DT is moderately isentropic, and approximately

follows an adiabat with an average γ varying from $3/2$ to 2. The fuel compression history shows moderate entropy changes due to ion-electron coupling and to energy transport by ion conduction. Figure 4-9 shows typical quasi-adiabats. In the late stages of the implosion, the DT ion range may be comparable to the radius. However, the range is much shorter in the surrounding glass. The implosion culminates when the impulse generated by the compressing DT stops the inward moving glass. The DT ion temperature generally greatly exceeds the electron temperature because the rate of compressive work is much larger than the ion-electron coupling and the ion conduction is much weaker than the electron conduction.

To a first approximation, the compressed DT density is proportional to that given by filling the original volume enclosed by the microsphere with the inner half of the glass mass. Typically the DT is compressed to approximately liquid density.

Electron conduction generates a moderately symmetric implosion even if the heating is somewhat asymmetric. Multi-keV laser-heated electrons transport energy through the low density plasma blowing off the pellet over distances comparable to the pellet size in a time comparable to the implosion time. The classical mean free path of a 20-keV electron in $Z = 10$ plasma at critical density for Nd light approximately equals 100 μm , a typical pellet diameter, and the corresponding electron velocity is about 10^{10} cm/s. However, a significant time is required for a substantial corona region to develop, and electron transport is inhibited by plasma turbulence and self-generated magnetic fields.

Plasma theory and computer simulations have successfully predicted the spectrum of superthermal electrons as a function of laser intensity and the absorption of laser light as a function of the angle of incidence and the polarization.⁶ Typically, for a simple Hyperion, 25% is absorbed overall, mainly by resonance absorption. For the targets with the highest neutron yields, the laser light is sufficiently intense so that inverse bremsstrahlung absorption is suppressed by self-steepening of the density profile and by superthermal electron quiver velocities. More efficient absorption has been achieved with advanced Hyperion designs.

In Table 4-2, the significant characteristics of Hyperion exploding-pusher targets are compared to those of intermediate-density and high-density targets.

Fig. 4-9. Pressure-density tracks followed by DT fuel in LLL laser fusion experiments with Hyperion targets. Maximum ion temperatures are also indicated. Curvature is due to energy coupling to DT electrons and to ion conduction to glass. Intermediate- and high-density projections are also shown.

Scaling

A key target design objective is for each laser power to find the optimum combination of glass dimensions, DT density, laser pulse length and focusing. The number of parameters to be varied is sufficiently large so that it is difficult and expensive to find these optima experimentally. At LLL we have predicted the optimum designs with the LASNEX computer program (see preceding article) and concentrated most of our experiments in the region of these predicted optima. Comparison of extensive and detailed diagnostic measurements of neutron yield, DT ion temperature, implosion velocity, x-ray spectra, etc., with LASNEX calculations shows good agreement. (See "Progress in Laser Fusion" section of this report.)

The optimum LASNEX results in the preceding article have several striking features. The compressed DT density is nearly constant. The capsule wall thickness is nearly proportional to the radius, and both increase slowly with power. The neutron yields vary approximately with the power squared.

Absorbed power (TW)	Neutrons
0.1	4×10^8
1.0	2.5×10^{10}
10.0	2×10^{12}

At constant power, maximum neutron yield is achieved by a group of capsule-pulse combinations in which the DT ion temperature varies from 6 to about 15 keV (Fig. 4-10).

Published theories and semi-empirical models of exploding pusher implosions do not predict these features. In Ref. 7, it is assumed incorrectly that absorption is mainly by inverse bremsstrahlung (so that relatively few superthermal electrons or x rays are generated), that the implosion is ablatively driven rather than exploding pusher, and that the imploded glass is relatively cold and dense. Consequently, the calculated DT densities increase with laser power, and are a factor of 10 to 100 fold too

Table 4-2. Comparison of low-, intermediate-, and high-density targets

	Low-density	Intermediate-density	High-density
Fuel compression (X liquid density)	0.1 - 10	10 - 300	300 - 10000
Fuel temperature (keV)	1 - 20 keV	$> \frac{1}{2}$ keV	10 - 100 keV
implosion velocity (cm/s)	$1 - 10 \times 10^7$	$1 - 10 \times 10^7$	$2 - 6 \times 10^7$
Gain	$10^{-6} - 10^{-1}$	?	$10^{-2} - 100$
Initial fuel state	Low-density gas	Moderate-density gas	Cryogenic shell
Surface finish fluid instabilities	$>1000 \text{ \AA}$ Insensitive	$\sim 1000 \text{ \AA}$ Moderately sensitive	100 - 1000 $\text{ \AA}$ Sensitive
Pulse shape entropy change	Gaussian high	Two-step Moderate	Five-step Near isentropic
Laser energy/power	$\geq 10 \text{ J/0.1 TW}$	$\geq 500 \text{ J/3 TW}$	$\geq 10 \text{ kJ/30 TW}$
Symmetry sensitivity	Low	Moderate	High
Preheat sensitivity	Low	Moderate	High

high. Also the ion temperatures are several fold too low. This theory does not predict the correct variation of neutron yield with laser power or the optimum target/laser pulse combinations.

The formula in Ref. 5 contains several parameters that have been adjusted to reproduce a set of experiments and LASNEX calculations. The results agree rather well with the neutron yields of most simple exploding-pusher experiments that have been conducted at LLL. However, even when normalized to the LASNEX results at 0.1 and 1 TW, this formula does not correctly predict the optimum target/pulse

combination at 10 TW. The predicted wall thickness is several fold too thin, and the neutron yield several fold too high. The compression assumption used in this formula is seriously in error so that the predicted compressions increase with specific energy. In addition the limiting effects of electron decoupling in the shell and thermal quenching in the fuel are not included. A current version of this formula with an improved compression assumption is described in the next section of this report.

In the remainder of this article, scaling rules are developed for the set of capsules that are optimum

Fig. 4-10. Optimum capsule-pulse combinations at absorbed laser powers of 0.12, 1.2, and 12 TW vs DT ion temperature. Table shows capsule radius and wall thickness and laser pulse width (Gaussian FWHM).

for absorbed laser powers varying from 0.1 to 10 TW. Both hydrodynamic and transport physics is scaled to generate these capsule-laser scaling rules.

In general, the maximum DT ion and electron temperatures, θ_i and θ_e , are related to the maximum implosion velocity, V_m , by

$$\theta_i + \theta_e \approx 25 V_m^2, \quad (1)$$

where temperatures are in keV and velocity in cm/shakes (10^8 cm/s). Let $p\tau$ be the pressure-time impulse generated at the culmination of the implosion. Then

$$p\tau \approx \rho_g \Delta r V_m, \quad (2)$$

where Δr is the thickness of glass that can be affected by this impulse in time τ , ρ_g is the imploded glass density, and p is the pressure in 10^{16} ergs/cm³. Using $\Delta r = \sqrt{p/\rho_g} \tau$, and the DT equation of state, we find

$$p \approx \rho_g V_m^2 = \frac{1}{25} \rho (\theta_i + \theta_e). \quad (3)$$

To a first approximation, the imploded glass immediately adjacent to the compressed DT is at the same pressure, temperature, and density as the DT (because of hydrodynamics and electron and ion conduction). The decreasing pressure with radius roughly compensates for the fewer particles per mass in the glass. Consequently,

$$25 V_m^2 \approx \theta_i + \theta_e. \quad (4)$$

This equation is in excellent agreement with LASNEX calculations. The electron temperature may be estimated by distributing half the absorbed energy throughout the capsule mass. (Roughly half the absorbed energy is in hydrodynamic motion.) However, for optimum capsules which we consider here, $\theta_i \gg \theta_e$ in the DT fuel.

In the implosion, the DT ions are first shocked, then compressed quasi-adiabatically. Assume the matter velocity behind the initial shock is V_0 and the shock compression is fourfold ($\gamma + 1/\gamma - 1 = 4$ for $\gamma = 5/3$). Then assume the pusher accelerates (because of isothermal blowoff) to velocity V_m , compressing the DT ions more or less adiabatically to η times the original uncompressed density. If the pressure and density in the DT after passage of the first shock are p_0 and $4\rho_0$, then

$$p_0 = \frac{2}{3} 4\rho_0 \frac{1}{2} V_0^2,$$

$$\text{using } p = (\gamma - 1) \rho \epsilon, \epsilon = \frac{1}{2} V_0^2. \quad (5)$$

The final pressure is $p = \rho V_m^2$. Then using $p = p_0(\eta/4)^\gamma$, $\gamma = 5/3$, it follows that

$$\eta = 20 \left(\frac{V_m}{V_0} \right)^3. \quad (6)$$

It is implicitly assumed that the glass mass is many times larger than the DT mass. Typically, V_0 approximately equals the average sound speed in the glass and $V_m < 2V_0$. For $V_m^2 \approx 2V_0^2$, $\eta \approx 60$ which is typical of LASNEX calculations.

When this compression equation is compared with detailed LASNEX calculations, it is found that V_0 varies rapidly with radius. Also there is significant energy conduction from the shocked DT ions to the colder glass and energy coupling to the DT electrons. Consequently γ varies from 3/2 to 2.

For optimum exploding-pusher capsules, the DT compression may also be simply approximated by filling the volume enclosed by the microsphere with the inner half of the microsphere mass. Then for an initial glass density of 2.5 g/cm³, the average glass density is

$$\bar{\rho} \approx \frac{\frac{1}{2} M_p}{V} = \frac{\frac{1}{2} M_p}{\rho_{0DT}^{-1} M_{DT}} = 4 \frac{\Delta R}{R}. \quad (7)$$

Because of the radial pressure gradient, the central glass density is several fold higher than $\bar{\rho}$. The DT density is proportional to the central glass density because the pressures are equalized by

hydrodynamics and the temperatures by thermal conduction. Hence the DT density, ρ , is also proportional to M_p/M_{DT} and to $\Delta R/R$. Inspection of LASNEX calculations shows a good approximation is

$$\rho \approx 16 \frac{\Delta R}{R} \quad (8)$$

Table 4-3 is a comparison of $\theta_i \approx 25 V_m^2$ and $\rho \approx 16 \Delta R/R$ to the LASNEX calculations in the preceding article. Agreement is excellent.

The capsule and laser pulse parameters may be related by the two expressions for density derived above:

$$\rho \sim \frac{\Delta R}{R} \sim \left(\frac{V_m}{V_0} \right)^3 \quad (9)$$

Assume the initial implosion velocity squared, V_0^2 , is proportional to the energy/mass: $V_0^2 \sim P t_g / R^2 \Delta R$, where t_g is the Gaussian pulse width. Then, since $V_m^2 \sim \theta_i$,

$$\theta_i \sim \frac{P t_g}{R^2 \Delta R} \left(\frac{\Delta R}{R} \right)^{2/3} \sim \frac{P t_g}{R^3} \left(\frac{R}{\Delta R} \right)^{1/3} \quad (10)$$

For the set of laser pulses and capsules which are optimally matched, we assume that t_g is proportional to the implosion time R/V_m . Since $V_m^2 \sim \theta_i$, we have

$$\theta_i^{3/2} \sim \frac{P}{R^2} \left(\frac{R}{\Delta R} \right)^{1/3} \quad (11)$$

Comparison with optimum LASNEX results show good agreement.

The neutron yield, N , is given by

$$N \sim M_{DT} \rho t \bar{\sigma v} \quad (12)$$

where t is the burn time and $\bar{\sigma v}$ is the temporal and spatial average of the Maxwell velocity averaged reaction rate.

Fokker-Planck calculations have been made in the parameter space over which these capsules are being scaled. These calculations show that the DT ion distribution is sufficiently Maxwell-Boltzmann so that use of $\bar{\sigma v}$ gives approximately the correct neutron yield.⁸

Depending on the imploded conditions, the burn time could be determined by hydrodynamics; thermal losses by ion-electron coupling, radiation, or conduction; or by mass losses by diffusion of the hot DT into the glass. The hydrodynamic (inertial) time is

$$t_{hyd} \sim \frac{r}{C} \quad (13)$$

where C , the sound speed in the compressed DT fuel, varies with the square root of the ion temperature. If the inertial time were limiting, then the optimum temperature would be 15 to 20 keV since the neutron yield would vary as $M_{DT} \bar{\sigma v}/C$ and at 15 to 20 keV $\bar{\sigma v}$ varies as the three halves power of temperature. (For a given energy, $M_{DT} \sim \theta_i^{-1}$.) However, in the range of DT masses which may be imploded with powers of 0.1 to 10 TW, the non-hydrodynamic processes would be limiting at these temperatures. Consequently, the optimum temperatures will be smaller than 15 to 20 keV.

As noted previously, for ng DT masses compressed to liquid densities and multi-keV temperatures, neither the radiation nor the ion-electron times are limiting. This is determined by the ratios of the rate of compressive work to the rate of ion-electron coupling and to the rate of radiative cooling. The ion conduction and mass loss are limited by the rate of diffusion from the DT through the adjacent layer of hot glass into the cooler glass beyond. For the optimum capsules, θ_i is sufficiently large so that these processes cannot be neglected. Consequently, in scaling from a point on the curve at power P (in Fig. 4-10) to one at P' , we require the number of ion mean free paths in the fuel to be constant. Hence,

$$\frac{r}{\lambda_i} \sim \text{constant, and } \rho r \sim \theta_i^2 \text{ since } \lambda_i \rho \sim \theta_i^{-1} \quad (14)$$

Table 4-3. Comparison of Lasnex and theoretical maximum DT ion temperature, θ_i and DT density, ρ

Peak absorbed power (TW)	Diam (μm)	Gaussian FWHM (ps)	Thickness (μm)	Peak velocity (V_m) ($\mu\text{m/ps}$)	Peak ion Temperature (keV)	25 V_m^2 (keV)	Peak density (g/cm^3)	16 $\frac{\Delta R}{R}$ (g/cm^3)
0.12	60	30	0.4	0.56	7.9	7.9	0.21	0.21
0.15	100	65	0.4	0.36	3.4	3.2	0.13	0.13
0.17	120	100	0.4	0.36	2.8	3.2	0.13	0.11
0.24	80	30	0.4	0.62	9.7	9.6	0.18	0.16
0.28	140	65	0.4	0.40	4.0	4.0	0.09	0.091
0.33	160	100	0.4	0.42	3.9	4.4	0.11	0.08
0.47	100	30	0.7	0.58	9.6	8.4	0.18	0.22
0.54	140	65	0.7	0.46	6.6	5.3	0.14	0.16
0.61	160	100	0.7	0.42	4.3	4.4	0.16	0.14
1.15	140	30	0.7	0.64	10.7	10.2	0.16	0.16
1.31	200	65	0.7	0.56	8.1	7.9	0.11	0.11
1.47	240	100	0.7	0.53	6.3	7.0	0.10	0.093
10.7	300	30	1	0.80	11.9	16	0.13	0.11
11.1	350	65	1.5	0.76	14.6	14.4	0.13	0.14
11.4	375	100	2	0.76	15.0	14.4	0.15	0.17
11.7	450	130	1.5	0.76	13.2	14.4	0.10	0.11
12	525	165	1.5	0.70	10.1	12.3	0.10	0.092

This is equivalent to setting the diffusion time proportional to the inertial time. The thickness of the glass "blanket" adjacent to the imploded DT is proportional to r since the condition $V_m^2 \approx 25 \theta_i$ implies that the tamper mass approximately equals the DT fuel mass. (Conversion of the DT kinetic energy into ion thermal energy would give $V_m^2 \approx 50 \theta_i$; hence roughly half the DT thermal energy comes from the kinetic energy of an equal mass of adjacent glass.)

Using the inertial time r/C for the burn time t , the neutron equation is

$$N \sim M_{DT} \rho t \bar{v} \sim M_{DT} \rho r \frac{\bar{v}}{C} \quad (15)$$

Then, since $\rho r \sim M_{DT}^{1/3} \rho^{2/3}$ and $\rho \sim \Delta R/R$,

$$N \sim R^{10/3} \Delta R^{2/3} \frac{\bar{v}}{C}, C \sim \theta_i^{1/2} \quad (16)$$

Finally we require the number of superthermal electron mean free paths in the glass shell to be constant for corresponding points on neutron vs temperature curves with powers P and P' . However, this

constant may vary slowly along each curve at constant power. This requirement is imposed because the shells are driven to the threshold of electron decoupling, and/or energy must be transported at a sufficient rate from the critical surface to the accelerating glass-DT interface. Hence,

$$\frac{\Delta R}{\lambda_e} = \text{constant}, \quad (17)$$

where $\rho_e \lambda_e \sim \theta_{ch}^2$. The hot electron temperature, θ_{ch} , is given by the flux limiter equation in LASNEX,

$$\frac{P}{R^2} \sim \theta_{ch}^{3/2}. \quad (18)$$

Experiments and theory show θ_{ch} is proportional to the 0.4 power of the laser intensity⁹ and the 0.5 power of the laser wavelength. Use of this relation instead of the flux limiter gives almost the same scaling rules if the laser wavelength is not varied. All the LASNEX calculations analyzed here were run with Nd light. In analyzing the effect of wavelength, the correct equation must be used.

When all of these conditions are used, the following scaling rules result:

$$R \sim P^{4/11}$$

$$\Delta R \sim P^{4/11} \sim R$$

$$t_g \sim P^{3/11} \sim R^{3/4}$$

$$\theta_i \sim P^{2/11} \sim R^{1/2}$$

If $\overline{\sigma v}$ varies as θ_i^n over a limited range, then

$$N \sim R^{10/3} \Delta R^{2/3} \theta_i^{n-1/2}. \quad (19)$$

In the 8- to 12-keV range, $n \sim 2.5$ and

$$N \sim P^{1.8}. \quad (20)$$

With this scaling, the neutron yield varies approximately with the square of the laser power in agreement with LASNEX calculations. In Table 4-4 these scaling rules are used to generate results at 12 and 0.12 TW, starting from a LASNEX calculation at 1.2 TW (point 3 in Fig. 4-10). For comparison, similar LASNEX calculations at 12 and 0.12 TW are also shown (points 6 and 0).

The lower temperature LASNEX calculations in Fig. 4-10 are also rather well related by the scaling rules as shown in Table 4-5.

The relatively weak dependence of neutron yield on peak ion temperature in the 6- to 15-keV range for powers greater than or equal to 1 TW may be understood as follows. The neutron yield is given by

$$N \sim R^{10/3} \Delta R^{2/3} \theta_i^2, \quad 7 < \theta_i < 14 \text{ keV}. \quad (21)$$

Table 4-4. Scaling from high-temperature LASNEX 1.2 TW point to 12.5 and 0.125 TW; comparison with LASNEX results

Point No. in Fig. 4-10	R (μm)	ΔR (μm)	t_g (ps)	θ_i (keV)	N
3 (1.2-TW LASNEX)	80	1	65	12	2.4×10^{10}
- (12.5-TW SCALE)	184	2.3	122	18	1.5×10^{12}
6 (11.4-TW LASNEX)	188	2	100	15	1.9×10^{12}
- (0.125-TW SCALE)	35	0.43	35	8	3.7×10^8
0 (0.12-TW LASNEX)	30	0.4	30	7.9	3.2×10^8

and θ_i is given by

$$\theta_i \sim \frac{P_t}{R^3} \left(\frac{R}{\Delta R} \right)^{1/3} \sim \frac{P}{R^2 \theta_i^{1/2}} \left(\frac{R}{\Delta R} \right)^{1/3}$$

$$(\text{using } R \sim \theta_i^{1/2} t_g). \quad (22)$$

Therefore, for constant P,

$$\theta_i^3 \sim R^{-10/3} \Delta R^{-2/3} \quad (23)$$

Table 4-5. Scaling from low and intermediate LASNEX points at 1.47 and 1.3 TW to 12.5 TW; comparison with LASNEX results

Point No. in Fig. 4-10	R (μm)	ΔR (μm)	t_g (ps)	θ_i (keV)	N
1 (1.47-TW LASNEX)	120	0.7	100	6.3	2.3×10^{10}
- (12.5-TW SCALE)	262	1.5	180	9.3	1.2×10^{12}
4 (12-TW LASNEX)	262	1.5	165	10.1	2×10^{12}
2 (1.3-TW LASNEX)	100	0.7	65	8.1	2.2×10^{10}
- (12.5-TW SCALE)	230	1.6	122	12.3	1.4×10^{12}
6 (11.7-TW LASNEX)	225	1.5	130	13.2	2×10^{12}

Table 4-6. Variation in basic parameters with ion temperature and power. (Points 1, 2, 3 at ~ 1.2 TW, 4, 5, 6 at ~ 12 TW). Quantities are normalized to point number 3

Point No. in Fig. 4-10	θ_i	$\frac{R}{\Delta R}$	$\frac{r}{\lambda_i}$	$\frac{\Delta R}{\lambda_e}$	$\frac{\theta_i R^3}{P_t} \left(\frac{\Delta R}{R} \right)^{1/3}$
1.2 TW {	1	2.1	3.3	2	0.9
	2	1.7	1.8	1.25	1.05
	3	1	1	1	1
12 TW {	4	2.1	2.7	2	0.86
	5	1.9	1.5	1.15	0.96
	6	1.2	1.3	1	0.98

Fig. 4-11. Figure 4-10 with contours of equal numbers of DT ion and superthermal electron mean free paths and scaling results. Note that No. 3 and No. 6 are not scaling pairs. The key role of transport processes in scaling is obvious.

and

$$N \sim \theta_i^{-3} \theta_i^2 \sim \theta_i^{-1}, \quad 7 < \theta_i < 14 \text{ keV.} \quad (24)$$

Hence, the variation in neutron yield in this temperature range should be only twofold and the optimum ion temperature is somewhat less than 10 keV.

Inspection of the LASNEX calculations shows that the number of electron-mean-free paths in the pusher, the number of ion-mean-free paths in the compressed fuel, and $R/\Delta R$ gradually increase as

the ion temperature decreases at constant power (Table 4-6). The ratios are normalized to those of point No. 3.

At the highest temperatures, some thermal quenching of the burn is occurring, so that the neutron yield is slightly increased by moderately increasing r/λ_i as θ_i is reduced. However, r/λ_i and $\Delta R/\lambda_{eh}$ are coupled and must increase together. Using $\rho\lambda_i \sim \theta_i^2$, $\rho\lambda_{eh} \sim \theta_{eh}^2$, $(P/R^2) \sim \theta_{eh}^{3/2}$, $P/R^2(R/\Delta R)^{1/3} \sim \theta_i^{3/2}$, it follows that

$$\frac{\Delta R/\lambda_{eh}}{r/\lambda_i} \sim \left(\frac{R}{\Delta R} \right)^{1/9}, \quad (25)$$

which is nearly constant since $R/\Delta R$ varies twofold. However, increasing $\Delta R/\lambda_{ch}$ reduces electron energy transport to the glass-DT interface, and results in less efficient use of the laser energy. The combined effect of changing θ_i , r/λ_i , and $\Delta R/\lambda_{ch}$ in a self consistent way results in nearly constant neutron yield for $7 < \theta_i < 15$ keV with $P \lesssim 1$ TW. Figure 4-11 shows Fig. 4-10 replotted with contours of equal numbers of mean free paths superimposed. The optimum LASNEX results form a simple and beautiful pattern determined by basic physical processes.

Possible sets of scaling rules at constant power are still being analyzed. Tentatively, a fairly good set is

$$\theta_i \sim \left(\frac{\Delta R}{R}\right)^{3/2} P^{2/11},$$

$$\frac{r}{\lambda_i} \sim \frac{P^{4/11}}{\theta_i^2} \sim \frac{\rho r}{\theta_i^2}; \quad \rho r \sim P^{4/11},$$

$$\frac{\Delta R}{\lambda_{ch}} \sim \frac{r}{\lambda_i} \left(\frac{R}{\Delta R}\right)^{1/9}.$$

The existence of an optimum initial DT density, ρ_0 , follows from two competing effects. Increasing ρ_0 increases M_{DT} , but decreases the DT ion temperature. Since the neutron yield is proportional to both the DT mass and to some power of the ion temperature (through σv), there is an optimum initial DT density. The near invariance of this optimum density for the capsules considered here follows from several considerations: the weak dependence of ion temperature on density; DT thermal quenching and mass loss limits on the ion temperature; and the ion temperatures being below the 15 to 20 keV optimum. For the 10-TW absorbed calculations where the ion temperature approaches 15 to 20 keV, LASNEX shows the optimum initial density has begun to increase and is 5×10^{-3} g/cm³. From these considerations, a steady increase in the optimum ρ_0 is expected for higher laser powers.

For suboptimal exploding pusher capsule-pulse combinations, these scaling rules may not apply. The pulse capsule mismatch may be compensated

for by use of the effective absorbed energy approximation in Ref. 5. However, this approximation has limited validity. If the pusher and fuel are driven to conditions where transport processes are limiting, then alternative scaling conditions must be applied. Implosions in which the pusher does not explode also follow different scaling rules.

References

1. J. H. Nuckolls, *Military Application Programs — Monthly Report*, Lawrence Livermore Laboratory, Rept. UCRL-50000-71-5 (1971) (title U, report SRD). This material was presented to the President's Scientific Advisory Committee on Dec. 15, 1970 and to the AEC General Advisory Committee, Dec. 16, 1970.
2. G. Charatis et al., *Plasma Physics and Controlled Nuclear Fusion Research IAEA*, Vol. II, p. 317, 1975.
3. J. H. Nuckolls, *Outlook for Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-76395 (1975). Also published in *Progress in Laser Fusion* (Plenum Press, N.Y., 1975), p. 105.
4. V. W. Slivinsky et al., *Phys. Rev. Lett.* **35**, 1083 (1975).
5. E. K. Storm et al., *Laser Fusion Experiments at 3 TW*, Lawrence Livermore Laboratory, Rept. UCRL-79031 (1976). Submitted to *Phys. Rev. Lett.*
6. K. G. Estabrook et al., *Phys. of Fluids* **18**, No. 9 (1975), p. 1151.
7. K. A. Brueckner, *Nuclear Fusion* **16**, 3 (1976), p. 387.
8. G. B. Zimmerman, *Non-Maxwellian Ion Distributions in Compressed Laser Targets*, Lawrence Livermore Laboratory, Rept. UCRL-76927 (1975).
9. D. V. Giovanelli, *Bull. Am. Phys. Soc.* (1976), p. 1047.

Author

J. H. Nuckolls

4-1.3 Intermediate-Density Targets: LASNEX Calculations

During the past year we have progressed rapidly with target designs that allow us to achieve high average fuel densities. In this article and the next, we present results obtained from targets designed to attain average DT densities of more than 100 times liquid density (greater than 20 g/cm³) within the constraints of near-term technology. This design effort is an extension of the super-liquid density experiments discussed in last year's Annual Report and elsewhere.¹⁰

Fig. 4-12. Step-Gaussian pulse shape used in high-density target design studies. The powers indicated and stated in the text are total incident power.

An important aspect of this work is one-dimensional parametric studies describing significant interactions among some design parameters. For these studies we employ one-dimensional LASNEX modeling, which includes most features found important in plasma simulations, theory, previous design studies, and experimental analysis. Electron and photon transport is by multigroup flux-limited diffusion. Electron conductivity is inhibited by a flux limit based on the Fried-Gould prescription for two-stream instability. This limit may overestimate the inhibition from this one effect, but it is indicative of the overall transport inhibition we expect from various sources.

Absorption is accounted for mainly by a simple model for collective processes. A fraction of the incident light (20%) is deposited at $0.8 n_c$, where n_c is the laser radiation's critical density, in a source function whose effective temperature is 6 times the mean electron temperature at $0.8 n_c$. Inverse bremsstrahlung absorption is reduced by a factor of 5 from its classical value to simulate the effect of steepened density profiles near the critical density surface.

Fig. 4-13. Neutron yield vs maximum average fuel density obtained in parameter study using step-step pulse. The target was $90 \mu\text{m}$ in diam by $4.8 \mu\text{m}$ thick. Pulse foot power was 0.03 TW. The final step power and width were varied to hold the energy constant at 500 J. Also shown is variation of the main pulse begin-time, t_b .

Glass microspheres of varying thickness and sizes, filled to an initial DT gas density of 1×10^{-2} g/cm³, are used. The laser requirements are restricted to be well within the Argus laser system capabilities: peak power less than 2 TW per beam, maximum laser energy less than 600 J, and simple temporal pulse shapes, for example, a variable-duration step of low, constant laser power followed by a Gaussian high-power main pulse (see Fig. 4-12). Some of our calculations use a step-step pulse in which the final Gaussian is replaced by a rectangular pulse, as noted below.

Figure 4-13 shows a three-parameter diagram of the results obtained with a 90- μ m-diam, 4.8- μ m-thick glass microsphere irradiated with a step-step laser pulse shape. The first pulse power is optimized

and held constant at 0.03 TW. Variations are made in the begin-time (t_b), the main step-pulse width (τ), and the peak power (P_M). But the energy in the pulse is held fixed at 500 J. The implosion generally ends after about 300 J of incident energy, so the latter part of the pulse has no effect.

As the laser power is raised and the pulse width decreased, the thermonuclear yield rises and the maximum average fuel density decreases, as seen in Fig. 4-13. These effects are the combined results of increased suprathreshold electron generation, preheat, and an upward shift of the implosion adiabat as the power step as time t_b increases. Note that a thicker-walled, smaller ball is desirable to achieve higher combined density/yield performance at higher laser powers. The figure also shows that

Fig. 4-14. Neutron yield vs maximum average fuel density using step-Gaussian pulse. Pulse shape was held fixed with a 1-ns, 0.025-TW foot followed by a 600-J, 300-ps FWHM Gaussian. Parametric variations of ball diameter and wall thickness are shown.

the pulse timing is fairly critical for the step-step pulse.

Results for a step-Gaussian temporal laser pulse shape are shown in Fig. 4-14. These results are obtained using a fixed pulse shape having a 0.025-TW step of duration $t_b = 1$ ns, followed by a 600-J Gaussian with FWHM $\tau = 300$ ps and a total duration of 790 ps. Several trends are discernible in the figure. For a given ball diameter, the density and yield both climb as the wall thickness is increased. This occurs for several reasons. For example, the preheat shielding is improving. Furthermore, the kinetic energy of the pusher increases, so the peak temperature and density attained during stagnation are higher. However, as the shell thickness continues to rise, the implosion performance maximizes. The dropoff is the result of the lower specific laser energy per unit target mass and the ineffectiveness of additional pusher mass when the compressed pusher ρr greatly exceeds that of the fuel.

As the ball diameter is reduced, preheat shielding is improved, since for a given mass the wall thickness can be higher. Also, the pusher density remains higher throughout the implosion since the number of thicknesses that the shell has to move is lower. For the best target shown here, a density of 50 g/cm^3 and a yield of about 10^4 neutrons is obtained.

Higher fuel density and lower yield can be obtained by lowering the fuel adiabat. This can be achieved with long rise-time temporal laser pulses, e.g., Gaussian-step, Gaussian-Gaussian, or the use of cryogenic target where the DT is frozen to the capsule wall.

The design work to date has indicated that densities greater than 100 times liquid density can be obtained in one-dimensional LASNEX simulations. Further optimization, two-dimensional simulations and further study of the suitability of the modeling will undoubtedly be required.

Reference

10. Yu-Li Pan and D. S. Bailey, *Bull. Am. Phys. Soc.* **21**, 1134 (1976); *Super Liquid Density Target Designs*, Lawrence Livermore Laboratory, Rept. UCRL-78472 (1976); see also Section 5.

Author

Y. L. Pan

4-1.4 Intermediate-Density Targets: Design Constraints and Physics

In this article we discuss the calculated one-dimensional implosion scenario for one particular example examining the importance of various physical effects. Estimates and preliminary results on the limits imposed by implosion symmetry and fluid instability requirements are provided as well as an overview of some of the most promising techniques for diagnosing the final state of these intermediate-density, low-yield implosions.

Implosion History

The target geometry is illustrated in Fig. 4-15. This target is a glass microsphere with a $70\text{-}\mu\text{m}$ inside diameter, a $10\text{-}\mu\text{m}$ wall thickness and is filled with an initial 0.01 g/cm^3 of a 50-50% DT mix. The pulse applied to the target [Fig. 4-16(a)] consists of a constant-low-power foot, followed by a Gaussian high-powered pulse. The positions vs time calculated in one dimension for the pusher/fuel boundary and for the ablation surface are plotted in Fig. 4-16(b), while Fig. 4-16(c) is a corresponding plot of the peak pressure vs time.

This calculation employed multigroup electron and photon transport. Of the total 660 J of incident

Fig. 4-15. Target geometry for intermediate-density example.

Fig. 4-16. Time history of $100\times$ liquid density target: (a) laser power, (b) positions of the ablation surface (dashed line) and pusher-fuel boundary (solid line), and (c) peak pressure.

laser energy, 28% (185 J) was absorbed. Of this absorbed energy, 67% was absorbed by collective processes into a suprathermal heated spectrum¹¹ with $\alpha = 6$.

The low-power foot applied to the microsphere generates a strong 20-Mbar shock which propagates into the shell at 3×10^6 cm/s, heating the matter behind it to about 10 eV. However, the laser-heated electrons of highest velocity have mean-free-paths long enough for a weak thermal signal to precede the shock. The coupling of these electrons to the inner portion of the pusher raises the pusher temperature above 1 eV early in the foot of the laser

pulse. This causes a rarefaction to move into the pusher; simultaneously, a weak shock begins to move into the fuel.

The constant laser power maintains just enough ablation at the outer surface of the pusher to provide a 6-Mbar pressure, keeping the outer pusher material moving slowly inward and slowing the decompression. Near the end of the foot, the main shock reaches the rarefied inner portion of the pusher and propagates down the density gradient.

By the time the shock reaches the fuel, the fuel density has increased to 0.1 g/cm^3 and the shock pressure is 400 kbar. This establishes an adiabat that is sufficient to achieve the desired density and thermonuclear yield. Subsequently, direct heating of the pusher interior and the fuel must be slow enough to avoid significant deterioration of this adiabat; also, further acceleration must not generate additional strong shocks. These conditions are adequately fulfilled, as shown by the fuel adiabat in Fig. 4-17.

The main pulse power rises slowly enough to allow the ablation-pressure increase to propagate inward as a weak compressional wave. The outer portion of the pusher is gradually accelerated and compressed as the peak pressure rises, until a maximum pressure of about 200 Mbar has accelerated a sizeable portion of the inner pusher to 1.5×10^7 cm/s at a density of 5 g/cm^3 .

Fig. 4-17. Fuel is compressed nearly adiabatically after initial shock.

Table 4-7. One-dimensional, calculated results for yield, maximum average DT density, $\bar{\rho}$ and peak ρr of fuel plus pusher for varying values of the effective laser-heating spectral "hardness," α , and the approximate overall electron-flux limit multiplier, f . The target design is very sensitive to both the driving energy spectrum and the transport coefficients used for electron conduction

α	f	Y, neutrons	$\bar{\rho}$, (g/cm ³)	ρr , g/cm ²
6	0.06	2.0×10^5	15.0	0.022
6	0.60	4.1×10^7	20.0	0.040
1	0.60	1.3×10^8	50.0	0.084

As the pusher converges, the fuel is compressed and heated by PdV work. The maximum ion temperature achieved is limited by the balance of peak mechanical power against losses through ion-electron coupling and electron conduction to the cooler outer fuel and pusher. The peak average ion temperature is about 0.8 keV. The thermonuclear burn is quenched by the losses as the PdV heating rate decreases during the deceleration of the pusher. The calculated yield is 2×10^5 neutrons, assuming that no burn occurs in the innermost 10% of the fuel mass as a result of imperfect convergence.

The fuel compression continues until the pusher kinetic energy dissipates as internal energy. The maximum average-fuel density attained is 15 g/cm³. The corresponding peak ρr of the fuel is 0.004 g/cm² and the ρr of the fuel plus pusher is 0.022 g/cm².

The timing of this implosion is relatively coarse. Variations of $\pm 25\%$ in the duration of the foot are required to produce significant alterations of the yield and density. As the foot is shortened, the main pressure pulse arrives sooner and the fuel receives less precompression; thus, the pressure rise produces a larger entropy change. In turn, higher peak temperatures in the compression phase are obtained, but at the expense of lower maximum density.

Target Performance Constraints

The performance of this target is severely degraded by the presence of suprathermal electrons.

If the laser absorption is assumed to result in a softer heating spectrum ($\alpha = 1$), improvements both in yield and density are obtainable (see Table 4-7). These improvements occur in several ways throughout the implosion history.

Early in time, the absence of suprathermals reduces the preheat of the inner portion of the pusher and fuel, decreasing the rarefaction of the pusher and allowing the pusher to be imploded on a lower adiabat. However, the calculational modeling of this aspect of the implosion is somewhat uncertain, because the low-intensity (8×10^{13} W/cm²) heating of glass microspheres has not been studied in sufficient detail. Also, the behavior of the inner pusher material at the relatively low preheat temperatures (1 to 3 eV) is less well-known than the higher-temperature behavior.

Later in time, during the intense phase of the laser pulse, the colder heated spectrum (obtained with $\alpha = 1$) delivers its energy to a thinner region around the ablation surface creating higher driving pressures and implosion velocities.

The performance obtainable with this target also depends on the transport coefficients used for the energy transport from the laser-heated region near the critical density into the dense matter. The transport model assumed for this calculation involves an inhibition factor applied to the thermal electron group, corresponding in this case to a flux limit¹¹ of $f \approx 0.06$. This inhibition factor has provided an adequate transport description for previous targets. The present target design is very sensitive to details of the relative-transport coefficients of electrons of varying energy as well as to

the overall inhibition (see Table 4-7). Further study of the transport processes is indicated.

Illumination uniformity requirements have not been investigated in detail for this design. However, they are likely to be more severe than those for previous exploding pusher designs. The relatively low-temperature early driving history implies that electron mean free paths are much shorter than those found in exploding pushers. As a result, thermal smoothing is expected to be considerably reduced.

The volume reduction of 1/1500 required for the pusher/fuel interface dictates radial convergence. In addition, to achieve the calculated yield a somewhat better radial convergence is required. We estimate from one-dimensional calculations that, for two-sided illumination with clamshells, the beam powers must be balanced to within 30% during the low-power foot and to within 10% during the Gaussian phase of the pulse. A ball-in-plate target configuration¹² may provide satisfactory illumination symmetry to exceed 10X liquid density. However, a significant penalty in driving energy is likely. Illumination with $f/0.47$ lenses might provide another alternative for implosions to reach $10\times$ li-

quid density. Alternative target designs are also advantageous.

Fluid instability growth does not pose a severe problem for this design because the shell decompresses so severely and the acceleration is achieved relatively impulsively (see Fig. 4-18 for the shell-thickness history).

Two-dimensional calculation of the growth of an $\ell = 25$ perturbation indicates about a tenfold growth at the ablation surface.¹³ However, this does not represent a serious problem as far as shell break-up is concerned. More importantly, there is a tendency for initial surface deformations (or laser-illumination nonuniformities) to cause the inward-propagating shock to impart perturbed velocities to the inside of the pusher. In turn, this can lead to a mixing at the glass/DT interface. Again, this probably is not significant for surface-perturbation amplitudes ($\ell \leq 25$) less than 500 Å or for an initial laser-illumination uniformity less than 20%. In addition, sensitivity to laser nonuniformities is decreased during the high-power part of the pulse.

Diagnostic Techniques

Diagnosis of early attempts to achieve $100\times$ liquid density requires special techniques because the compressed state is relatively cold and the ρr is relatively high. The alpha particles produced during burn do not emerge from the pusher. Similarly, low-energy x rays are produced copiously but are detected only to an optical depth of about unity, far outside the fuel region. X rays with energies of about 4 keV or more can emerge from the compressed core but, because of the low temperatures, their intensity is low. However, promising diagnostic techniques have been proposed and are being developed.

Nuclear activation of the pusher material provides a measure of the pusher ρr during the thermonuclear burn. The reaction, $n(14 \text{ MeV}) + {}^{28}\text{Si} \rightarrow {}^{28}\text{Al} + p$, has a cross section of 0.25 b. For a yield of 10^6 neutrons and an average pusher ρr of 0.02 g/cm², an activation yield of $75 {}^{28}\text{Al}$ atoms is obtained. If the target debris is collected, the ${}^{28}\text{Al}$ yield can be measured by detecting the 2.3-min half-life beta decay, ${}^{28}\text{Al} \rightarrow {}^{28}\text{Si}^* + \beta$ (2.8 MeV), and the subsequent emission of a 1.77-keV deexcitation γ ray. Then, from a separate measurement of the number of neutrons, the average pusher ρr is determined. Because the threshold of this diagnostic is

Fig. 4-18. Shell-thickness history: the shell thickness is the distance between the two points having one third the peak shell density. The large thickness contributes to a low sensitivity to fluid instabilities.

about 75 activations, good implosion performance is essential.

Two other diagnostic techniques are based on the observation of line emission from argon seed material in the capsule fuel. Calculations of ionization kinetics and radiative transport (see Ref. 14) indicate detectable amounts of helium- and hydrogen-like argon resonance-line emissions, providing the opacity of the outer part of the pusher is lowered by replacing the glass with a lower-Z material. Measurement of the line broadening (expected to be a few eV) can be used to obtain an estimate for the density. Alternatively, W. Slivinsky has suggested observing the argon line emission with a low-dispersion spectrometer whose recorded line width is determined by the source size. This allows the determination of a diameter for the emission region.

Conclusions

In summary, our design progress indicates that it should be possible to achieve and diagnose $100\times$ liquid DT density with the Argus laser system in the relatively near future. Experiments such as the one described here offer considerable opportunities to learn about the physics and technology relevant to laser fusion.

References

11. R. A. Haas, W. C. Mead, W. L. Kruer, D. W. Phillion, H. N. Kornblum, J. D. Lindl, D. MacQuigg, V. C. Rupert, and K. G. Tirsell, *Phys. Fluids* **20**, 322 (1977).
12. Y. L. Pan, "Analysis of the Ball-Plate Laser Fusion Target Experiments," in *Laser Program Annual Report — 1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p. 285.
13. J. D. Lindl and W. C. Mead, *Phys. Rev. Lett.* **34**, 1273 (1974).
14. D. S. Bailey, "LASNEX X-Ray Line Post Processor," *Laser Program Annual Report — 1976*, Lawrence Livermore Laboratory, Rept. UCRL-50021-76 (1977), Section 5.

4-1.5 High-Gain Targets

We have calculated the performance of various high-gain target designs. With laser energies of 3 to 5 MJ at powers of 200 to 400 TW, gains of 200 to 400 are calculated. For 150- to 300-kJ lasers with 50 to 100 TW of power, the calculated gains are 25 to 50. Those calculated for Shiva are a few percent or more. Some target designs have a single composite shell, with an $R/\Delta R$ of 3 to 10, consisting of a low-Z, low-density ablator; a low-density, low-mass pusher preheat shield; and a layer of cryogenic, solid DT fuel.

To get the high densities required for efficient burn, the fuel must be imploded within two or three times the Fermi degenerate adiabat. The low-entropy adiabat serves two functions. First, it minimizes the energy needed for achieving a given compression. This is particularly important for targets of smaller size, such as those for Shiva, that require densities of 1000 g/cm^3 or more for efficient burn. Second, for shell-type targets, a low adiabat is needed to ensure that the shell remains dense during implosion and also assembles properly (with the correct timing) during final compression. This demands a fairly sophisticated pulse-shaping ability. A sample pulse shape with five steps is described in the following article. A smooth curve drawn through the various steps would work equally well, but, for experimental optimization, precise control of power and pulse length at each step probably would facilitate a determination of the optimum pulse shape. The minimum number of individual steps varies from four to six. This minimum is determined by the requirement that the fuel's entropy, generated by the multiple shocks from the discontinuous power, must remain small throughout the implosion.

To reach high density, the targets must be designed to prevent preheating of the fuel region. By utilizing the "get lost" region described in the preceding article, the energetic electrons causing preheat can be bled off. In this design there is no physically distinct shielding region in the initial pellet configuration although the outside of the fuel is somewhat decompressed, resulting in 30 to 50% yield degradation. The shielding can also be a layer seeded with high-Z material. This layer must be comparable in density to the ablator, to minimize the growth of perturbations at the ablator/preheat shield boundary. Because designs of various sizes

Author
W. C. Mead

Major Contributor
Y. L. Pan

are driven with nearly the same peak intensity and thus generate very similar preheat spectra, the thickness of the shielding material changes only slowly with size. Consequently, at the megajoule level, the shielding material is less massive than the fuel; yield degradation is small because the extra mass to be pushed is small. At Shiva Nova size, the shielding mass is a few times the fuel mass and hence impacts significantly on the calculated gains.

To function successfully, all high-gain targets must be insensitive enough to fluid instability so they can be fabricated. In practice, this means that the targets must be able to withstand perturbations of 100 Å or more. One technique for reducing the growth of fluid instabilities is explained in the preceding article.

Every design must provide some means to symmetrize the implosion pressures if the intrinsic beam illumination nonuniformity is more than about 1%. Convergence ratios vary from about 30 to as much as 100. Designs such as that described below will probably require a 2-μm laser pulse during the early time history to provide the required symmetry. The requirements of atmosphere formation utilizing an exploding outer shell are also discussed below.

Author
J. D. Lindl

4-1.6 High-Gain Targets: Symmetry

In view of the rapid growth rates calculated for fluid instabilities in many isentropic, ablative, laser-driven pellet implosions,¹⁵ the following question arises: how can an implosion be initiated by a nonuniform laser illumination profile in a way that does not imprint an intolerably large surface perturbation on the pellet? One possibility is to produce a low-density, relatively cold plasma cloud around the pellet, then supersonically heat the atmosphere with a large, short duration prepulse. Maintaining the critical surface at some distance from the pellet ablation surface should allow thermal conduction to smooth illumination nonuniformities to tolerable

levels.¹⁵⁻¹⁸ In the following, we present calculations indicating the degree of smoothing obtainable and the associated design trade-offs for an example designed to be imploded with about 20 TW of absorbed laser power. The results are extended from those reported previously¹⁹ to include initiation of the implosion using 2-μm laser light.

Figure 4-19 shows schematically the configuration of a pellet with an atmosphere at an early time. The pellet ablation surface has radius R_a , and the critical surface for the laser of wavelength λ is at radius R_c . We assume laser deposition at the critical surface to be nonuniform, and for convenience, consider it to be axisymmetric and expanded in terms of spherical harmonics

$$I_\ell(\Omega) = \sum_{\ell} C_{\ell} Y_{\ell}(\Omega), \quad (26)$$

where C gives the partial amplitude of each mode ℓ .

A simple qualitative idea of the behavior to be expected from thermal smoothing can be gained by considering solutions of the source-free heat equation. In steady state, we have $\nabla^2 T = 0$, and the radial solutions take the form

$$\delta T_{\ell} = \left(\frac{R}{R_c} \right)^{\ell} T_{\ell c}, \quad (27)$$

where $\delta T_{\ell c}$ is the component of the temperature at the critical surface, which has mode number ℓ . The perturbed temperature drops as R/R_c decreases, and drops more rapidly for higher ℓ modes.

To benefit from conduction smoothing, the pellet surface must receive a thermal signal before a hydrodynamic shock, and subsequent shocks must be sufficiently small and late to have negligible imprint. The atmosphere must be preheated to a temperature sufficiently high to permit the thermal conduction time, τ_1 , to be much less than the sonic transit time, τ_s . Assuming classical thermal conductivity,²⁰ one obtains $\tau_1 \propto T^{-5/2}$. Since $\tau_s \propto T^{-1/2}$, then at sufficiently high temperatures the condition $\tau_1 \ll \tau_s$ can be satisfied. If we assume a constant density atmosphere, with density nearly equal to the critical density for a laser of wavelength λ (in μm), the condition $\tau_1 \ll \tau_s$ becomes

Fig. 4-19. Schematic of laser-illuminated pellet. Laser light is absorbed near the critical surface with absorbed intensity I_L , and some of the energy deposited is conducted inward to ablate the pellet surface.

$$T \gg \frac{L^{1/2}}{\lambda}$$

$$\times \left[0.08 \left(\frac{Z \eta_n \lambda}{\epsilon \delta} \right)^{1/2} \left(\frac{\gamma(\bar{Z} + 1)}{\bar{A}} \right)^{1/4} \right] \text{ keV.} \quad (28)$$

With this temperature at the critical surface, the initial energy flux delivered to the pellet surface after prepulse heating of the atmosphere can be estimated. The result is

$$\Phi \simeq \kappa \frac{T}{L} \propto \frac{T^{7/2}}{L}, \quad (29)$$

neglecting spherical geometry.

The atmosphere formation process described here precipitates two penalties that must be minimized to obtain optimal implosion performance.

First, when the thermal wave reaches the pellet surface, the ablation process begins, and a shock propagates inward. The magnitude of the initial pressure generated increases as the flux delivered to the ablation surfaces increases with

$$P_s \propto \Phi^{2/3} \rho_0^{1/3} \propto \frac{T^{7/3} \rho_0^{1/3}}{L}. \quad (30)$$

In turn, the strength of the initial shock through the target shell determines the subsequent implosion behavior. If the adiabat of the shell is set too high initially, the shell will decompress during the implosion. Thus, one side effect of the atmosphere heating is to limit pulse-shaping flexibility, which will degrade implosion performance by an amount that is dependent on target design. To minimize the effects of this initial shock, the initial laser wavelength should be increased, the atmosphere density decreased, the scale height decreased, and the temperature operated as low as possible within the constraint of Eq. (28).

The second penalty associated with the use of a protective atmosphere is the reduction in implosion driving efficiency caused by maintaining the critical surface farther from the ablation surface than in a no-atmosphere pellet. This efficiency reduction is most severe early in time, but this is not of major concern since the laser power and energy delivered early are low, and consequently can probably be increased without major cost. However, the added

mass of the atmosphere continues to manifest itself throughout the laser pulse, and results in an overall increase in driving energy. To minimize this penalty, the initial atmosphere mass should be minimized, and the laser wavelength during the latter part of the implosion should be as short as possible.

To demonstrate the ideas presented above, we discuss a double shell target designed to attain high densities even in the presence of substantial laser-production of suprathermal electrons. Figure 4-20 shows the design geometry.

The target itself consists of a low-aspect-ratio gold shell (pusher) filled with DT gas at density

0.075 g/cm^3 . An interstitial region filled with 0.03 g/cm^3 of foam supports the gold shell within the outer glass shell. In the "bare" target (without atmosphere), the laser light is incident on the outer glass shell. The separation between the laser driven shell and the pusher provides preheat protection in three ways. First, the gap provides a region of reduced conductivity to limit the number of suprathermal electrons that can reach the inner shell. Second, only a fraction of the suprathermal electrons or photons originating at the outer shell or absorption region will hit the inner shell. Third, and perhaps most important, moving the pusher to

Fig. 4-20. Geometry of double shell target for obtaining high densities. Outermost glass shell is used only in atmosphere-protected cases.

Fig. 4-21. Pulse shapes obtained in optimization of double shell target.

small radius allows it to have large ρr per unit mass, giving improved shielding from the electrons and photons that do hit the inner shell.

The outer shell can be driven on a relatively high adiabat and accelerated quite rapidly. The decompression that occurs decreases the efficiency of energy transfer when the outer shell collides with the inner shell. But, as compensation, the feathered collision accelerates the inner shell fairly isentropically, allowing the inner shell and fuel to reach quite high densities. Further, the shell thickness of the outer shell is kept large throughout the implosion, increasing the target's tolerance to fluid instabilities.

Three cases have been optimized in one dimension using the code LASNEX to illustrate the atmosphere production process and its effects. The calculations were performed using multigroup diffusion for electrons and photons. Laser energy was 100% absorbed, with about 25% by inverse bremsstrahlung and 75% through collective processes using $\alpha = 6$ (see Ref. 21). Of course actual target absorption is likely to be lower than 100%, so the incident energy would be higher than the absorbed energies quoted here. Target performance depends on the mix of classical and collective absorption processes, with an increasing fraction of classical absorption resulting in improved implosion performance.

Pulse shapes for the three cases are shown in Fig. 4-21. Case 1 was a "bare" target (no atmosphere)

imploded using the front half of a Gaussian with peak power of 10 TW and $\sigma = 0.45$ ns, followed by a linear ramp to a final power of 20 TW.

Two cases have been optimized with a protective atmosphere. Case 2 was driven entirely by a 1 μ m laser. The pulse shape shown consists of three parts. A small initial prepulse heats the atmosphere shell slightly. After an appropriate delay to allow formation of a low density cloud, a second, larger prepulse heats the atmosphere to the temperature required for supersonic thermal penetration. Finally, the main pulse, consisting of an exponential rise to 10 TW followed by a linear ramp to 20 TW, drives the outer shell implosion.

In Case 3, the initial laser illumination was assumed to be 2 μ m. At the transition from an exponential to a linear rise, the laser wavelength was shifted to 1 μ m. The initial thickness of the atmosphere shell was reduced to 0.25 μ m for this case.

The performance of the atmosphere in keeping the critical surface at large radius initially is shown in Fig. 4-22. The figure shows a plot of the ratio of the critical surface radius to the ablation surface radius as a function of time during the implosion. To facilitate comparison, the origin for time is taken at t_0 , the time of the start of the main pulse, and the time is normalized to τ_i , the implosion time.

The three cases considered were optimized within certain constraints. The maximum power in all cases was set to 20 TW. Each case was optimized to obtain the highest yield possible while reaching a

Fig. 4-22. Ratio of critical surface radius to ablation surface radius as a function of time. At early times, atmosphere-production cases have $R_c/R_a = 1.6$.

peak average fuel density of 250 g/cm^3 . The energy input to the two cases with atmosphere formation was increased enough to reach this same maximum average fuel density with a yield comparable to that of the "bare" target.

Table 4-8 presents the results of the optimizations. In spite of the 40% increase in driving energy, the 1- μm -driven implosion, Case 2, obtained a yield about 1/3 that of Case 1. This is attributable in part to the 30-Mbar initial shock that arises during the atmosphere-heating phase, decompressing the outer shell considerably as it implodes. Single shell targets are generally much more sensitive than this design to the generation of a large initial shock, since in that case the entropy of the inside of the pusher and the fuel is raised considerably.

The case driven with both 2- μm and 1- μm light has partially recovered the losses incurred in Case 2. The lower temperature atmosphere permitted for a 2- μm laser's critical density has reduced the initial shock to about 4 Mbar. The 40% higher driving energy, compared with Case 1, is now sufficient to produce a nearly equivalent pusher implosion velocity, and hence a nearly equal yield.

Using two-dimensional LASNEX calculations, we investigated the tolerances to fluid instability and thermal smoothing of nonuniform illumination. Here, we concentrate on the mode $\ell = 8$, the mode that corresponds roughly to the whole-beam

perturbations in illumination using 20 laser beams spread over the target sphere and that is relatively difficult to symmetrize because of the long physical wavelength.

Calculations for Case 1 were performed assuming uniform illumination and an initially perturbed outer shell surface. The initial amplitude for $\ell = 8$ was adjusted until the calculated implosion performance began to deteriorate. For this mode, a final perturbation amplitude of $2 \mu\text{m}$ rms degraded the maximum average fuel density from 250 g/cm^3 to 60 g/cm^3 and gave a yield within a factor of 2 of the 1-D yield. Decreasing the amplitude by a factor of 2 gave implosion performance comparable with the 1-D calculations, with about a factor of 2 degradation in maximum average fuel density from distortion of the compressed fuel and no degradation in yield. The final state of the imploded pusher and fuel region is shown in Fig. 4-23 for a calculation that reached a final amplitude of $1 \mu\text{m}$ rms.

The growth history of an $\ell = 8$ initial surface perturbation of $20 \text{ \AA}$ rms is shown in Fig. 4-24, together with the amplitude history obtained in a calculation with an $\ell = 8$ illumination nonuniformity of 2% peak. The amplitude plotted is taken at the unstable interface, which shifts from the outer shell to the inner shell at about 3.5 ns, and from the outer surface of the inner shell to the inner surface at about 4.8 ns, as the pusher begins decelerating. In the surface perturbed case, most of the growth occurs near the end of the implosion when convergence is becoming large, and the last factor of 10 of growth appears to be a result of instability of the pusher-fuel interface as the pusher decelerates.

Table 4-8. Calculated performance parameters of double-shell-target examples

	"Bare" 1 μm	With atmosphere	
		1 μm	2 μm + 1 μm
Energy input (kJ)	23.0	32.0	31.0
Initial pressure (Mbar)	2	30	4
Yield (J)	0.6	0.2	0.5

The laser-perturbed $\ell = 8$ case shows a very rapid "growth" early in time as the nonuniform heating imprints a perturbation on the initially smooth surface. After a short time, the imprinting effectively stops, as the ablated matter moves the critical surface away from the ablation surface. Subsequently, the laser-perturbed case develops in much the same way as the surface perturbed case. Another way of viewing this is that the target's tolerance to laser perturbations increases with time. As the implosion progresses, the tolerance to illumination nonuniformities increases.

Similar calculations were run for the $\ell = 8$ mode for targets with atmosphere production, Cases 2 and 3. The laser perturbation was applied to both prepulses, as well as to the main pulse, using a constant peak amplitude of 10%. The amplitude histories were similar to the "bare" target case, except that the imprinted surface perturbation was reduced by a factor of about 10 in both atmosphere-protected cases.

At modes higher than $\ell = 8$, the amount of fluid instability growth would be expected to increase, although this is design dependent. As discussed earlier, the amount of thermal smoothing increases at higher modes, so it is likely that the imprinted

Fig. 4-24. Amplitude vs time for surface- and laser-perturbed calculations.

surface perturbations can be kept adequately small to prevent design failure in most cases. For the particular example discussed here, LASNEX predicts an overall fluid instability growth factor at $\ell = 80$, which is comparable with that at $\ell = 8$. Although the growth rate at $\ell = 80$ is higher than at $\ell = 8$, the transfer of perturbations between the outer shell and the inner one is more inefficient than at $\ell = 8$ as a result of the long density gradient scale lengths involved. Thus, for the present case, a fairly large tolerance to $\ell = 80$ illumination nonuniformity results, and calculations with 10% peak amplitude at $\ell = 80$ survive easily, indicating tolerance to nonuniformities of 30% or more.

The effect of thermoelectric magnetic field generation has been investigated in this example. The magnitude of the peak field in the case of the $\ell = 8$, 10% peak illumination nonuniformity was only 20 kG, and its spatial extent was of order 20 μm . The inhibition produced by this field was not significant in modifying the thermal smoothing obtained. Other magnetic field generation mechanisms, that could perhaps alter this result such as resonance absorption,²² have been discussed.

Finally, we note that various processes can result in modifications of the angular distributions of suprathermal electrons and that the isotropy assumed in the present case is an oversimplification. For example, plasma instabilities in the region between the critical surface and the ablation surface can result in formation of current filaments.²³ In the case considered, the transport is

Fig. 4-23. Isodensity contours of implosion of a perturbed target. Amplitude shown is 1 μm rms. Tolerable final amplitude was estimated to be 1 μm rms at $\ell = 8$, using two-dimensional LASNEX calculations. Final amplitude of 1.5 μm rms degraded implosion performance slightly.

largely collisional, and the transport modifications produced are not expected to change the basic conclusions reached here, although some quantitative changes could occur.

References

15. J. D. Lindl and W. C. Mead, *Phys. Rev. Lett.* **34**, 1273 (1975); W. C. Mead and J. D. Lindl, "Behavior of Fluids Instabilities in Laser Fusion Pellets: Results of 2-D Calculations," presented at *Gordon Research Conference on Laser Interaction with Matter*, Aug. 18-22, 1975, Tilton School, Tilton, NH.
16. D. B. Henderson and R. L. Morse, *Phys. Rev. Lett.* **32**, 355 (1973).
17. A. R. Thiessen and J. H. Nuckolls, *Bull. Amer. Phys. Soc.* **19**, 950 (1974).
18. R. E. Kldder, *Nucl. Fusion* **16**, 3 (1976).
19. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1975).
20. L. Spitzer, *Physics of Fully Ionized Gases* (Interscience Publishers, New York, 1962), 2nd ed., p. 144.
21. W. C. Mead, R. A. Haas, W. L. Kruer, D. W. Phillion, H. N. Kornblum, J. D. Lindl, D. R. MacQuigg, and V. C. Rupert, *Phys. Rev. Lett.* **37**, 489 (1976).
22. J. J. Thomson, C. E. Max, and K. Estabrook, *Phys. Rev. Lett.* **35**, 663 (1975).
23. E. J. Valeo, *Growth of Current Filaments in Laser Fusion Plasmas*, Lawrence Livermore Laboratory, Rept. UCRL-77923 (1976). Submitted to *Phys. Fluids*.

Author
W. C. Mead

Major Contributor
J. D. Lindl

4-1.7 High-Gain Targets: Effects of Density-Gradient Modification on Fluid Instabilities in Thermonuclear Micro-Implosions

Fluid instabilities arising during the implosion of spherical shells in laser-driven and charged-particle-driven fusion put a limit on the aspect ratio, $r/\Delta r$,

that one can use, where r is the target radius and Δr the shell thickness. The limitation arises because fluid instability can result in mixing of high- and low-density and high- and low-temperature matter. This mixing greatly reducing the compression one can achieve.

In both laser-driven and charged-particle-driven targets, it is possible to achieve a significant reduction in growth rate by using density-gradient stabilization. This effect has been examined by Chandrasekhar²⁴ and for a case more appropriate to fusion pellets by Lelevier et al.²⁵ Lelevier assumed a density ρ of the form

$$\rho = \begin{cases} \rho_1 - 1/2 \delta \rho \exp(-\beta y) & y > 0, \\ \rho_2 + 1/2 \delta \rho \exp(\beta y) & y < 0, \end{cases}$$

where $\delta \rho = (\rho_1 - \rho_2) > 0$. For such a density profile, the growth rate, γ , becomes

$$\gamma = \left(\alpha k a \frac{\beta}{k + \beta} \right)^{1/2} = \gamma_0 \left(\frac{\beta}{k + \beta} \right)^{1/2}, \quad (31)$$

where $\alpha = (\rho_1 - \rho_2)/(\rho_1 + \rho_2)$ is the Atwood number and $\gamma_0 = \sqrt{\alpha k a}$ is the growth rate for instabilities between two fluids of density ρ_1 and ρ_2 , which have a sharp interface. As $\beta \rightarrow 0$ or $L = 1/\beta \rightarrow \infty$, the growth rate goes to zero. The effect starts becoming important when k is about equal to β .

For laser-driven implosions it is possible to make use of the properties of suprathermal electrons, generated in the absorption process, to generate a shallow-density gradient. The suprathermal electrons are generated primarily by resonance absorption and parametric decay instability near the critical surface. The high energy tail of these electrons result in preheat of the central fuel region, preventing efficient compression. However, if this very high energy end of the spectrum can be eliminated, the moderate energy suprathermals

Fig. 4-25. Laser-driven DT target used for density-gradient stabilization study.

Fig. 4-26. Laser time-power history required for a low entropy implosion.

penetrate beyond the ablation surface to give a shallower density gradient, but do not result in preheat of the center. Electrons from parametric decay are generated with a velocity parallel to the critical surface. Those from resonance absorption are ejected radially outward from the critical surface. The important point is that these electrons can only cause preheat after reflecting from the plasma sheath at the outside of the corona. However, if the target is sitting in a very low density gas whose density is about equal to that of all electrons above a cutoff energy, the high energy electrons will escape from the pellet and be replaced by low energy electrons from this cloud. The moderate energy electrons below the cutoff will be reflected back into the interior.

It is possible that magnetic fields or density fluctuations could scatter the high energy electrons back into the core before they reach the plasma sheath. However, the reduction in scattering length would have to be two orders of magnitude or more, since for calculations presented here, the distance from the critical surface to the edge of the corona is less than 1% of the scattering range of a 50-keV electron. Figure 4-25 is a pie diagram of such a pellet. Figure 4-26 gives the laser power history used to drive the pellet. The total input energy is 160 kJ and the thermonuclear gain is 40. This target is the size that could be imploded with the Shiva Nova laser being designed here.

All computer calculations presented are done with the two-dimensional Lagrangian computer

Fig. 4-27. Density scale length as a function of time. If $L \lesssim 1/k$, sensitivity to fluid instability is significantly reduced.

Fig. 4-28. Relative perturbation amplitude vs time using a 45-keV suprathermal cutoff and a spherical harmonic with $l = 160$.

code LASNEX,²⁶ written by G. Zimmerman. This code includes the multi-group electron transport used in the following calculations. Electrons are treated using a Maxwellian thermal group together with multiple higher energy groups that can represent arbitrary suprathermal distributions. Both absorption and transport can produce electron distributions that differ significantly from a Maxwellian.

In the following calculations, an electron spectrum is generated that matches that of recent experiments with parylene disks between 10^{15} and 10^{17} W. Since the numerical model in LASNEX assumes an isotropic distribution of electrons, the bins were just terminated at the cutoff energy. Hence, the effectiveness of the "get lost" region has not been self-consistently calculated. The required density of the "get lost" region of 10^{-7} to 10^{-8} g/cm³ is estimated from the density of electrons at the cutoff energy.

This "get lost" region is very important. To get a density stabilization effect, a large number of electrons in the suprathermal population is required. However, if the upper end of the spectrum is not removed, preheat is so bad that virtually no density can be achieved with even quite thick shells such as shown in Fig. 4-25. Because of this preheat, we had been forced to do designs that assumed a $1/4 \mu$ or shorter wavelength to minimize the number of very hot electrons. However, using such a laser, there is no longer a density stabilization effect because the suprathermals that are produced arise so late in the implosion that there is no effect on the growth rate. It turns out that with the "get-lost" region to truncate the spectrum, $1\text{-}\mu\text{m}$ light is about optimal. There is less than 1% of energy above the required cutoff, yet there is enough energy below the cutoff to produce a significant modification of the density gradient. Using a 45-keV cutoff, there is about a

Fig. 4-29. E-foldings as a function of wavenumber for laser-driven target.

twofold degradation in yield due to preheat and about a fourfold increase in the average density gradient. A higher energy cutoff gives a shallower density gradient but a greater yield degradation. What is required is that the density scale length be greater than $1/k$ for the time when most of the growth of perturbations is occurring. Plotted in Fig. 4-27 is the scale length of the density-gradient L as a function of time for the 3-T case and the case with a 45-keV cutoff; $1/k$ is plotted for $\ell = 160$ for reference.

During most of the implosion, the 45-keV cutoff has L a factor of 2 or more greater than $1/k$, whereas the 3-T implosion has L much less than $1/k$ during almost all of the implosion.

Figure 4-28 shows a comparison of the LASNEX calculated relative amplitudes η/η_0 and an integration of Eq. (31) corrected for compression. The agreement is quite good.

Figure 4-29 shows the calculated dispersion rela-

tion for the 3-T and 45-keV cutoff examples. Accelerations and density gradients are taken from LASNEX in doing this integration. A dispersion relation for $L = 0$ is shown for reference. The two points at $\ell = 100$ and $\ell = 160$, with error bars on the 45-keV curve are from LASNEX calculations where $\ell = kr$ and is the order of the spherical harmonic applied to the target. These are about the worst unstable wavelengths for this example and have a growth rate about 60% of that for the 3-T dispersion relation or a reduction in amplitude of 100 to 200. For the $\ell = 160$ calculation, the actual reduction in amplitude for comparable LASNEX calculations was a factor of 20 as shown in Fig. 4-29. The LASNEX calculation lags the predicted curve for the 3-T example because of nonlinear saturation at the large amplitudes achieved.

Density-gradient modification is somewhat easier to achieve with charged-particle-driven sources than with lasers. For example, because of straggling and

bremsstrahlung, 1-MeV electrons have a deposition profile that falls off very gradually at the end of the range. Such an extended deposition profile results in minimal sensitivity to fluid instabilities, but also considerable preheat and low thermonuclear gains. Ions, with a sharp cutoff at the end of their range, result in more efficient, lower power implosions but greatly increased sensitivity to fluid instability. However, putting an energy spread on the ion beam will spread out the deposition at the end of the range. By suitably choosing this spread in energy and by adjusting shell thicknesses appropriately, one can still achieve a relatively efficient implosion but with greatly reduced sensitivity to fluid instability. Figure 4-30 shows the plots of dE/dx for an ion beam with an average energy of 10 MeV un-

der various conditions. Curve A is the deposition profile for a monoenergetic beam focused radially onto a spherical target. Curve B is the profile for a monoenergetic beam but assumes a 10-eV transverse temperature at the source, which spreads the beam to 1.66-mm FWHM at a distance of 1 m from the source. Hence, the beam is no longer radially focused. Curve C is the profile for a beam with an average energy of 10 MeV but with a Gaussian spread in energies of 17.6% FWHM and a 10-eV transverse temperature at the source. These sources are applied to the target shown in Fig. 4-31. The target consists of a gold shell with a 2-mm inner radius and 1 mg of solid DT in 100- μ -thick inner layer. The gold shell varies in thickness from 0.21 mm for the radial deposition A to 0.23 mm for the

Fig. 4-30. Energy deposition of 10-MeV protons in gold at a temperature of 200 eV and density of 5 g/cm³.

Fig. 4-31. Target used for ion beam, density-gradient stabilization study.

Fig. 4-32. Density scale length as a function of time for ion beam target using various beam deposition profiles.

Fig. 4-33. Number of e-foldings as a function of wavenumber for ion beam target.

deposition C. With radial deposition, a thermonuclear gain of about 40 is calculated in LASNEX simulations with an input of 6.0 MJ and peak power of 500 TW. Thermonuclear gain of about 30 with an input of 8.4 MJ and peak power of 700 TW is calculated for deposition C. The higher power and lower gain for case C occur because the gold shell is thicker to accommodate the greater ion range and because the implosion is somewhat less efficient with the spread-out deposition profile.

Shown in Fig. 4-32 is a plot of the density scale length L as a function of time for the three deposition profiles. Plotted for reference is $1/k$ vs time for $\ell = 100$. For the radial profile A, the scale length is much less than $1/k$, whereas for C, the scale length exceeds $1/k$.

The reduction in growth as one goes from A to C is evident from the dispersion relations given in Fig. 4-33. The curves are analytic results from integrating Eq. (31) and show $\ln(n/n_0) = \int \gamma dt$ as a function of k . Points with error bars are from

LASNEX calculations. As a result of the modified density gradient, case C easily survives with a 100 Å surface finish at $\ell = 100$. Case A fails even with 10 Å surface finish at $\ell = 100$, and because of the reduced shell thickness, this is not the worst unstable mode.

In conclusion, we should be able to exploit density-gradient modification to reduce the sensitivity to fluid instability of both laser-driven and charged-particle-driven microfusion implosions.

In both cases, a 1 to 2 order-of-magnitude reduction in surface finish requirement occurs. For laser-driven targets this reduction is achieved by using suprathermal electrons with a high-energy "get-lost" region to eliminate severe preheat problems. For charged-particle sources, the reduction is achieved by introducing an energy spread on the driving source. This order of magnitude improvement is very important for target fabrication costs because 100- to 200-Å surface finishes are expected to be relatively easy to achieve²⁷ whereas 10 Å would be extremely difficult.

Both techniques need further study for optimization. For laser-driven targets, the effect of various nonlinear scattering mechanisms on the high energy suprathermal electrons must be investigated. If such scattering is important, shielding the interior of the pellet with some high-Z material may be necessary to cut preheat.

References

24. S. Chandrasekhar, *Hydrodynamic and Hydromagnetic Stability* (Oxford University Press, London 1968), p. 456.

25. R. Lelevier, G. Lasher, and F. Bjorklund, *Effect of a Density Gradient on Taylor Instability*, Lawrence Livermore Laboratory, Rept. UCRL-4459 (1955).
26. G. B. Zimmerman, *Numerical Simulation of the High Density Approach to Laser-Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-74811 (1973).
27. C. D. Hendricks, Lawrence Livermore Laboratory, private communication (1976).

Authors

J. D. Lindl
R. O. Bangerter

J. H. Nuckolls
W. C. Mead

4-2 ELECTRON AND ION BEAM TARGET DESIGN AND ANALYSIS

4-2.1 Ion Beam Targets

When designing ion beam fusion targets suitable for commercial power production, we expect that the following criteria may be important:

- The target should be cheap; hence, it should be made of inexpensive materials, it should be simple to fabricate, and it should be relatively insensitive to fluid instabilities to minimize the precision required in its construction.
- The target should produce minimum residual radioactivity.
- The target should have a high gain (energy yield/beam energy) to minimize recirculating power costs in the power plant.
- The target should have low beam power and energy requirements.
- The target should not be overly sensitive to irradiation asymmetries.
- The target should be insensitive to preheat effects.

However, many of these requirements impose contradictory constraints on target design. For example, power requirements can be lowered by using high-aspect-ratio (radius/shell thickness) shells or multiple-shell designs; however, such targets are relatively unstable and usually have high irradiation symmetry requirements.²⁸⁻³¹

We have designed a new type of target that satisfies many of the above requirements (see Fig. 4-34). The principal feature of this target is the low-density, low-Z pusher material that is located between the high-Z tamper and the fuel. In addition, this target is made of inexpensive materials and should be relatively easy to fabricate.

Fig. 4-34. Section of a spherical ion beam fusion target with a low-density pusher.

Fig. 4-35. Energy-deposition profile for 6.5-MeV protons incident on the target illustrated in Fig. 4-34.

The high-density tamper serves as a confinement shell to increase the efficiency of the implosion. The pusher material, TaCOH is CH_2 , that has been seeded with tantalum oxide. The tantalum constitutes only about 1 at% of the pusher, but this is sufficient to inhibit energy transport into the fuel, preventing preheat. Because of its low density, the pusher can be relatively thick to decrease the fluid-instability problem and yet contain little mass. In addition, the fluid instabilities causing pusher-fuel mixing during the final stages of the implosion³¹ are ameliorated as a result of the small density difference between fuel and pusher. Our calculations typically give Atwood numbers much less than 1 across the pusher-fuel interface during the final stages of the implosion. In some cases, the fuel actually becomes denser than the pusher, resulting in a stable condition.

In our calculations involving high-Z pushers, the density $\times$ radial thickness (ρr) of the pusher in targets comparable to the one in Fig. 4-34 is roughly 10 g/cm^2 during thermonuclear burn. In our new target, the bulk of the high-Z material remains uncompressed at a large radius. The total ρr of the high-Z material in both the pusher and tamper is less than 1 g/cm^2 . Thus our new target produces less than 10% as much high-Z radioactive debris as a target with a high-Z pusher.

Fig. 4-36. Ion beam power vs time for the target illustrated in Fig. 4-34.

Low-Z materials stop ions more effectively than do high-Z materials. Thus the ion-beam energy is preferentially deposited in the pusher region where it is most effective (see Fig. 4-35). The curve in this figure was calculated for 6.5-MeV protons at temperatures and densities occurring 18 ns into the implosion.

To achieve high gain, fuel must be efficiently compressed and only the central portion ignited. A radially propagating burn ignites the remainder of the fuel. These two conditions are achieved by using the pulse shape shown in Fig. 4-36.

The overall gain of this new target is 88. The energy output is 113 MJ; the energy input is 1.28 MJ at a peak power of $2.4 \times 10^{14} \text{ W}$. In addition, this target can be readily scaled to different sizes and ion-beam voltages. (See Ref. 32 for more details of this target.)

Thus, we conclude that, when measured against the criteria cited, this new target design offers significant advantages over many previous types of target designs.

References

28. J. H. Nuckolls, L. Wood, A. Thiessen, G. Zimmerman, *Nature* **239**, 129 (1972).

29. J. D. Lindl and W. C. Mead, *Phys. Rev. Lett.* **35**, 1273 (1975).
30. R. C. Kirkpatrick, C. C. Cremer, L. C. Madsen, H. H. Rogers, R. S. Cooper, *Nucl. Fus.* **15**, 333 (1975).
31. R. O. Bangerter, J. D. Lindl, C. E. Max, and W. C. Mead, *Proceedings of the International Topical Conference on Electron Beam Research and Technology*, Sandia Laboratories, Albuquerque, NM, Rept. SAND76-5122 1, 15 (1976).
32. R. Bangerter, D. Meeker, *Ion Beam Inertial Fusion Target Designs*, Lawrence Livermore Laboratory, Rept. UCRL-78474 (1976).

Author

R. O. Bangerter

4-2.2 Electron and Ion Beam Targets

High-gain designs of inertially confined targets for both laser and charged-particle sources are tailored to reach ignition temperatures only in a small fraction of the DT mass (near the center of convergence) rather than raising the total fuel to burn conditions (e.g., see Ref. 33). This central lighting usually is achieved by first shock heating the DT mass center and then adiabatically compressing it to ignition conditions. The remaining fuel is then ignited by an outward-propagating thermonuclear detonation wave.

Here, we propose an alternative method where ignition is attained by first externally preheating and then adiabatically compressing a small portion of the DT fuel, initially at low density. This localized preheat is accomplished with a highly focused, axially directed ion beam that passes through the outer shell of the target and into the fuel region. This nonuniform heating of the fuel region also creates a self-generated magnetic field.

This method differs from previous approaches described by Rudakov³⁹ and Meeker³⁵ where the magnetic field is formed by the beam itself and very large beam currents are required to generate adequate magnetic fields. In both of these designs, the electron beam penetrates into the fuel region through an outer shell that is thinner than a classical range. However, in our case, the shell is slightly thicker than a classical range for the 10-MeV protons that serve as the main compression source, but is barely less than the range of the 11-MeV axial ion beam used to preheat the fuel. The magnetic

field is an especially desirable addition because it can inhibit loss mechanisms that exist in the fuel region and can trap burn products at low densities to enhance the propagation. For the field to be truly effective, however, it must be of sufficient magnitude to affect the electron conduction in the DT fuel; in addition, it must be able to diffuse through the DT during implosion but not through the outer gold shell.

One-Dimensional Computer Study

A series of one-dimensional tests were run on LASNEX to determine if a magnetic field and localized preheat could reduce the input power and energy requirements for breakeven targets. We chose two target sizes, one with a radius of 0.25 mm and the other with a radius of 0.5 mm. Both geometries had a 200- μ m-thick outer gold shell and fuel masses of 2.6 and 10.7 μ g, respectively. The input for both targets was a 10-MeV proton beam, deposited uniformly and with radial convergence.

To include the effects of preheat, a small fraction of the fuel was initially set at some arbitrary temperature. Although LASNEX has self-consistent electric and magnetic field terms, the magnetic field was approximated by appropriate multipliers on both the electron and ion conduction terms as well as on the alpha transport equations. This approximation greatly reduced the running time for individual problems and allowed the optimization of

Table 4-9. Effect of magnetic field and preheat on energy yield

Parameter	Target radius, mm	
	0.25	0.5
Peak power, TW	30.0	35.0
Input energy, kJ	81.9	196.0
Yield with preheat and B field, kJ	100.2	671.0
Yield with preheat and no B field, kJ	0.323	1.17
Yield without preheat but with B field, kJ	8.82	43.9

a greater number of variables, an essential point where pulse shaping is required.

Results for the 0.25-mm target radius with the ideal source are shown in Table 4-9. Breakeven occurs at an input energy of 80 kJ and peak power of 30 TW with an initial fuel temperature of 10 eV and a magnetic field of 5.0 MG. Both values of preheat and magnetic field have been optimized; outputs with either of these variables set equal to zero are shown in Table 4-9 for comparison. It is evident that there is a distinct advantage in using both the magnetic field and initial temperature in the plasma for producing significant thermonuclear burn.

Use of a larger diameter pellet does not raise the peak power substantially but does cause a large increase in the required input energy. The optimum target parameters for breakeven indicate that gains of unity are expected for a peak power of 35 TW and input energies of 200 kJ. Preheat can be reduced to 5 eV without substantial changes in output but the initial magnetic field is still approximately 5.0 MG.

From this one-dimensional parameter study, we can conclude that both a preheat and a magnetic field are desirable in the geometries studied. In addition, their inclusion appears to lower the source requirements for breakeven targets. The question to be addressed next is how to generate such conditions without degrading the basic symmetry of the fuel compression. One possible solution is a small-diameter, directed ion beam with just enough range to selectively heat a portion of the fuel.

Generation of Magnetic Field and Preheat

Ions passing through matter lose their energy predominantly by inelastic collisions with the target material. The characteristic Bragg ionization curve³⁶ depicting this energy loss as a function of the ion's total range is shown in Fig. 4-37(a). We selected a beam energy that places the peak of the dE/dx curve in the fuel region [see Fig. 4-37(b)]. By varying the size of the beam and the total energy, we can study the heating of the DT layer. One result of this nonuniform heating is the formation of temperature and density gradients, that, if oriented in different directions, give rise to local current flow and thus, to magnetic fields.

Fig. 4-37. Bragg ionization curve (a) and diagram of a target segment (b), illustrating how the range of the 11-MeV ions is chosen to peak in the solid DT fuel region.

Fig. 4-38. Proposed target geometry for generating a magnetic field and preheat in an ion-beam-driven pellet. The radius of this target (measured from the target center to the outer edge of the solid DT shell) is 0.5 mm. This solid DT shell is 15 μm thick with a mass of 10 μg and a density of 0.21 g/cm^3 . The DT gas in the center has a density of 10^{-3} g/cm^3 ; the outer gold shell measures 200 μm thick.

Table 4-10. Effect of axial 11-MeV ion beam on fuel parameters where $\tau_{\text{beam}} = 50$ ns

Beam radius, μm	Beam energy, kJ	Maximum ion temperature	Maximum magnetic field, kG
10	0.1	80	700
10	1.0	120	2500
25	0.1	70	300
25	1.0	100	1200
50	0.1	15	20
50	0.2	15	35
50	1.0	20	100

To study the effect of the axially-directed ion beam, two-dimensional computer runs were made with the target geometry shown in Fig. 4-38, but with the main source turned off. The area of the fuel shell intercepted by the ion beam is only a few percent of the total area and therefore represents only a small perturbation.

Table 4-10 presents the results of several LASNEX runs with 11-MeV protons incident on a 200- μm -thick gold shell. From these data, we see that a 100- μm -diam beam containing 1 kJ that is delivered over 50 ns can preheat the fuel to 30 eV, resulting in a magnetic field of 100 kG. Tighter beam geometries increase these values for the same energy but are correspondingly harder to obtain.

The major loss component at these fuel temperatures is the electronic thermal conduction which can be strongly affected by magnetic fields. Following the approach of Braginskii,³⁷ we find that thermal conduction is proportional to $\rho^2/B^2 T_e^{1/2}$, decreasing with higher B field and temperature. Thus, the larger the magnetic field we can generate, the less power that is required from the axial ion beam.

An important consideration is the time required for the magnetic field to diffuse from its point of origin and fill the entire fuel volume. With the temperatures given in Table 4-10, the diffusion time is approximately 1.0 ns. A second diffusion time is required for the field to diffuse through the gold shell. This time is well beyond the time for implosion at about 0.1 μs .

Conclusions

The results from the one-dimensional parameter study indicate that preheat and magnetic field components would enhance the thermonuclear burn. The studies with the axial ion beam imply that such conditions might be met by using this beam in conjunction with the main source. Therefore, to study the target behavior with both sources operating simultaneously, two-dimensional runs were made on LASNEX with full-magnetic-field physics, allowing proper treatment of the thermal conductivity terms and the enhanced alpha deposition. Preliminary results indicate that the fuel area becomes very turbulent (the LASNEX mesh is scrambled). In addition, a beam diameter of 10 μm is required to achieve sufficient magnetic field values because the self-generated field is smaller than predicted.

In the near future, we plan to investigate three new approaches to increase the magnitude of the magnetic field. These include irregularities in the DT fill and inner surface of the pusher, seed particles in the fuel,³⁸ and tighter focusing of the ion beam. The first two suggestions would magnify local gradients of density and temperature, thereby increasing the magnetic field produced. However, they also might destroy the uniformity of implosion or increase the radiative losses from the compressed fuel. The third approach is the most desirable, but the present focusing technology is not yet advanced enough.

References

33. J. D. Lindl and R. O. Bangerter, "Low Power Multiple Shell Fusion Targets for Use with Electron and Ion Beams," *International Topical Conference on Electron Beam Research and Technology* (Albuquerque, NM, 1975), Vol. 1, p. 37.
34. M. V. Babykin, Ye. K. Zavoisky, A. A. Ivanov, and L. I. Rudakov, *Nucl. Fus. Suppl.*, p. 75 (1972).
35. D. J. Meeker, J. H. Nuckolls, and R. O. Bangerter, *Bull. Am. Phys. Soc.* 20, 1352 (1975).
36. R. D. Evans, *The Atomic Nucleus*, (McGraw-Hill Book Co., New York, 1955), p. 665.
37. S. I. Braginskii, *Rev. Plasma Phys.* 1, 205 (1965).
38. D. Tidman, "Seeded Mega-Gauss Turbulence in Dense Fusion Target Plasmas," *International Topical Conference on Electron Beam Research and Technology* (Albuquerque, NM, 1975), Vol. 1, p. 115.

Author	Major Contributor
D. J. Meeker	J. H. Nuckolls

4-2.3 Heavy Ion Target Technical Summary

(The following is abstracted from LBL-5543, Final Report of the ERDA Summer Study of Heavy Ions for Inertial Fusion, Lawrence Berkeley Laboratory, Berkeley, California.)

To generate useful fusion energy with heavy-ion accelerators, two major developments must occur in target areas:

- An efficient fusion microexplosion must be generated.
 - A target factory must be built that can manufacture cheap targets.
- These objectives seem feasible if practical heavy-ion accelerators can be developed that have appropriate power, energy, voltage, pulse-shaping, and focusing properties.

Target Design

None of the ion-beam-imploded target designs that have been published^{39,40} or reported^{41,42} are adequate for electrical-energy production. Either the gain is too small or the required power is too

high. In addition, there are serious problems involving fluid instabilities driven by irradiation asymmetries. Consequently, the success of practical heavy-ion fusion depends not only on the success of advances in accelerators but also on the success of advances in targets. Recently we have designed a number of targets having energy gains in excess of 100. Such targets seem suitable for commercial power production when imploded by appropriate heavy-ion accelerators.

After considering the various proposals for target designs and estimating the potential growth in performance to be reasonably expected in the next few years, the target panel (Heavy Ion Target Panel) agreed on the following target input requirements for commercially useful power plants.

The gains greater than 100 implied by Case 1 (see Table 4-11) are achieved despite the long deposition length of the ion beam relative to that for laser light because the massive absorber acts as a hydrodynamic tamper that is much less lossy than the ablation to vacuum in a laser implosion. This compensates for the extra energy required to heat the absorber. In both cases, high gains are achieved by using low-density, lightweight pushers driven by shaped pulses.

In Case 2 our confidence is significantly reduced because the shells are made thinner to reduce the required power and energy. Consequently, there is greater risk of failure resulting from fluid instabilities.

Cases 3 and 4 exploit the potentially very high efficiency of certain types of accelerators. In Case 3, the fuel is mostly deuterium. Some tritium and ³He seeding is used, but the amounts of these materials that are consumed are generated in the burning deuterium. Consequently, there is no need to breed tritium in a lithium blanket. Note that, because of the high efficiency requirement, this very important option is unique to heavy-ion accelerator fusion. In Case 4, the DT fuel is a noncryogenic gas. This provides an option that may be exercised if the fabrication of cryogenic targets is too expensive.

The number of beams should be at least 2 and may be 100 or more. The focused beam radius should not be less than 1 mm. In general, for a given range, the beam radius will be determined by the specific energy requirement in Table 4-11.

The accelerator should be capable of focusing to the 1-mm (or larger) beam spot from the reactor chamber wall, which is 10 to 15 m from the target

Table 4-11. Target input (all accelerator) requirements

Parameter	Case			
	1	2	3	4
Total beam energy (E), MJ	10	1	10	10
Pulse length at peak power (Δt), ns	10	6	10	10
Peak power (P), TW	600	100	600	600
Energy/mass deposited in target (ϵ), 10^7 J/g	3	2	3	3
Accelerator efficiency (ϕ), %	10	10	50	50
Rep rate, s^{-1}	2	20	20	10
Voltage (for uranium ^a), GeV	100	40	100	100
Special features	Nominal	Advanced	D-burner	Noncryogenic
Confidence level	High	Mode rate	Moderate	Moderate

^aInstead of uranium, lower-Z charged particles may be used if the voltage is reduced to give the same range (see Fig. 4-39). For energies greater than 100 GeV, target preheat may be a serious problem.

for a single chamber and 5 to 7.5 m for eight chambers. The total area of the beam and vacuum ports should not exceed 10% of the reactor wall area.

The required pulse shape is approximately as shown in Fig. 4-40. This pulse shape may be approximated by a series of shorter Gaussian or

square pulses of varying height. Typically, five or more shorter pulses are needed for an adequate approximation.

Further work is needed in the target area to evaluate the advanced designs. Improvements here could have a great impact on heavy-ion accelerator

Fig. 4-39. Range vs energy for various ions incident on gold.

Fig. 4-40. Required pulse shape where E is the total beam energy, P is the peak power, and Δt is the pulse length at peak power (the characteristic time) in ns (see Table 4-11).

design. There is some uncertainty concerning the range of heavy ions.^{43,44} However, this uncertainty is believed to be relatively small, requiring experiments in hot plasmas and with high-intensity beams. Further theoretical study is merited.

It has been suggested that target performance might be degraded by preheat resulting from nuclear fragmentation of the ion beam.⁴⁵ However, we have made calculations of this effect and determined that it is not a problem.

Target Fabrication

The principal problem as regards target fabrication is the allowable target cost. The cryogenic nature of the pellet tends to increase this cost. We

require microexplosions in the 0.1- to 1-ton yield range so that the tolerable fabrication costs are 5 to 50¢ per target (assuming that electricity sells for 20 mils/kWh and that 2 mils/kWh may be allocated to target fabrication). The noncryogenic target option covers the possibility that cryogenic-related problems might prove more difficult than anticipated.

Our current estimates of target cost are less than 50¢. More reliable estimates can be made when prototype targets are constructed and the target factory design is roughed out.

References

39. M. J. Clauser, *Phys. Rev. Lett.* **35**, 848 (1975).
40. J. W. Shearer, *Nucl. Fusion* **15**, 952 (1975).
41. J. D. Lindl and R. O. Bangerter, *Low Power Multiple Shell Fusion Targets for Use with Electron and Ion Beams*, Lawrence Livermore Laboratory, Rept. UCRL-77042 (1975).
42. R. O. Bangerter, J. D. Lindl, C. E. Max, and W. C. Mead, *Stability and Symmetry Requirements of Electron and Ion Beam Fusion Targets*, Lawrence Livermore Laboratory, Rept. UCRL-77048 (1975).
43. E. Nardi and Z. Zinamon, Weizmann Institute of Science, Rehovot, Israel, Rept. WIS-76/37Ph (1976).
44. R. O. Bangerter and D. S. Bailey, *Stopping Power of Ions in Partially Ionized Matter*, Lawrence Livermore Laboratory, Rept. UCRL-78468 (1976).
45. C. Alonso, *On the Interaction of Intense Heavy Ion Beams with Various Targets*, Lawrence Livermore Laboratory, Rept. UCID-17201 (1976).

Author

J. H. Nuckolls

4-3 LASNEX: OVERVIEW

Because of the increasing complexity of our target design plus improvements in the accuracy and reproducibility of experimental diagnostics, we have made several modifications to LASNEX, our code for designing laser, electron, and ion-beam targets and analyzing experimental results.⁴⁶⁻⁵¹ Improvements made this past year are in three categories: 1) those increasing the accuracy of the computer

simulation so that it now more closely represents the true physics, 2) those introducing new physics, allowing us to design ion beam targets, and 3) those improving our ability to compare calculations with experimental results.

The LASNEX spatial mesh, on which all calculations are performed, must conform to all perturbations of the simulated target; thus a distorted mesh

is required. The technique originally used to solve the diffusion equation could not handle energy flow diagonally across the mesh, but a new method has been developed which incorporates diagonal coupling terms to account for the skewness of the mesh and implicitly solves the diffusion equation for the entire problem using the ICCG linear system solver.⁵² Using this method to solve the diffusion equation has significantly improved the accuracy and increased our confidence in several target designs. A new method of solving the transport equation without making the diffusion approximation has also been developed and is now being implemented.

The need to design targets for ion-beam fusion has required us to implement an ion-beam deposition model in LASNEX, in addition to the already existing laser and electron-beam models. Basically the model produces the spatial dependence of energy deposition and depends on the type of ions used, their energy and energy spread, and the thermal properties of the target plasma.

To improve our ability to compare calculations with experiments, we have developed several post-processing codes, those not used in basic LASNEX design calculations but which use the LASNEX output to produce results that are directly comparable with experimental measurements. For example, diagnosing intermediate density compression experiments involves spectral linewidths of trace elements mixed with the compressed DT fuel. We have written a spectral line-analysis program to produce the theoretically expected line profiles. Modifications have also been made to the x-ray micrograph simulator so that it can now produce theoretical pictures that compare directly with experimental x-ray streak pictures. Thus, time-dependent implosion histories can be checked against calculations.

Generally, LASNEX simulations have been in good agreement with experimental measurements of x-ray spectra and images, neutron yields, alpha particle spectra, and ion calorimetry. We are continuing to improve the accuracy of our simulation techniques, expand the physics available for target designs, and improve post-processing codes that link the calculation and experiment.

References

46. G. B. Zimmerman, *Numerical Simulation of the High Density Approach to Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-74811 (1973).

47. G. B. Zimmerman and W. L. Kruer, *Comments in Plasma Phys. and Controlled Thermonuclear Fusion* 2, 85 (1975).
48. *Laser Program Semiannual Report January-June, 1972*, Lawrence Livermore Laboratory, Rept. UCRL-50021-72-1 (1972), pp. 107-109.
49. *Laser Program Semiannual Report July-December, 1973*, Lawrence Livermore Laboratory, Rept. UCRL-50021-73-2 (1974), pp. 69-72.
50. *Laser Program Annual Report 1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1974), pp. 368-371.
51. *Laser Program Annual Report 1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), pp. 289-292.
52. D. S. Kershaw, *The Incomplete Cholesky Conjugate Gradient Method for the Iterative Solution of Systems of Linear Equations*, Lawrence Livermore Laboratory, Rept. UCRL-78333, Rev. 1 (1977), submitted to *J. Comput. Phys.*

Author

G. B. Zimmerman

Major Contributors

D. S. Kershaw

D. S. Bailey

J. A. Harte

R. E. vonHoldt

4-3.1 Matrix Inversion Techniques

A basic problem in modeling laser fusion is computer simulation of radiative transport, electron thermal conduction, and ion thermal conduction in a two-dimensional Lagrangian hydrodynamics codes such as LASNEX. In LASNEX, these are all treated as diffusion processes and so the problem becomes how to solve the diffusion equation on a two-dimensional Lagrangian hydrodynamic grid (a grid whose zones are arbitrary quadrilaterals). Thus, we wish to solve an equation

$$\frac{\partial U}{\partial t} = \nabla \cdot D \nabla U, \quad (32)$$

where $U \geq 0$ is the energy density and $D \geq 0$ is the diffusion coefficient. The smallest practical time step, Δt , we can take (and still have the computer finish the problem) is often 1000 times larger than

the characteristic relaxation time τ ($\tau \approx \ell^2/D$, where ℓ is the zone size) for Eq. (1). However, often all we are interested in is the successive steady-state distributions of U as the boundary conditions change and the time scale, τ' , for an appreciable change in boundary conditions can be 10^3 or $10^4 \tau$.

Therefore, to get decent answers, we must difference Eq. (32) fully implicitly, i.e.,

$$\frac{U^{(n+1)} - U^n}{(\Delta t)} = \vec{\nabla} \cdot D \vec{\nabla} U^{(n+1)}, \quad (33)$$

where U^n is U at the end of the n th time step. Fully implicit differencing has the advantage that if $(\Delta t) \gg \tau$, the left side of Eq. (33) is negligible compared to the right side and so we are solving for the steady-state solution. Thus, we can take time steps $(\Delta t) \approx \tau' \approx 10^3$ or $10^4 \tau$. Fully implicit differencing has the additional advantage of unconditional stability.

When we difference $\vec{\nabla} \cdot D \vec{\nabla}$ on our Lagrangian grid, it becomes some finite difference matrix M and we have

$$\frac{U^{(n+1)} - U^n}{(\Delta t)} = MU^{(n+1)},$$

or

$$[I - (\Delta t)M] U^{(n+1)} = U^n. \quad (34)$$

U^n is now a vector $U_{(k,f)}^n$ where (k,f) label the zones in our two-dimensional grid. M is typically the sum of three terms

$$M = M_K + M_L + M_D,$$

where M_K (K sweep operator) couples $U_{(k,f)}$ to $U_{(k+1,f)}$ and $U_{(k-1,f)}$, M_L (L sweep operator) couples $U_{(k,f)}$ to $U_{(k,f+1)}$ and $U_{(k,f-1)}$ and M_D (diagonal coupling term) couples $U_{(k,f)}$ to $U_{(k+1,f+1)}$, $U_{(k-1,f-1)}$, $U_{(k+1,f-1)}$, and $U_{(k-1,f+1)}$.

Equation (34) is a very large system of linear equations [real problems typically have 1000 to

6000 zones (equations)], and its solution has in the past presented such formidable difficulties that instead of solving it, computer modeling codes like LASNEX used an approximation to Eq. (34) [i.e., butchering of Eq. (34)] called operator splitting.

In particular, LASNEX once used

$$\begin{aligned} U^{(n+1)} &= [I - \Delta t (M_K + M_L + M_D)]^{-1} U^n \\ &\approx (I - \Delta t M_K)^{-1} (I - \Delta t M_L)^{-1} U^n. \end{aligned} \quad (35)$$

The approximate expression [right side of Eq. (35)] is easily and rapidly evaluated by tridiagonal back-substitution, but the approximation is really only valid for $\Delta t < \tau$, and only if the K and L lines are orthogonal. Since both of these restrictions are usually violated in real problems, this approximation caused many anomalies in trying to model laser fusion.

A new method for solution of systems like Eq. (34), the Incomplete Cholesky-Conjugate Gradient (ICCG) method, has been generalized so as to apply to Eq. (34) and has been used on real problems.⁵³ This method has proved enormously more powerful than any previous method. With this new method, it is possible to solve Eq. (34) exactly, and do so rapidly enough so that the code does not run appreciably slower than it did with the old operator-splitting approximation. Furthermore, the new method is iterative and so takes full advantage of the fact that we often have a good initial guess for the solution vector of Eq. (34), namely U^n from the last cycle.

Finally a new way of differencing $\vec{\nabla} \cdot D \vec{\nabla} U$ on a Lagrangian grid has been developed⁵⁴ that has all the following highly desirable properties:

- When the characteristic gradient length of U is much larger than the zone size, $MU = \vec{\nabla} \cdot D \vec{\nabla} U$.
- $(I - \Delta t M)$ is positive definite which insures unconditional numerical stability.
- M is symmetric, which ensures exact energy conservation.
- If the K and L lines of the mesh are orthogonal, $M_D = 0$ and M_K and M_L are just the standard three-point difference schemes for

$$\frac{d}{dx} D \frac{dU}{dx}$$

on a line. Thus, in this special case we reduce to the standard well-tested way of differencing on an orthogonal mesh.

The new way of differencing $\vec{\nabla} \cdot D \vec{\nabla} U$ has been put into LASNEX electron thermal conduction, ion thermal conduction, and radiation transport both for multigroup photonics and for three-temperature calculations. A hand-coded package that solves systems like Eq. (34), using the ICCG method, has been written by Dick von Holdt of LLL and incorporated into LASNEX. All this is in the production version of LASNEX and is being widely used for both laser, electron beam, and ion beam fusion design. A very appealing feature of the ICCG method is its reliability. The new version of LASNEX has been used now for upwards of 900 h of CPU time and the ICCG method has yet to find a LASNEX problem where Eq. (34) couldn't be solved to six-place accuracy in just a few iterations (always less than 50 iterations and usually less than 25).

The new code has produced dramatic changes in various problems. Figure 4-41 shows a model problem on which the new code was compared with the old LASNEX (with operator splitting). The problem is a slab of uniform material with a 10^{-4} keV temperature sink placed along the left boundary and a 81-keV temperature source placed along the right boundary. The initial temperature of the whole slab is 10^{-4} keV and all physics is turned off except electron conduction. The electron specific heat is held constant throughout the problem. The upper and lower boundaries are reflection boundaries so this is really just a one-dimensional problem and the isotherms should be straight vertical lines, which move across from source to sink until they reach their steady-state position where they stop. Figure 4-41 shows the way the problem was zoned (75 by 75 zones), and the question is how badly will the code be fooled by the highly skewed zoning (which is typical of real problems) and not realize that this is just a one-dimensional problem. Figure 4-42 shows just the source regions and the $K = 39$ mesh line, which gives an indication of the skewed zoning. The isotherms in Figs. 4-43 and 4-44 are presented against the background of Fig. 4-42. Isotherms are shown for $T_e = 1, 5, 20, 40$, and 60 (keV). Since we are diffusing in radiation energy density $= CT_e$, the steady-state solution is given by

$$T_e(Z) = 10^{-4} \text{ (keV)} + [81 \text{ keV} - 10^{-4} \text{ keV}] Z$$

Fig. 4-41. Zoning for model problem of radiation diffusion through a slab. Zones on right edge are of a 3-keV source. Zones on left edge are of a 0.1-keV sink. Steady-state isotherms should be vertical straight lines. How badly will the code be fooled by the skewed zoning?

Fig. 4-42. Source regions and $K = 39$ mesh line. This figure serves as background for Figs. 4-43 and 4-44; K lines 1, 2, 39, 77, and 78 and L lines 1 and 76.

Fig. 4-43. Steady-state isotherms as calculated by old LASNEX.

Fig. 4-44. Steady-state isotherms as calculated by new LASNEX with ICCG.

Thus the last three isotherms divide the slab approximately into fourths. Figures 4-43 and 4-44 show the steady-state solution (they are the final frames of movies showing the whole time development of the problem) as calculated by old LASNEX and new LASNEX. Only the new method does a decent job on this model problem.

Dramatic changes are also seen in real problems. Zoning anomalies where the heat flow depended strongly on how the problem was zoned have largely disappeared. Formerly, one could obtain radically different final answers by simply interchanging K and L lines. This is no longer true. Implosion asymmetries and jets of material (again strongly zoning dependent and therefore unreal) suddenly disappear when the same problems are run on the new code.

The ability of the ICCG method to invert large sparse, positive definite, and symmetric matrices much faster immediately suggests many other applications such as:

- Diffusive transport in Lagrangian codes with slip surfaces. Since ICCG does not care what the sparsity pattern of the matrix looks like, it can be very useful where other methods for solving matrix equations such as block SOR or ADI become inapplicable because the nonzero elements do not lie in nice diagonal rows.

- Including the implicit coupling between radiation energy density and electron temperature with the multigroup radiation transport.

- Diffusion transport in codes which simulate hydrodynamic turbulence and grid points are free to move independently of each other. Thus a grid point is constantly changing its nearest neighbors, and the matrix M [see Eq. (34)] for diffusive transport across such a grid has a sparsity pattern that looks like ink splattered on a page.

References

53. D. S. Kershaw, *The Incomplete Cholesky — Conjugate Gradient Method for the Iterative Solution of Linear Systems*, Lawrence Livermore Laboratory, Rept. UCRL-78333 Rev. 1 (1977).
54. D. S. Kershaw, *Differencing of the Diffusion Equation in LASNEX*, Lawrence Livermore Laboratory, Rept. UCID-17424 (1977).

Author

D. S. Kershaw

4-3.2 A New Method for Numerically Solving the Transport Equation

A new method for numerical solution of the transport equation has been developed that is an improvement (or refinement) of the P_n or spherical harmonic method.⁵⁵

The transport equation (for slab symmetric problems) has the form

$$\frac{1}{v} \frac{\partial f}{\partial t} + \cos(\theta) \frac{\partial f}{\partial z} = -\sigma f + \int K(\cos(\theta - \theta')) f(\cos(\theta')) d(\cos(\theta')) + S, \quad (36)$$

where $f = f(z, t, \cos \theta, E)$ is the number of particles per unit volume, per unit solid angle, per unit energy.

The right side of the equation describes emission, absorption, and scattering. The left side describes the kinematics.

In the spherical harmonic or P_n method, we expand f in Legendre polynomials

$$f = \sum_{\ell=0}^{\infty} f_{\ell}(z, t, E) P_{\ell}(\cos \theta)$$

and rewrite Eq. (36) as an infinite set of coupled equations, one for each f_{ℓ} . The equation for f_{ℓ} couples it to $f_{\ell+1}$ and to $f_{\ell-1}$. To solve this set of equations numerically, we then throw away all the equations for f with $\ell > L$, and keep only the first $L+1$ equations. The equation for f_L (which we have kept) still contains a term in f_{L+1} (whose value we don't know), and the usual practice has been to just set $f_{L+1} = 0$ in the equation for f_L .

The P_n method has not been much used at LLL because previous work done on it has shown that, for small L ($L = 1, 2, \dots, 5$), one gets poor results — often worse than simple flux-limited diffusion. Reasonable answers require a large L (10 or more) so that the method is not practical for production codes.

In Ref. 55 we show that the poor results obtained with the P_n method using $L \leq 5$ result from setting $f_{L+1} = 0$ in the equation for f_L . We show that this actually violates probability theory. Using probability theory alone, we show that given f_ℓ , $\ell = 0, 1, 2, \dots, L$, one can find upper and lower bounds for f_{L+1} and that setting $f_{L+1} = 0$ usually violates these bounds except in very diffusive regions of the problem. A simple method for calculating these upper and lower bounds is presented, and we show that if in the equation for f_L we give the f_{L+1} term a value compatible with these bounds (instead of setting $f_{L+1} = 0$), greatly improved results can be expected for small L calculations.

This new method is now being put into LASNEX and will be tried on various problems. Numerical results will be forthcoming.

Reference

55. D. S. Kershaw, *Flux Limiting on Nature's Own Way*, Lawrence Livermore Laboratory, Rept. UCRL-78378 (1976).

Author

D. S. Kershaw

4-3.3 Ion-Beam Deposition Physics

Early calculations of ion-beam fusion targets were made using the simplifying assumption that ion energy loss is independent of the temperature of the medium in which the beam is deposited. According to this assumption, the energy loss per unit length is given by an expression of the form⁵⁶

$$\frac{dE}{dx} = \frac{Az^2 n_b}{v^2} \ln \Lambda_b \quad (37)$$

where A is a constant, z is the charge of the ion, n_b is the density of bound atomic electrons, v is the ion velocity, and $\ln \Lambda_b$ is the Coulomb logarithm for the atomic electrons.

In hot matter, this formula can be considerably in error. A correct formulation must include a contribution from free electrons. The energy loss is then of the form⁵⁷

$$\frac{dE}{dx} = \frac{Az^2}{v^2} [n_b \ln \Lambda_b + n_f G(y) \ln \Lambda_f], \quad (38)$$

where n_f is the free electron density and $\ln \Lambda_f$ is the Coulomb logarithm of the free electrons. The function $G(y)$ is given by

$$G(y) = \text{erf}(y) - \frac{2}{\pi^{1/2}} y e^{-y^2}$$

where $y = v/w$ and $w^2 = 2\theta/m_e c^2$. In this expression, θ is the electron temperature given in the same units as the electron rest energy $m_e c^2$. The formula for dE/dx also contains a contribution from the ions in the deposition medium. However, this term is usually very small and we have neglected it in Eq. (38).

In addition to the explicit temperature dependence of y , the quantities n_b , n_f , Λ_b , and Λ_f are functions of both temperature and density.

Statistical range straggling is also an important factor in ion-beam target design. For the increase in energy variance per unit length we derive

$$\frac{d\sigma^2}{dx} = n_b \left(\frac{d\sigma^2}{dx} \right)_b + A m_e n_f G(y) \left[1 + \frac{\ln \Lambda_f}{y^2} \right]. \quad (39)$$

The expression for the contribution from bound electrons $(d\sigma^2/dx)_b$ is discussed in Ref. 56. The quantity 1 in the brackets in Eq. (39) is sometimes neglected⁵⁷ but can be large when compared to $\ln \Lambda_f/y^2$. Equations (38) and (39) have been coded into LASNEX.

In addition to having the correct value of dE/dx in LASNEX, we must also calculate the electron spectrum produced by an ion beam. Assuming that ion-electron scattering is given by the usual Mott formula, we derive a differential electron-energy spectrum of the form

$$\frac{dn}{dE} \propto \frac{1}{E^2} - \frac{1}{2m_e c^2 \gamma^2 E} \quad (40)$$

The maximum electron energy is given by $E_{\max} = 2m_e c^2 (\beta \gamma)^2$. In these formulas, β and γ refer to the ion and have their usual relativistic meanings [i.e., $\beta = v/c$ and $\gamma = (1 - \beta^2)^{-1/2}$].

Because Eq. (40) diverges as $E \rightarrow 0$, it is necessary to impose some $E_{\min}$ as a lower limit to the spectrum. We choose the value of $E_{\min}$ to ensure consistency of Eqs. (38) and (40). Physically, $E_{\min}$ arises because screening limits the maximum impact parameter for scattering.

The capability to generate an electron spectrum given by Eq. (40) has also been coded into LASNEX but is not yet part of the ion-deposition package described above.

References

56. R. D. Evans, *The Atomic Nucleus*, (McGraw-Hill, New York, 1955), p. 632.
57. L. Spitzer, Jr., *Physics of Fully Ionized Gases*, (Interscience, New York, 1962), 2nd ed., p. 120.

Author

R. O. Bangerter

4-3.4 LASNEX Line Postprocessor

To calculate the line emission from a "seed" gas during an implosion, we have constructed a postprocessor code coupled to the LASNEX magnetohydrodynamic computer program. Since the influence of line radiation on the implosion is negligible, it suffices to record the LASNEX-calculated material properties (density, temperature) during the implosion and then perform the line calculations separately. This evaluation, performed by the postprocessor code, requires several distinct calculations.

(1) *Time-Dependent Ionization State of Seed Material.* In the density and temperature regimes of interest, the longest rate constants can be of the order of 100 ps — comparable with the implosion time. Therefore, the time history of the ionization state of the seed must be followed by solving the

time-dependent rate equations. To do this, we take from LASNEX the matter density and temperature at a given time, then use the collisional ionization rates of MacWhirter,⁵⁸ together with radiative and three-body recombination, for temporally advancing the ground state populations of the last four ionization states (lithium-like to fully stripped). In this way we get a time history of the various ionization states for input to the line-emission source function.

(2) *Steady-State Excited State Populations.* In contrast to the ground states, the excited states equilibrate very rapidly relative to the implosion time scale, so for them we use a steady-state determination of the excited state populations from a fixed ground state. Given these populations, the optically thin (resonance) emission intensity is simply $I_n(Z) = A_n(Z) \cdot N_{z,n} \cdot \Delta\tau$.

(3) *Radiative Transfer Effects in Core.* To enhance the line intensity while remaining optically thin enough to still transmit information on the intrinsic line profile, we have chosen for the experiments a seed fill pressure to achieve an optical depth of 10 to 100 at maximum implosion density. Since typical implosion histories show very uniform spatial distribution of the temperature and density in the core region, we use a time-dependent, homogeneous-sphere model for the radiative transfer, solving the two-level transfer equation by the kernel-approximation technique of Avrett and Hummer⁵⁹ using either a Doppler or Lorentz profile appropriate, respectively, to ion thermal broadening and electron impact broadening. The thermal half-width ($\propto \sqrt{T_e}$) and impact half-width [$\propto (N_e \sqrt{T_e})$, from Griem⁶⁰] are calculated from the LASNEX-supplied material properties. The line center optical depth $[(N_e / \Delta\nu) \cdot L]$ involves the ground state seed density [see (1) above] and several matter variables.

(4) *Outer shell attenuation.* Outside the core region, where there is no seed material, the line is merely attenuated, predominately by bound-free absorption from the nearest K-edge. To calculate this, we find the ionization history of each shell constituent (just as for the seed material) and evaluate the bound-free absorption for the hydrogen and helium-like ions at the energy corresponding to the line position.

As output, the postprocessor code yields the time history of the various ionization states plus thin and thick emission powers, the time-integrated emergent line profile, and the outer shell attenuation factors.

References

58. R. Huddleston, S. Leonard, and R. W. P. MacWhirter, "Spectral Line Intensities," in *Plasma Diagnostic Techniques* (Academic Press, New York, 1965), Chap. 5, p. 20.
59. E. H. Avrett and D. G. Hummer, *Mon. Not. R. Astron. Soc.* **130**, 295 (1965).
60. H. R. Griem, *Spectral Line Broadening by Plasmas* (Academic Press, New York, 1974), Chap. IV.6.

Author

D. S. Bailey

4-3.5 Theoretical X-Ray Streak Pictures

A code has been written that uses LASNEX output to produce theoretical x-ray streak pictures. The

resulting x-ray intensity as a function of time and position along the streak slit gives us the ability to make detailed comparisons with experimental implosion histories.

As input, the code uses space- and time-dependent temperatures, densities, and frequency-dependent opacities from the LASNEX simulation of a particular target. We also specify the position and orientation of the pinhole and streak slit, the frequency response of the streak camera assembly, and its resolutions in space and time. The target can be viewed in emission or in absorption by backlighting with a spatially uniform blackbody x-ray source. The code integrates the emission properly attenuated by absorption along the line of sight to the detector plane. The primary output is the streak picture, showing x-ray intensity as a function of time and distance along the slit. The code also produces densitometer traces across this picture.

Author

G. B. Zimmerman

4-4 LASER PLASMA THEORY AND SIMULATION

To design laser fusion targets, we need an understanding of (1) how laser light is absorbed, (2) the energy of the electrons generated, and (3) how these heated electrons are transported into the target. Although none of these topics is well understood quantitatively, we have formulated models which have successfully predicted many important features of our experiments, including non-classical absorption, modest absorption efficiencies, reductions in inverse bremsstrahlung, profile steepening, generation of hot electrons, polarization-dependent light scattering, and time-dependent stimulated reflectivity. Our principal activity this year has been to explore the consequences of these models and search for important effects which have been overlooked.

Our model for light absorption is based on resonance absorption and enhanced heating through ion fluctuations in nonlinearly steepened density profiles. With the basic model^{61,62} that incorporates these effects, we have predicted both the absorption and heated electron energies to within better than a factor of two. In addition, we have predicted and observed the important features⁶² of polarization-dependent light scattering and time-dependent reflectivity. This absorption model, based on plane waves incident onto a plasma slab, has been extended to include the effects of a light beam focused onto glass microspheres. Calculations⁶³ of both the absorption magnitude and its dependence on focusing were in good agreement with experiments.

We have also gained an improved understanding of the heated electron distributions. The heated electron energies due to resonance absorption, in general, do not scale as the square root of the incident light intensity,^{64,65} a result which had been suggested by a cold plasma model widely used to roughly estimate magnitudes. Indeed, some early results shown in Fig. 8-52 of our 1974 Annual Report⁶⁶ indicate a variation of θ_h as I^β , where β is about 0.37 (θ_h is the hot electron temperature, I the incident intensity.) We principally attribute the weaker intensity variation to the fact that the local scale length at the critical density decreases with increasing intensity.⁶⁴ We have also investigated how the background plasma temperature affects the heated temperature. One interesting effect is that the background temperature reduces the amplitude of the resonantly driven waves, an effect which has been explored in a simple model of wave breaking in warm plasmas. This warm plasma model compares favorably with the results of large two-dimensional simulations.

Although it is encouraging that the model for light absorption has been largely consistent with our past experiments, this model is deficient in a number of ways. For example, we expect that the angle and polarization dependence of the absorption is quantitatively overestimated. Infinite plane waves incident onto a plasma slab can be a fair approximation for p-polarized light incident at appreciable angles. However, for normally incident light (or for obliquely incident s-polarized light), it is much more important to understand how the critical surface becomes rippled or distorted. We have examined many of the mechanisms which ripple or dent this surface, including the finite size of the incident light beam, hot spots in the beam, and the formation of bubbles.⁶⁷ Simulations have been carried out with tightly focused light beams to show how the critical surface is dented by ponderomotive forces, and a new code has been written to extend these results to larger focal spots. The qualitative effect is clear: these effects smooth the angle and polarization dependence of the absorption. For example, recent focused beam calculations with ZOHAR have shown about 30% absorption even for normally incident light. Because of the difficulty of predicting in detail the size and scale length of the surface distortions, we are continuing to seek more quantitative results.

We have continued to examine other light absorption mechanisms. One that is commonly overlooked in laser plasma applications is resonance absorption of even normally incident light due to large self-generated dc magnetic fields.⁶⁸ We have examined this mechanism in theory and simulations and have found that absorption results of about 10% are readily obtained provided the magnetic fields are in the multimegagauss range. Short-wavelength ion turbulence in the underdense plasma also enhances the absorption and reduces its polarization dependence. Possible sources of this ion turbulence which we have examined^{69,70} are the electron-ion instability driven by heat flow and the ion-ion instability driven by plasma expansion. We have shown that a modest level of this turbulence, estimated from ion trapping arguments can lead to an absorption of about 10 to 20% in our recent short pulselength experiments. However, we do not yet know the actual level of this turbulence with any confidence. In addition, we have isolated an interesting mechanism for light absorption by fields nonlinearly generated in the skin of a very overdense plasma ($J_\perp \times B_\perp$ heating, where $J_\perp$ is the oscillating electron current in the electric field of the light and $B_\perp$ is its oscillating magnetic field). This effect looks interesting for extremely intense light, such as may be used in future target designs for CO₂ lasers. Lastly, we have examined how relativistic effects introduce and/or modify instabilities driven by intense laser light.

Stimulated scattering through the Brillouin instability continues to be a concern for future targets with longer, shaped pulses and large spot sizes. Thus, we extended our stimulated scattering calculations to study the angular dependence of the scattered light. These calculations emphasize that the scattered light generally comes back into a broad range of angles. We have also formulated some zeroth-order nonlinear estimates of times to be cautious of induced scatter.

Absorbed energy transport into the target is also an important topic for optimum target design. Experimental results and LASNEX simulations have shown that the heat transport is often very inhibited. Self-generated magnetic fields continue to be our favored explanation for this inhibition. We have examined an additional source for these fields: the Weibel instability driven by an anisotropy in the angle of the heated electrons. It was found that this

effect can lead the hot electrons to form into current filaments as they stream into the target.

A simple model for the effect of ion turbulence on heat transport was formulated.⁶⁹ Calculations with this model subsequently carried out at NRL⁷¹ show only a modest reduction (a factor of about 5) of the heat transport from the usual free-streaming limit. We have also examined several mechanisms for a polarization-dependent inhibition of heat transport and have developed a model to describe the effect of flux limiting on ablation. This analytic model compares well with LASNEX simulations and yields new scaling laws for the ablation rate and efficiency.

References

61. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975).
62. W. L. Kruer, R. A. Haas, W. C. Mead, D. W. Phillion, and V. C. Rupert, in *Plasma Physics: Nonlinear Theory and*

Experiments, H. Wilhelmsson, Ed. (Plenum Press, New York, 1977) pp. 64-81.

63. J. J. Thomson, C. E. Max, J. Erkkila, and J. E. Tull, *Phys. Rev. Lett.* **37**, 1052 (1976).
64. E. Valeo, W. Kruer, K. Estabrook, B. Langdon, B. Lasinski, C. Max, and J. Thomson, in *Plasma Physics and Controlled Nuclear Fusion Research* (International Atomic Energy Agency, Vienna, in press).
65. D. Forslund, *Bull. Am. Phys. Soc.* **21**, 1066 (1976).
66. *Laser Program Annual Report — 1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975) p. 400.
67. K. G. Estabrook, *Phys. Fluids* **19**, 1733 (1976).
68. W. L. Kruer and K. G. Estabrook, in *Laser Interaction and Related Plasma Phenomena*, Vol. 4, H. Schwarz and H. Hora, Eds. (Plenum Press, New York, in press).
69. W. H. Manheimer, *Phys. Fluids* **20**, 265 (1977).
70. R. J. Faehl and W. L. Kruer, *Phys. Fluids* **20** 55 (1977).
71. W. Manheimer, D. Colombant, and B. H. Ripin, *Efficient Laser Light Absorption by Ion Acoustic Fluctuations*, Naval Research Laboratory, Rept. 3426 (1976).

Author

W. L. Kruer

4-5 THEORY AND SIMULATION: LASER LIGHT ABSORPTION

4-5.1 Absorption and Harmonic Generation Due to Self-Generated Magnetic Fields

Recent laser-plasma experiments⁷²⁻⁷⁹ have shown that self-generated dc magnetic fields can strongly inhibit electron heat flow. These fields can also introduce a significant amount of light absorption and harmonic generation. Physically, absorption and harmonic generation occur as a result of electrostatic waves resonantly generated by the oscillation of electrons driven by the $v_{\text{ex}} \times B_0$ force where v_{ex} is the quiver velocity of an electron in the laser light field and B_0 is the self-generated dc magnetic field. In contrast to the resonance absorption⁸⁰⁻⁸²

generally considered in laser-target problems, absorption and harmonic generation are operative even for normally incident light. The magnitude of the dc magnetic field (B) — experimentally measured⁷³ as ~ 4 MG — is large enough to make the light conversion to plasma waves sizeable but not large enough to make the critical surfaces inaccessible to the light. (The effects are negligible for the case of radio waves in the ionosphere.⁸⁰)

Although the above physical mechanism is well known,⁸³ its application to laser-plasma targets is novel and potentially important. We are investigating this mode-conversion process in a regime complementary to that studied in magnetic fusion applications.⁸⁴ In the latter, the electron cyclotron frequency (ω_{ce}) is greater than the electron plasma frequency (ω_{pe}), whereas in our applications ω_{ce} is much less than ω_{pe} . For example, for a

neodymium laser with $B = 4$ MG, $\omega_{ce}/\omega_{pe} \approx 0.04$ at the critical density.

Theoretical estimates for coupling, saturation amplitudes, absorption, and harmonic generation are given below and examined in computer simulations for parameters characteristic of recent laser-plasma experiments. Our calculations also suggest that the second-harmonic generation may provide information about both the local scale length near the critical density and the size of the self-generated dc magnetic fields.

Theoretical Estimates for Mode Conversion

The basic mode-conversion process is investigated in a simple geometry. Let $B_0 = B_0 \hat{x}$ and consider the laser light to be normally incident [$k = k(z)\hat{z}$] on a plasma with density $n = n(z)$. The electric vector of the light is orthogonal to B_0 as it enters the plasma from vacuum. From Maxwell's equations and the linearized cold-plasma equations, we can readily get coupled equations for E_y and E_z . Assuming a time dependence of $e^{-i\omega_0 t}$, we find

$$\frac{d^2 E_y}{dz^2} = -\frac{\omega_0^2}{c^2} \epsilon_1 E_y \quad (41)$$

and

$$E_z = -\frac{\omega_{pe}^2}{\omega_0^2 - \omega_{ce}^2} \frac{i\omega_{ce}}{\omega_0} \frac{E_y}{\epsilon_2}, \quad (42)$$

where ϵ_1 and ϵ_2 are the dielectric functions

$$\epsilon_1 = 1 - \frac{\omega_{pe}^2}{\omega_0^2} \frac{(\omega_0^2 - \omega_{pe}^2)}{(\omega_0^2 - \omega_{UH}^2)} \quad (43)$$

and

$$\epsilon_2 = 1 - \frac{\omega_{pe}^2}{(\omega_0^2 - \omega_{ce}^2)}. \quad (44)$$

Here, ω_0 is the light frequency and ω_{pe} is the local electron plasma frequency. Also,

$$\omega_{ce} = \frac{eB_0}{mc}$$

and

$$\omega_{UH} = \sqrt{\omega_{pe}^2 + \omega_{ce}^2}$$

Equation (41) gives the well-known dispersion relation for the extraordinary wave. For laser-pellet applications, $\omega_{ce} \ll \omega_0$, and the cutoff density, n_{cut} (the density at which propagation cuts off for light waves incident from low density), is determined by $\omega_0^2 = \omega_{pe}^2 + \omega_{pe} \omega_{ce}$. Since $\omega_{ce} \ll \omega_0$, this cutoff density is only slightly less than the critical density, n_{cr} (defined by $\omega_0 = \omega_{pe}$). For example, for $(\omega_{ce}/\omega_0) = 0.04$, $n_{cut} = 0.96 n_{cr}$.

As is apparent from Eq. (42), the extraordinary wave is partly longitudinal. This electrostatic field is simply the plasma response to the oscillation of electrons in the $v_{os} \times B_0$ force. This field becomes infinite when $\epsilon_2 = 0$, because the plasma response is then resonant. The resonance occurs at $n_R = n_{cr} [1 - (\omega_{ce}/\omega_0)^2]$, which is essentially the critical density for $\omega_{ce} \ll \omega_0$. Physically, the light is reflected at the cutoff density ($n_{cut} < n_R$), but its electric field tunnels into the higher-density region where upper hybrid waves are resonantly driven. Collisions, thermal corrections, or nonlinear effects keep the resonantly driven field finite. For the light intensities commonly used, E_z is limited by strong wave breaking.

The principal features of this absorption mechanism can be obtained rather simply. Because $E_z = E_d/\epsilon_2$, the behavior of the electrostatic fields is determined by the value of the effective driver field, E_d , at the resonance point. To determine this driver field, we need to estimate E_y at the resonance point. Assuming a locally linear density profile,⁸⁰ we first estimate E_y at the cutoff density by analogy to the well-known Airy-function solution for the $B_0 = 0$ case and then multiply by the exponential decay of the field to the resonance point. The result is

$$E_d \approx 1.3(k_0 L)^{1/6}$$

$$E_L \left(\frac{\omega_{ce}}{\omega_0} \right) \exp \left[- \frac{\pi}{2} (k_0 L) \left(\frac{\omega_{ce}}{\omega_0} \right)^{3/2} \right], \quad (45)$$

where L is the density scale length and k_0 and E_L are, respectively, the wave number and electric field of the light in vacuum. Although an improved value of E_d can be obtained by a detailed solution of Eq. (41), as is done in the simulations, this simple estimate will suffice to illustrate some of the scalings.

Several results can be readily obtained. First, the maximum plasma-wave amplitude as determined by wave breaking is

$$E_d \approx \frac{E_d}{\sqrt{X_d/L} + (\sqrt{3} \lambda_{De}/L)}, \quad (46)$$

where $X_d = (eE_d/m\omega_0^2)$ and λ_{De} is the electron Debye length. The second term in the denominator approximates a thermal correction to the cold-plasma prediction. In addition, the absorption efficiency, f , is obtained by invoking energy balance, such that

$$f \frac{cE_L^2}{8\pi} = \int dz \frac{\nu E_p^2(z)}{8\pi},$$

where ν is the magnitude of the plasma-wave damping (either linear or nonlinear). As long as $\nu \ll \omega_0$, the integral is independent of the detailed value of ν (the height of the resonance is $\alpha 1/\nu$ and the width of the resonant region is $\alpha \nu$). Hence, we obtain

$$f \approx 5(k_0 L)^{4/3} \left(\frac{\omega_{ce}}{\omega_0} \right)^2 \exp \left[- \pi (k_0 L) \left(\frac{\omega_{ce}}{\omega_0} \right)^{3/2} \right]. \quad (47)$$

Defining $\beta \equiv (k_0 L)^{1/3} (\omega_{ce}/\omega_0)^{1/2}$, we have $f \approx \beta^4 \exp(-\pi \beta^3)$, and so the estimated absorption peaks at approximately 40% for $\beta \approx 0.8$. This behavior is easy to understand physically. As $\beta \rightarrow 0$ (for example, for $B_0 = 0$), the coupling goes to zero.

For large β , the resonance point becomes inaccessible. For laser-pellet applications, we will see that β can be $O(1)$, based on recent measurements of the magnitude of the self-generated magnetic fields.

We note that the basic conversion mechanism is linear, although the size of the self-generated magnetic field will depend on both the intensity and the uniformity of the irradiation. We also note that this mode conversion is operative whenever $E_L \times B_0 \neq 0$. In the toroidal fields due to $\nabla n \times \nabla T$ sources, the coupling then occurs at preferred locations in the focal spot. However, we emphasize that there are a number of other sources of magnetic fields that may change their spatial structure.

Computer Simulations of Mode Conversion

To test this coupling, we have carried out simulations using an electromagnetic, relativistic particle code.⁸⁵ In choosing the parameters of a representative simulation, we are chiefly motivated by the recent NRL work^{72,73}; in particular, we choose $B_0 = 4$ MG, $I = 10^{16}$ W/cm² (neodymium light), and a rather short density-gradient length, $L/\lambda_0 = 1.5$. Such a short gradient is also consistent with some recent measurements of the density scale lengths in laser-produced plasmas.⁸⁶ For simplicity, we use a fixed neutralizing ion background because the basic conversion mechanism is independent of ion motion. In the code, the light is normally incident on an inhomogeneous plasma slab. To model the dc magnetic fields shown by the fluid calculations, we simply impose a constant magnetic field that is orthogonal both to the density gradient and to the electric-field vector of the incident light.

The strong plasma-wave generation near the critical density is clearly shown in Fig. 4-45, an electron-phase-space plot from the simulation. The electrostatic field is clearly limited by wave breaking and reaches a peak value of $eE_p/m\omega_0 c \approx 0.15$. (The simple estimate in Eq. (46) predicts $eE_p/m\omega_0 c \approx 0.17$.) The time-averaged, laser-light absorption measured in the simulation is about 15%, also in reasonable agreement with the Eq. (47) estimate of 16%. Although modest, this absorption does not require oblique incidence or p-polarization and hence will reduce the sensitivity of mode conversion to the angle of incidence and polarization.

Fig. 4-45. Plot of electron phase space (p_x vs x) from the simulation at $\omega_0 t = 125.2$. The parameters are $eE_L/m\omega_0 c = 0.1$, $v_e/c = 0.1$, $k_0 L = 10$, $\omega_{ce}/\omega_0 = 0.04$, and fixed ions.

We have also conducted a number of simulations, varying both the density gradient and the size of the magnetic field. As shown in Fig. 4-46, the calculated electrostatic field is quite large and scales in reasonable agreement with the theoretical estimates.

Such close agreement is probably fortuitous because our theoretical estimates are rather crude. The absorptions measured in these short-time simulations also scale in reasonable agreement with the theoretical estimate. For example, when $\beta = 0.6$, we

Fig. 4-46. Peak electrostatic field from the simulations as a function of (a), the magnitude of the magnetic field ($k_0 L = 10$) and (b), the density-gradient scale length ($B = 2.5$ MG). The dashed line represents our theoretical estimate. The parameters of the simulations are $eE_L/m\omega_0 c = 0.1$, $v_e/c = 0.1$ (v is the electron thermal velocity), and fixed ions.

find an absorption of approximately 30% (the estimated value is 35%). We emphasize that both the actual scale lengths and the values of B_0 in the experiments are not well known and depend on such features as energy-transport inhibition and the radial-intensity profile of the light beam. However, for parameters that are characteristic of those recently measured, the self-generated magnetic field can clearly introduce an interesting amount of absorption.

To amplify this point, we can compare the mode conversion introduced by a magnetic field with that introduced by oblique incidence. Comparing our results from the above section with similar estimates from a case with no magnetic field (but with obliquely incident p-polarized light), we readily see that the presence of the magnetic field corresponds to an angle of incidence of $\theta \approx \sin^{-1}(\omega_{ce}/\omega_0)^{1/2}$. Thus, for $\omega_{ce}/\omega_0 = 0.04$, $\theta \approx 11^\circ$. This is approximately the mean angle of incidence (averaged over energy) for light focused by an $f/2$ lens onto a planar target. Hence, when large-f-number lenses are used, mode conversion resulting from a self-generated field can dominate that due to oblique incidence. (This is also true when clamshells are used to focus light nearly normally onto spherical targets.)

Second-Harmonic Generation

The mode conversion gives rise to large electrostatic fields near the critical density and thus we can expect a sizeable level of second-harmonic emission. This emission can be computed simply by iterating the wave equation to obtain

$$\left(\frac{d^2}{dz^2} + \frac{4\omega_0^2}{c^2} \right) E_y^{(2)} = \frac{-4\omega_0^2}{c^2} \frac{4\pi}{2i\omega_0} J_y^{(2)}$$

where the parenthetical superscripts refer to the component at frequency $2\omega_0$. Also,

$$J_y^{(2)} = -n_0 e v_y^{(2)} - n^{(1)} e v_y^{(1)},$$

where n_0 is the background density, $n^{(1)}$ is the density fluctuation, and $v_y^{(1)}$ is the oscillation velocity of electrons in the transverse field. Using our crude es-

timate [Eq. (45)] for the effective driver, noting that $J_y^{(2)}$ is very peaked near the critical density, and taking the magnetic field as small, we obtain

$$\frac{E_y^{(2)}}{E_L} \approx 2.7 \left(\frac{eE_L}{m\omega_0 c} \right) (k_0 L)^{2/3} \beta^2 \exp(-\pi\beta^3).$$

Here, $E_y^{(2)}/(E_L)$ is the amplitude of the back-reflected, second-harmonic light (the incident laser light) in vacuum.

This simple estimate is compared with 1.5-dimensional simulation results in Fig. 4-47. The dependence on both magnetic field and density scale length is in reasonable agreement. The second-harmonic emission can be quite large when the local scale length is long. However, with scale lengths more characteristic of steepened profiles, the energy in the second harmonic is about 1% of the incident light energy. A similar strong dependence of the magnitude of the second-harmonic emission on local scale length has also been found⁸⁷ for the emission that accompanies resonance absorption of obliquely incident light. Hence, the magnitude of the second-harmonic emission provides an indirect indication of the local scale length near the critical density.

The reduction of the $2\omega_0$ emission by profile steepening suggests a simple explanation of some recent measurements at Limeil.⁸⁸ At low intensities, the second-harmonic emission increases in magnitude as the square of the incident light intensity. However, at a critical intensity of approximately 5×10^{13} W/cm² (neodymium laser light), the dependence of this emission on intensity changes abruptly. Simple estimates show that this is the intensity at which significant nonlinear profile steepening near the critical density is expected, reducing the emission.

Finally, our simulations also show that frequency structure in the second harmonic light may provide a means for detecting the presence of large self-generated magnetic fields. As shown in Fig. 4-48, we observe a satellite line shifted down in frequency from $2\omega_0$ by an amount approximately equal to ω_{ce} . When the size of the magnetic field is doubled, the frequency shift becomes twice as large, confirming its dependence on B_0 . Such frequency structure may arise, for example, from the coupling of different Bernstein modes. An analytic theory of the structure should account for finite Larmor-radius effects.

A magnetic-field-induced line structure in the $2\omega_0$ light may, indeed, have been observed in the Limeil experiments.⁸⁸ A satellite line was observed to be shifted in frequency from the main line at $2\omega_0$ by an amount which was too large to be accounted for by an ion acoustic wave. If attributed to a magnetic field, the magnitude of the shift would correspond to a field of about 0.5 MG, a plausible value at the light intensity used in these experiments.

It is worth noting that self-generated magnetic fields can also account for a frequency splitting of the $3/2 \omega_0$ light (see Refs. 88 and 89). In simulations of stimulated scattering in underdense plasma with $n \approx 0.25 n_{ce}$, we found that the incident light decayed into scattered light waves plus several different Bernstein modes. The result was a spectrum of electrostatic waves near $\omega_0/2$ but differing in frequency by an amount proportional to ω_{ce} . These electrostatic waves, in turn, scatter the incident light to give a split line near $3/2 \omega_0$.

Summary

In conclusion, our calculations show that self-

generated magnetic fields can play a significant role in laser-plasma interactions. These fields introduce resonance absorption, even of normally incident light, and thus can strongly reduce the dependence of linear-mode conversion on angle of incidence and polarization. In addition, these magnetic fields provide an additional mechanism for second harmonic generation. Several features of this harmonic emission may provide indirect information about both the local density gradients and the size of the magnetic fields. More detailed calculations must wait for a better understanding of the size and structure of the self-generated fields.

References

72. B. H. Ripin, P. G. Burkhalter, F. C. Young, J. M. McMahon, D. G. Colombant, S. E. Bodner, R. R. Whitlock, D. J. Nagel, D. J. Johnson, N. K. Winsor, C. M. Dozier, R. D. Bleuch, J. A. Stamper, and E. A. McLean, *Phys. Rev. Lett.* **34**, 1313 (1975).
73. J. A. Stamper and B. H. Ripin, *Phys. Rev. Lett.* **34**, 138 (1975); J. A. Stamper, K. Papadapoulos, R. N. Sudan, S. O. Dean, E. A. McLean, and J. M. Dawson, *Phys. Rev. Lett.* **26**, 1012 (1971).
74. J. B. Chase, J. M. LeBlanc, and J. R. Wilson, *Phys. Fluids* **16**, 1142 (1973).

Fig. 4-47. The second harmonic field as a function of (a), the magnetic field where $k_0 L = 10$ and (b), the density scale length where $(\omega_{ce}/\omega_0) = 0.05$. The dashed lines represent our theoretical estimates. For these results, a 1.5-dimensional code was used; $v_{os}/c = 0.1$, and $v_e/c = 0.09$.

Fig. 4-48. The Fourier-analyzed electric field of the incident and reflected light from a simulation using a 1.5-dimensional code. The parameters are $v_{0s}/c = 0.1$, $v_e/c = 0.09$, $\omega_{ce}/\omega_0 = 0.1$, and $k_0 L = 20$.

75. R. Haas, W. Mead, W. Kruer, D. Phillion, H. Kornblum, J. Lindl, D. MacQui, V. Rupert, and K. Tirsell, *Phys. Fluids* **20**, 322 (1977).
76. N. K. Winsor and D. A. Tidman, *Phys. Rev. Lett.* **31**, 1044 (1973); D. A. Tidman and R. A. Shany, *Phys. Fluids* **17**, 1207 (1974).
77. J. J. Thomson, C. E. Max, and K. G. Estabrook, *Phys. Rev. Lett.* **35**, 663 (1975).
78. E. Lindman, D. Forslund, J. Kindel, K. Lee, and W. Shanahan, *Bull. Am. Phys. Soc.* **20**, 1378 (1975).
79. G. H. Dahlbacka, W. C. Mead, C. E. Max, and J. J. Thomson, *Calculations of Self-Generated Magnetic Fields in Parylene Disk Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-77150 (1975).
80. V. L. Ginzburg, *The Propagation of Electromagnetic Waves in Plasmas* (Pergamon Press, London, 1965), Chs. 4, 5.
81. J. P. Friedberg, R. W. Mitchell, R. L. Morse, and L. I. Rudinski, *Phys. Rev. Lett.* **28**, 795 (1972); D. Forslund, J. M. Kindel, and E. L. Lindman, *Phys. Rev. A* **11**, 679 (1975); K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975).
82. J. S. DeGroot and J. Tull, *Phys. Fluids* **18**, 672 (1975); P. Koch and J. Albritton, *Phys. Rev. Lett.* **32**, 1420 (1975).
83. T. Stix, *Phys. Rev. Lett.* **6**, 878 (1965).
84. J. J. Schuss and J. C. Hosea, *Phys. Fluids* **18**, 727 (1975).
85. A. B. Langdon and B. F. Lasinski, in *Methods in Computational Physics*, J. Killeen, B. Alder, S. Fernbach, and M. Rotenberg, Eds. (Academic Press, New York, 1976), Vol. 16, pp. 327-365.
86. T. P. Donaldson and I. J. Spalding, *Phys. Rev. Lett.* **36**, 467 (1976).
87. N. S. Erokhin, S. S. Moiseev, and V. V. Mukhin, *Nucl. Fus.* **14**, 333 (1974); K. Eidmann and R. Sigel, *Phys. Rev. Lett.* **34**, 799 (1975).
88. J. L. Bobin, in *Plasma Physics: Nonlinear Theory and Experiments*, H. Wilhelmsson, Ed. (Plenum Press, New York, 1977), pp. 102-121.

89. H. C. Pnat, K. Eidmann, P. Sachsenmaier, and R. Sigel, *Optics Comm.* **16**, 396 (1976).

Authors

W. L. Kruer

K. G. Estabrook

4-5.2 $J_L \times B_L$ Plasma Heating by Very Intense Laser Light

Most calculations of laser light absorption have been in an intensity regime such that $v_L/c \gtrsim 0.2$. Here $v_L = eE_L/m\omega_0$, where E_L is the free-space value of the electric field of the light and ω_0 is its frequency. There are now lasers capable of providing much higher intensities, for example, $v_L/c = O(1)$. In fact, in fusion target designs for future CO_2 lasers, intensities in this regime are sometimes used. Here, we briefly examine an interesting mechanism for the absorption of light in this intensity regime.

Fig. 4-49. Electron phase space plot (p_x vs x) from the 1.5-dimensional simulation. The parameters are $n = 5 n_{cr}$, $v_L/c = 1.0$, $v_e/c = 0.09$, and fixed ions.

The basic mechanism⁹⁰ is easy to understand. For simplicity, consider very intense light normally incident onto an overdense plasma slab. For every intense light, the plasma density will be sharply steepened to a value much larger than the critical density (n_{cr}). As the light decays into this overdense plasma, the current (J_L) due to electrons oscillating in the electric field of the light couples with its oscillating magnetic field (B_L) to produce an electrostatic field at $2\omega_0$. (Of course, the component of this force at zero frequency contributes to the light pressure.) Note that the field is confined to a region which is less than or about equal to few times the relativistic skin depth⁹¹ for the light in the overdense plasma. It is not, in general, resonantly built-up except in a thin surface layer with density approximately equal to $4 n_{cr}$. However, the (assumed) collisionless electrons can still be heated as they nonadiabatically interact with the localized field. The amount of absorption is proportional to the square of the electric field component at $2\omega_0$.

Hence, the fractional absorption is proportional to $(v_L/c)^2$ and is expected to be significant only for $v_L/c = O(1)$.

To see this basic mechanism in its simplest content, we have carried out some simulations with a 1.5-dimensional electromagnetic, relativistic particle code.⁹² In the code, we propagate light from vacuum into an overdense slab of plasma. As a first example, we considered an overdense plasma slab with a density of $5 n_{cr}$, an electron temperature of 4 keV, fixed ions, and an intensity of 10^{18} W/cm² for $1.06\text{-}\mu$ light. The strong heating is apparent in the electron-phase-space plot shown in Fig. 4-49. In this example, the fractional absorption is approximately equal to 12%. To confirm the mechanism, we checked the frequency of the electrostatic field responsible for the heating, and it was indeed at $2\omega_0$.

Of course, the magnitude of the absorption depends on the density of the overdense plasma slab. This is as expected since the penetration depth of

Fig. 4-50. Surface plot of the time-averaged magnetic field from the 2.5-dimensional simulation. The time average is taken over the interval $\omega_0 t = 62.8$ to $\omega_0 t = 125.7$. The maximum value of B is 1.2×10^{-7} Gauss. The parameters are $n = 5 n_{cr}$, $v_L/c = 1.0$, $v_e/c = 0.09$, and fixed ions.

the light into the plasma becomes less as the density increases. A simulation with the same parameters as above except with a plasma density of $100 n_{cr}$ confirms this qualitative trend: a fractional absorption of about 5% was then computed. We note that, on the basis of pressure balance, we expect the plasma to steepen to approximately this density for the assumed temperature.

Observe from Fig. 4-49 that the heated electrons are beamed into the slab. We simulated the problem shown in this figure with a 2.5-dimensional particle code⁹³ and found that these beamed electrons generate dc magnetic fields as they stream into the slab. As shown in Fig. 4-50, these fields become very large in magnitude; i.e., about 10^{-7} Gauss in this example. We attribute this field generation to the Weibel instability,^{94,95} which is driven by the anisotropy in angle of the heated electrons. The wavelength of the fields are approximately the longest unstable wavelength predicted by linear theory.

Finally we also carried out some simulations allowing for ion motion. These simulations confirmed the enormous density steepening due to the laser-light pressure at these high intensities. The same heating mechanism isolated in the above

simulations was observed, augmented, however, by additional heating along the electric vector of the incident light, which is introduced by surface ripples.

In summary, we have isolated an interesting mechanism for the absorption of extremely intense laser light. This heating mechanism produces beamed electrons, which generated dc magnitude fields. Fractional absorptions of about 5-10% by this mechanism were found for light with intensity such that $v_L/c \sim 1$.

References

90. A similar mechanism has been investigated by D. Ensley and R. White of LLL for microwave heating.
91. P. K. Kaw and J. Dawson, *Phys. Fluids* **13**, 472 (1970).
92. W. L. Kruer, K. G. Estabrook, and K. H. Sinz, *Nucl. Fusion* **13**, 952 (1973).
93. A. B. Langdon and B. F. Lasinski, in *Methods in Computational Physics*, edited by J. Killeen et al. (Academic, N.Y., 1976), Vol. 16.
94. E. S. Weibel, *Phys. Rev. Lett.* **2**, 83 (1959).
95. E. Lindman, D. Forslund, J. Kindel, K. Lee, and W. Shanahan, *Bull. Am. Phys. Soc.* **20**, 1378 (1975).

Authors

K. G. Estabrook
W. L. Kruer

4-5.3 Interaction of Focused Laser Beams with Nonspherical Targets

In the last annual report, we described a method for numerical and analytical calculation of the interaction of focused beams with a spherical plasma.^{96,97} We separated the light into two modes (Debye potentials), one called the transverse magnetic or TM mode and corresponding to a p-polarized wave, and the other called the transverse electric or TE mode and corresponding to an s-polarized wave. These potentials, from which any component of the electromagnetic field may be derived, are expanded in terms of the Legendre functions; i.e.,

$$\begin{pmatrix} \chi \\ \psi \end{pmatrix} = \sum_{\ell} \begin{pmatrix} \chi_{\ell}(kr) \cos \phi \\ \psi_{\ell}(kr) \sin \phi \end{pmatrix} P'_{\ell}(\cos \theta) \chi_{\ell}(kr), \quad (48)$$

where k is the free-space wave vector, ϕ the azimuthal angle, and θ the polar angle. The consequence of spherical symmetry is such that the χ , and ψ , modes are independent. Thus, we only need to solve a linear second-order differential equation in the plasma and to match the boundary conditions to those of incoming waves.

However, in a real situation, the target is not spherical. Because of asymmetric heating, the expansion is generally ellipsoidal. Also, there is a strong possibility of a rippled critical surface as a result of plasma instability. Accordingly, we have begun to extend our analysis to the case where the plasma dielectric function is given by

$$\epsilon = \epsilon_0(r) + \sum_{n=1}^{\infty} \epsilon_n \cos n\theta. \quad (49)$$

Low n values correspond to ellipsoidal blowoff, whereas large n values (~ 10) correspond to surface rippling. In the future, we plan to include a ϕ asymmetry.

However, a difficulty now arises because the ψ , χ , modes are no longer independent. There is

coupling between various ℓ numbers of the same mode as well as between the two modes. Physically, this means that the angles of the various rays are being scattered both in and out of the plane of incidence. We describe here a formal method for solving this problem and present some analytical solutions that we have found in various limits.

The basic formalism we use is taken from Gutman⁹⁸ where three classes of vector eigenfunctions are defined

$$\begin{aligned} \underline{L}_{\ell m} &= (\psi_{\ell m}/r) \hat{r}, \\ \underline{M}_{\ell m} &= \nabla_0 \psi_{\ell m}/\kappa r, \\ \underline{N}_{\ell m} &= \underline{M}_{\ell m} \times \hat{r}, \end{aligned} \quad (50)$$

where

$$\psi_{\ell m} = A_{\ell m} P_{\ell}^m(\cos \theta) \begin{pmatrix} \cos m\phi \\ \sin m\phi \end{pmatrix} \quad (0 \leq m \leq \ell),$$

$$\kappa = \sqrt{\ell(\ell+1)},$$

$$\nabla_0 = \frac{\partial}{\partial \theta} \hat{\theta} + \frac{1}{\sin \theta} \frac{\partial}{\partial \phi} \hat{\phi},$$

and $A_{\ell m}$ is a normalization factor. For a linearly polarized beam, $m = 1$. The TM-like mode follows $\cos \phi$; the TE-like mode follows $\sin \phi$. We specialize Gutman's treatment to only allow $\epsilon(r, \theta)$ and constant magnetic permeability, μ .

We define $\underline{\chi}$ as a vector whose components are the ℓ -modes $\{\chi_{\ell}\}$; $\underline{\psi}$ is defined similarly. We can find coupled matrix equations for $\underline{\chi}$ and $\underline{\psi}$:

$$\begin{aligned} \kappa \epsilon_1 \cdot \frac{1}{\kappa} \frac{d}{dr} \epsilon_2^{-1} \cdot \frac{d\underline{\chi}}{dr} + \left(k^2 \epsilon_1 - \frac{\kappa^2}{r^2} \right) \underline{\chi} \\ = -i k \kappa \epsilon_1 \cdot \frac{1}{\kappa} \frac{d}{dr} \epsilon_2^{-1} \cdot \epsilon_3 \cdot \underline{\psi}, \end{aligned} \quad (51)$$

$$\begin{aligned} \left[\frac{d^2}{dr^2} + k^2 \left(\epsilon_2 - \epsilon_3 \cdot \epsilon_2^{-1} \cdot \epsilon_3 \right) - \frac{\kappa^2}{r^2} \right] \underline{\psi} \\ = -i k \kappa \epsilon_3 \cdot \epsilon_2^{-1} \cdot \frac{d\underline{\chi}}{dr} \end{aligned} \quad (52)$$

where the coupling matrices are given by

$$\begin{aligned}\epsilon_{1\ell\ell'} &= \int \epsilon_{\ell\ell 1} \cdot \ell_{\ell'1} \sin \theta d\theta d\phi, \\ \epsilon_{2\ell\ell'} &= \int \epsilon_{\ell\ell 1} \cdot M_{\ell'1} \sin \theta d\theta d\phi, \\ \epsilon_{3\ell\ell'} &= \int \epsilon_{\ell\ell 1} \cdot N_{\ell'1} \sin \theta d\theta d\phi.\end{aligned}\quad (53)$$

For a focused laser beam, most of the energy is in modes for which $\ell > 10$. In such cases, we can use the large- ℓ expansion for P_ℓ' and obtain

$$\begin{aligned}\epsilon_{1\ell\ell'} &= \epsilon_{2\ell\ell'} = \epsilon_0 \delta(\ell - \ell') \\ &+ \sum_n \frac{\epsilon_n}{2} \delta(\ell - \ell' \pm n), \\ \epsilon_{3\ell\ell'} &= \sum_n \frac{n\epsilon_n}{\ell\ell'} \left[\delta(\ell - \ell' + n-1) \right. \\ &\left. + \delta(\ell - \ell' + n-3) + \delta(\ell - \ell' - n+1) \right].\end{aligned}\quad (54)$$

Thus far, we have obtained analytical expressions for χ and ψ in two limits: $n = 1, \epsilon_1 \ll 1$ and $n \gg 1, \epsilon_n \ll \nu/\omega$ (ν is the plasma absorption rate). In the first case, there is not much effect on absorption but the focusing distance for maximum absorption is displaced. In the second case, we have not yet progressed to the point of evaluating absorption and scattering. However, we are attempting to write a code analogous to that of Erkkila⁹⁶ that will be able to handle the general case of nonsymmetrical targets.

References

96. J. H. Erkkila, *Laser Light Scattering and Absorption in Dense Spherically Symmetric Plasmas*, Lawrence Livermore Laboratory, Rept. UCRL-51914 (1975).
97. J. J. Thomson, C. E. Max, J. Erkkila, and J. E. Tull, *Phys. Rev. Lett.* **37**, 1052, (1976).
98. A. L. Gutman, *Radio Eng. and Electr. Phys.* **10**, 1363, (1965).

Authors

J. J. Thomson

D. L. Wright

4-5.4 Relativistic Effects in Laser Plasma Interactions at High Intensities

For laser intensities of 10^{17} W/cm² at Nd wavelengths and 10^{15} W/cm² for CO₂ lasers, the oscillating velocity of a plasma electron in the laser electric field becomes an appreciable fraction of the speed of light. Likewise, at hot electron temperatures above 100 keV, the electron thermal velocity is no longer much smaller than c . Realizing that the Argus laser here and the new CO₂ systems at Los Alamos are in or near this regime, we have begun to consider how plasma processes may be modified by relativistic effects.

Our present studies emphasize two areas in particular. First, we have examined how relativity changes the well-known oscillating two-stream (OTS) instability and filamentation processes near the critical density. We find that growth rates can be enhanced by the inclusion of weak relativistic effects near the critical surface. Second, we have studied stimulated scattering instabilities (such as Raman and Brillouin) in the underdense plasma region, emphasizing the new effects of very high electron temperatures. Resonant Raman scattering is suppressed, being replaced by a modulational, or forward scattering instability in which resonant plasma oscillations are convected along with the electromagnetic waves. Stimulated Brillouin scattering is found to persist in a modified form at very high electron temperatures.

Modulational Instabilities Due to Weak Relativistic Mass Corrections

At high intensities (about 10^{17} W/cm² for Nd), modulational instabilities due to weak relativistic effects begin to compete in terms of growth rate with the conventional forms, such as OTS instability and filamentation. Although the relativistic mass corrections are small, no ion motion need occur. Hence the growth rate is rapid compared to the usual forms, in which the nonlinear coupling is by ion perturbations driven up by ponderomotive forces. Our new, more general theoretical analysis includes and unifies simple examples already known, predicts new branches, and shows the enhancement, due to relativistic effects, of OTS, filamentation, and other conventional forms of modulational instabilities.

The main features of this analysis are seen in a fluid analysis with a pump field near critical density. To third order in the pump velocity $v^{(0)}(t)$ and first order in the perturbation $v^{(1)}(x, t)$, the electron momentum equation in a frame of reference oscillating with the pump is

$$\begin{aligned} \frac{\partial}{\partial t} \left(\left[1 + \frac{1}{2c^2} v^{(0)2} + \frac{1}{c^2} \tilde{v}^{(0)} \tilde{v}^{(0)} \right] \cdot \tilde{v}^{(1)} \right) \\ = \frac{q}{m} \left(\tilde{E}^{(1)} + \frac{1}{c} \tilde{v}^{(0)} \times \tilde{B}^{(1)} \right) - \frac{1}{\rho_0} \nabla \cdot p^{(1)}. \end{aligned} \quad (55)$$

The relativistic, nonlinear mode-coupling terms appear in the square bracket. (In this and subsequent equations, scalar quantities are to be interpreted as multiplying the unit tensor $\underline{1}$.) The perturbation is a linear combination of Fourier modes with frequencies $\omega_n = \omega + n\omega_0$ and wavevector $\underline{k}$. With $\omega \ll \omega_0$, we eliminate other modes in favor of E_1 , E_{-1} to obtain

$$\begin{aligned} D(\underline{k}, \omega_{\pm 1}) \cdot \underline{E}_{\pm 1} \\ = -(\underline{C}_r + \underline{C}_i) \cdot (\underline{E}_{\pm 1} - \underline{E}_{\mp 1}), \end{aligned} \quad (56)$$

where

$$\begin{aligned} D(\underline{k}, \omega) = \omega^2 - \omega_p^2 - 3v_t^2 \underline{k} \underline{k} + c^2 \underline{k} \underline{k} \\ - c^2 k^2 + \frac{\omega_p^2}{4c^2} \left(\frac{v_0^2}{2} + v_0 v_0 \right) \end{aligned}$$

is the dispersion tensor for the decay waves with relativistic modifications,

$$\underline{C}_r = \frac{\omega_p^2}{4c^2} \left(\frac{v_0^2}{2} + v_0 v_0 \right)$$

expresses the relativistic mode coupling, and $\underline{C}_i$ is the usual coupling due to ion perturbations. For compactness we have omitted additional terms of order v_0^2 that do not contribute to the instability for $ck \lesssim \omega_p$.

Equation (56) leads directly to a dispersion relation in the form of a 6 by 6 determinant. Instead we cast the dispersion relation into a familiar, physically interpretable form through the use of the eigenmodes of $D(\underline{k}, \omega) - \omega^2$, which is a real, symmetric tensor with real eigenvalues $-\omega_L^2$, $-\omega_T^2$, $-\omega_{\perp}^2$, and orthonormal eigenvectors $\underline{E}_L$, $\underline{E}_T$, and $\underline{E}_{\perp}$. The identification is such that $\underline{E}_L$ is parallel to $\underline{k}$ as $v_0 \rightarrow 0$ and $\underline{E}_{\perp}$ is always parallel to $\underline{k} \times v_0$. However, the anisotropic relativistic corrections cause the decay waves $\underline{E}_1$ and $\underline{E}_{-1}$ to not be simply longitudinal and transverse waves.

Inverting $\underline{D}$ in Eq. (56), we obtain

$$\begin{aligned} \underline{E}_{\pm 1} = - \sum_j \left(\omega_{\pm 1}^2 - \omega_j^2 \right)^{-1} \underline{E}_j \underline{E}_j \\ \cdot (\underline{C}_r + \underline{C}_i) \cdot (\underline{E}_{\pm 1} - \underline{E}_{\mp 1}), \end{aligned} \quad (57)$$

where $j = L, T, \perp$. Forming a homogeneous equation for $\underline{E}_1 - \underline{E}_{-1}$, we find the dispersion relation

$$\begin{aligned} 0 = \det \left[1 + \sum_j \left(\omega_{\pm 1}^2 - \omega_j^2 \right)^{-1} \right. \\ \left. \times \underline{E}_j \underline{E}_j \cdot (\underline{C}_r + \underline{C}_i) \right]. \end{aligned} \quad (58)$$

The $\perp$ part factors trivially, yielding a mode with low growth rate and leaving a 2 by 2 determinant

for the modes of interest. This reduces to the classical result (see for example Ref. 99) when relativistic terms are dropped. With $k_{\perp} \ll \omega_0 / |E_{\pm 1}|$ and fixed ions we recover the longitudinal instability of Ref. 100, while for $k_{\perp} \gg \omega_0 / |E_{\pm 1}|$ we recover a limit of the transverse instability of Ref. 101. Near critical density the latter two have equal maximum growth rates occurring for equal values of frequency mismatch. With realistic ion masses, we find² that the relativistic mechanism dominates initial growth of the OTS instability when $v_0 \lesssim 0.3 c$.

Allowing a three-dimensional perturbation has made evident the close relationship of known special cases. Further, the growth rate is found to be fairly insensitive to the direction of k under some conditions, implying spatial collapse of an initially uniform pump. Computer simulations, using the ZOHAR code,¹⁰² confirm this result.

Stimulated Scattering in the Underdense Plasma at Relativistic Electron Temperatures

We have studied the effect of very large thermal motions on the two most common stimulated scattering processes, stimulated Raman and Brillouin scattering, using a relativistic Vlasov model. Specifically, the regime $m_e c^2 \ll kT_e \ll m_i c^2$ has been examined in detail. Here m_e , m_i , are electron and ion masses, and T_e is the electron temperature. Our principal conclusion¹⁰³ is that scattering instabilities do persist in this relativistically high temperature regime, but only in rather restricted forms.

Stimulated Raman backscatter is quenched for $T_e \ll m_e c^2$. This is because the phase velocity ($\omega/2k_0$) of the driven plasma oscillations is much smaller than the electron thermal velocity $v_{te} \sim c$, causing very strong Landau damping of the plasma waves. Thus the plasma oscillations are nonresonant, and the instability is suppressed.

Since the ordinary form of Raman scattering is absent in a very hot plasma, other types of scattering from electron plasma waves can become dominant. One interesting example of this kind is a forward-scattering instability which we have named modulational Raman scattering (MRS). (The nonrelativistic analog of MRS was discussed in Ref.

104.) In the limit $kT_e \gg m_e c^2$, MRS has the interesting property that the driven plasma oscillations can be resonant normal modes. These resonant plasma oscillations are convected along with the group velocity of the pump wave and the two scattered light waves. The entire strong-wave envelope is modulated at a wavelength compared with that of the pump.

Stimulated Brillouin scattering exists if the ion temperature satisfies $(T_i/m_e c^2) \ll 0.3(\omega_{pe}/\omega_0)^2$, where ω_{pe} is the usual electron plasma frequency and ω_0 is the frequency of the driving electromagnetic wave.* The main change from nonrelativistic Brillouin scattering is that the driven ion waves become resonant ion plasma oscillations, with frequency $\sim \omega_{pi}$, instead of ion acoustic waves. Except for numerical factors of order unity, growth rates for stimulated Brillouin scattering may be obtained from their nonrelativistic values by replacing the quantity $(eE_0/m_e c \omega_0)$ by $(eE_0/m_e c \omega_0)(m_e c^2/kT_e)$. This simply reflects the fact that the inertia of an electron in a relativistically hot plasma is $\gamma m_e = (kT_e/m_e c^2)m_e$.

We conclude that stimulated scattering instabilities in the underdense regions persist at very high electron temperatures. However, growth rates may be severely reduced. For Raman scattering, reduction occurs because the driven plasma waves are no longer resonant. Brillouin scattering exists only in a rather limited regime of ion temperatures, and hence may not be present in many parameter ranges of interest.

References

99. L. M. Gorbunov, *Zh. Eksp. Teor. Fiz.* **55**, 2298 (1968) [*Sov. Phys. JETP* **28**, 1220 (1969)].
100. A. T. Lin and N. L. Tsintsadze, *Phys. Fluids* **19**, 708 (1976).
101. C. E. Max, J. Arons, and A. B. Langdon, *Phys. Rev. Lett.* **33**, 209 (1974).
102. A. B. Langdon and B. F. Lasinski, in *Methods in Computational Physics*, Vol. 16, B. Alder, S. Fernbach, J. Killeen, Eds. (Academic Press, New York, 1976).
103. J. Arons, C. A. Neuman, and C. E. Max, *Electromagnetic Instabilities in an Ultrarelativistic Plasma*, Lawrence Livermore Laboratory, Rept. UCRL-78864 (1976). (Accepted for publication in *Phys. Fluids*.)
104. D. W. Forslund, J. M. Kindel, and E. L. Lindman, *Phys. Fluids* **18**, 1002 (1975).

Authors

A. B. Langdon
C. E. Max

4-5.5 Brillouin Side Scattering of Laser Light

Many past LLL experiments with high intensity light have used a short pulse length and/or a small spot size. Although stimulated scattering instabilities¹⁰⁵ could be far above threshold, the

small amount of plasma in the underdense region would not reflect a great deal of light without, for example, the plasma being pushed aside by the light's momentum. A time-dependent reflectivity consistent with this interpretation has been observed in experiments.¹⁰⁶ However in experiments with longer pulse lengths and larger focal spots, the underdense plasma can be much more extensive and cause significant back and side scatter of the light, particularly via the Brillouin instability. Hence we

Fig. 4-51. Ion density surface after irradiation by plane s-polarized light incident from the left. The initial plasma density profile consisted of a linear ramp from 0.3 to 1.2 times the critical density in 12.8 vacuum wavelengths and was 10 wavelengths wide. The height of the line is proportional to the relative density at that position. The electron temperature is 0.5 keV, the laser intensity is 2.7×10^{14} W/cm², and the snapshot is taken at time 600 laser cycles.

must be cautious in extrapolating past experimental results on light absorption to future experiments.

We have continued to examine Brillouin scattering in order to better identify its principal features. Here we briefly describe some simulations using a two-dimensional, one-fluid plasma model¹⁰⁷ that follows the behavior in the plane orthogonal to the direction of polarization of the light. Although this model does not include kinetic effects for the ions, it enables us to obtain some estimates of the angular behavior of side scatter in larger systems than can be conveniently handled in a particle code. These simulations indicate that Brillouin side scatter gives rise to angular lobes in the intensity of the reflected light. These lobes are preferentially out of the plane of polarization, which is consistent with some recent experimental observations. At high intensity, these lobes can become very broad in angle.

A simple example motivated by some recent experiments¹⁰⁸ with large spots will be discussed. In this example, the plasma initially consists of a linear density ramp, rising from $n = 0.3 n_{cr}$ to $n = 1.2 n_{cr}$ in a distance of $12.8 \lambda_0$, where n_{cr} is the critical density and λ_0 is the free space wavelength. The system is periodic in the other direction, which is the direction of the magnetic field of the incident light. The incident light intensity is 2.7×10^{14} W/cm², the electron temperature is 0.5 keV, the viscous damping¹⁰⁷ is small, and the mass ratio is 100. Absorption at the critical surface is crudely modeled by means of a collision frequency with a Lorentzian shape peaked at the critical density.

Figure 4-51 shows a surface plot of ion density at time $\omega_p t = 3770$. Note the two-dimensional lattice of ion fluctuations that have been driven up by the back and side scattering in the underdense plasma. In this example, about 14% of the incident light is absorbed at the critical density (no inverse bremsstrahlung has been included). The angular distribution of the reflected light, which includes light that is simply reflected at the critical surface due to lack of absorption, is shown in Fig. 4-52. Of particular interest are the angular lobes in the reflected light as a result of Brillouin side scatter. Note the side-scattered light comes out of the plasma in this example with angles of about 20 to 40°, consistent with side scatter taking place at n about 0.6 to 0.9 n_{cr} . Since this scattering preferentially occurs out of the plane of polarization, these angular lobes will be dominantly in that direction.

Similar lobes in the asymmetrically reflected light

Fig. 4-52. Polar plot of the intensity of the reflected light vs angle, averaged from 500 to 600 laser cycles. The rippled ion density shown in Fig. 4-51 back- and side-scattered the light into this pattern.

have been observed in some recent experiments¹⁰⁸ using light with large focal spots. In these experiments, the asymmetry of this scattered light is fairly large (at the angle where the lobes peak, the scattered light intensity out of the plane of polarization is about 2 to 3 times greater than the intensity in the plane of polarization). The magnitude of this asymmetry is greater than that expected from the polarization dependence of resonance absorption. In addition, the amount of light asymmetrically scattered increases with intensity and appears to onset near the predicted threshold for Brillouin side scattering.

At higher intensities, the simulations show that these lobes in the reflected light broaden in angle. The broader distribution of the reflected light is due both to side scattering and to formation of

bubbles¹⁰⁷ within the critical surface. Hence at very high intensity, the scattered light is expected to be rather broad in angle, rather than principally backwards.

References

105. C. S. Liu, M. N. Rosenbluth, and R. B. White, *Phys. Fluids* **17**, 1211 (1974).
106. W. L. Kruer, R. A. Haas, W. C. Mead, D. W. Phillion, and V. C. Rupert, in *Plasma Physics: Nonlinear Theory and Experiments*, edited by H. Wilhelmsson (Plenum Press, NY, 1977) p. 64-81.
107. E. J. Valeo and Kent Estabrook, *Phys. Rev. Lett.* **34**, 1008 (1975); Kent Estabrook, *Phys. Fluids* **19**, 1733 (1976).
108. R. A. Haas, H. Shay, M. Boyle, W. Kruer, D. Phillion, F. Rainer, V. Rupert, and H. Kornblum, *Interaction of 1.06- μ Laser Radiation with Planar Targets*, Lawrence Livermore Laboratory, Rept. UCRL-78927 (1976).

Authors

K. G. Estabrook
W. L. Kruer

4-5.6 Stimulated Brillouin Scatter and Density Profile Studies

The problems of stimulated Brillouin scatter have been examined theoretically¹⁰⁹ and in simulation.¹¹⁰⁻¹¹³ Last year's annual report described the self-limitation of Brillouin backscatter by profile steepening due to momentum and energy deposition from the laser into the underdense plasma. This section extends the previous work by looking more closely at the ion heating by Brillouin scatter and the resulting increase in Landau damping. We also look at profile steepening by Brillouin sidescatter in an isothermal two-dimensional fluid model. Finally, we briefly discuss progress on an empirical Brillouin-scatter, density-profile, absorption model for use with fluid target design codes such as LASNEX.

Distance and Time Scales

Figure 4-53 is a plot of the ion density surface which has been irradiated by light at 3×10^{16} W/cm² incident upon a 4-keV plasma with an original density gradient length of 10 vacuum wavelengths (λ_0). Figure 4-54 is the electron density averaged across y and plotted as a function of x. These figures are from the same run at the same time. There are four density scale and gradient lengths of interest in the region between the critical density (n_{crit}) and blowoff regions. (1) The density gradient length about the critical surface steepens in about one ion plasma period (much less than a picosecond) for angles of incidence and underdense density profiles that allow resonant absorption and/or instabilities to occur vigorously. (2) The region between about 0.25 critical and critical is a more or less constant density shelf and becomes shorter (neglecting external hydrodynamics) due to Brillouin scattering. It requires a much longer time to steepen (many picoseconds) depending on $v_{os}/v_{te} \cdot \theta_{os} = eE/(mc\omega)$ where e is the electron charge, E is the laser peak electric field in vacuum, m is the electron mass, c is the speed of light, and ω is the angular frequency of the laser light. $V_{te}^2 = T_e/(mc^2)$ where T_e is the electron temperature. This regime has been explored with one-dimensional (1D) particle simulations.¹¹⁰⁻¹¹³ (3) Two-dimensional (2D) simulations¹¹⁴ in the one-quarter critical region have shown that the $2\omega_{pe}$ and Raman sidescatter also steepen the plasma about the one-quarter critical surface. (4) The blowoff region up to about 0.2 critical could reflect a significant amount of light if there were a very large number of wavelengths at reasonable densities there. (The Compton and Brillouin stimulated scatter may be interesting there, but will not be considered here. It is not economically feasible to do a long-time two-dimensional study of a large underdense region and the critical region. Consequently, we have done a combination of one- and two-dimensional simulations.

Figure 4-53 shows that the distance between 0.25 and critical (L) is only a few wavelengths, and Brillouin scatter does not prevent most of the light from reaching critical. However, if the distance L were large, the light radiance reaching the critical surface would be reduced by Brillouin reflection. Consequently, this section considers the short- and long-time reflection in that region.

Fig. 4-53. Ion density surface at time $\omega_0 t = 806$. Laser light is tilted at 30° to the initial critical surface. Brillouin ion acoustic waves are rolling towards the critical surface from the incident pump. Lower amplitude ion waves are being driven by the reflected light. The initial plasma was $2\lambda_0$ wide and $v_{\text{ex}} = 0.167$, $v_{\text{te}} = 0.0885$, and $T_e/T_i = 30$.

Fig. 4-54. Same run as Fig. 4-53 and same time. Ion density averaged across y and plotted as a function of x .

Short Time-Scale Reflection Effects

Reference 111 discusses the reflection of laser light from a plasma with an initial density profile of 0 to 0.7 critical in 10 wavelengths as a function of v_{os}/v_{te} . Since the density shelf region is probably flat (see Fig. 4-53), these 1D runs were repeated with a flat density of 0.50 critical and 10 wavelengths long. Reflecting boundary conditions were used to confine the plasma so that we could clearly observe the heating rate. The current densities near the ends were multiplied by a ramp between 0 and 1 so that classical reflection was reduced. Additionally, an example of the runs was repeated with ions fixed to determine the classical reflection. This run was then subtracted out, as shown in the square points in Fig. 4-55. Surprisingly, there is little difference between the points with the density gradient and expanding plasma and the points with a flat plasma with confining boundary conditions. However, this is mostly coincidence since the average plasma density was about the same.

The effect of temperature ratio is shown in Fig. 4-

55 by the difference between the diamonds $T_e/T_i = 30$ and the squares $T_e/T_i = 3$. The runs at $1/2(v_{os}/v_{te})^2 = 0.21$ differ by about the difference between the Landau damping for the two temperature ratios for mass ratio 100. However, at $1/2(v_{os}/v_{te})^2 = 0.63$, the difference in reflection is only about a factor of 2, which is less than that predicted by Landau damping for two reasons: (1) the essential damping is larger due to wave breaking, and (2) the ions heat rapidly as discussed in the next section.

To study reflection as a function of plasma length, we have made simulations of plasmas that were initially at 0.33 and 0.55 critical and 10, 30, and 60 vacuum wavelengths long (Fig. 4-56). We found that even at high v_{os}/v_{te} , the worst average reflection was about 80%, slowly decreasing in time. This result is explained in more detail in Ref. 113.

We have several suggestions as to why the curve bends over as a function of length and shows surprisingly high transmission at even 60 wavelengths and high v_{os}/v_{te} . First, the ion waves in a localized region of a few λ_0 spend only about half their time

Fig. 4-55. Fraction of light reflected due to Brillouin backscatter from a plasma of fixed initial length of 10 vacuum wavelengths. The squares indicate runs from an initially flat plasma at $0.5 n/n_{crit}$, $T_e/T_i = 3$, the diamonds are from an initially flat plasma at $0.5 n/n_{crit}$, $T_e/T_i = 30$, and the triangles are from runs with an initial density from 0 to $0.7 n/n_{crit}$, $T_e/T_i = 5$. All runs have length 10 vacuum wavelengths. The equations and dashed lines are simple empirical fits.

Fig. 4-56. Brillouin reflection vs length for 15; the triangles are for $n/n_{\text{crit}} = 0.55$, $T_e/T_i = 3$.

with large $\delta n/n$, which acts with the electrons to reflect the light. The other half of the time, the localized waves crash and the light goes through. Of course the ion waves in a long region are not all in phase. For example, the ion-phase space plot of Fig.

4-57 shows that about the first eight wavelengths of ion waves are about to crash. A later plot (not shown) shows that first dozen wavelengths have less $\delta n/n$ than the second dozen, which have not yet crashed, and the process repeats.

Fig. 4-57. Ion phase space showing vigorous Brillouin ion acoustic waves. Initially, $T_e = 1$ keV, $T_e/T_i = 5$, $M_i/m_e = 100$; the plasma was flat at 0.33 critical and 30 wavelengths long.

A second suggestion is that most of the reflection occurs in only the first ten wavelengths (Fig. 4-57 shows ion phase space of Brillouin ion waves) until that part heats and steepens. Beyond the reflection part the light v_{os}/v_{te} is reduced and the bandwidth is increased (although the bandwidth effect is small).¹¹⁵ A third possibility is that since the light is reflected in small increments at each ion acoustic density peak, there is less light to be reflected at each successive ion acoustic wavelength. Finally, there is evidence that the reflected light drives Brillouin towards the laser, which re-reflects some light back towards the pellet. The evidence for this is that ions accelerated by the wave are accelerated in the direction of the ion wave phase velocity. Figure 4-57 shows ions accelerated towards the laser as evidence for re-reflection. Similar runs with a shorter plasma do not show this re-reflection

If the plasma were in a turbulent state so that the light damping by short wavelength ion fluctuations

multiplied by the ion Landau damping were enough to damp the Brillouin below threshold for a homogeneous plasma,¹⁰⁹ then the transmission would increase; however, this effect may not be generally important.

Simulations of Brillouin show that the reflection is approximately proportional to the density between densities 0.33 and 0.55 critical for plasmas less than 10 wavelengths long. However, for long plasmas this is probably not true. At about 0.25 critical, Raman back- and sidescatter and $2\omega_{pe}$ steepen the density rapidly as discussed in Ref. 114. Above about 0.8 critical, the density peaks of Brillouin appear above critical, and a great deal of light is reflected even at rather low v_{os}/v_{te} . Consequently, the 1D model is poor here, and it is likely that large absorption would occur on the density peaks as observed in similar 2D runs.

Instantaneous reflection varies considerably as a function of time, as will be shown in the Poynting's

Fig. 4-58. (a) Ion density vs length at four different times showing profile steepening due to light momentum deposition. The numbers indicated are the times in laser cycles. (b) Temperature increase and consequent (c) decrease in reflection as shown in the transmitted Poynting vector. The initial plasma parameters were $T_e = 1$ keV, $T_e/T_i = 5$, $v_{os} = 0.06$.

Fig. 4-59. (a) Surface plot of ion density from a fluid code showing ion acoustic waves resulting from Brillouin sidescatter. The plasma initially had a density from 0.3 to 0.7 critical in 13.4 wavelengths and was 4 wavelengths wide. (b) Average ion density vs x at same time as in (a). Note steepening of density gradient as in the one-dimensional simulations.

vector plots in the next section. Consequently, there is some inherent arbitrariness in the average reflection shown in Figs. 4-55 and 4-57 due to the averaging time. We used 300 laser cycles for $M_e/m_e = 100$ and 600 laser cycles for $M_e/m_e = 400$, at which time the short time-scale effects were reasonably averaged out.

Long Time-Scale Reflection Effects

As is discussed in Ref. 113, reflection decreases over many ion plasma periods because the underdense plasma length, L , decreases due to momentum deposition¹¹⁶ by the laser [Fig. 4-58(a)] and due to ion and electron heating [Fig. 4-58(b)]. These effects reduce v_{os}/v_{te} and generally decrease T_e/T_i , which increases the ion Landau damping. The combined heating and steepening cause the reduced reflection, as shown in the plot of the transmitted Poynting's vector [Fig. 4-58(c)]. As described in Ref. 113, over many picoseconds the reflection gradually decreases due to momentum and energy deposition from the laser to the plasma. Also, we have done two-dimensional simulations with a fluid

code (isothermal, ion species, s polarization)¹¹⁷ to look for sidescatter steepening due to Brillouin sidescatter. Figure 4-59(a) shows a surface plot of the ion density with vigorous sidescatter. Figure 4-59(b) shows the y -averaged density profile; it has steepened in a fashion similar to Brillouin backscatter. Although a careful parameter study has not been made, it is reasonable to assume that we can model this steepening by simple momentum deposition, as in the 1D results.

Back- and sidescatter can be reduced by energy deposition in two ways: either the electrons heat and reduce v_{os}/v_{te} or the ions heat and increase the ion Landau damping. Of course ion pressure also reduces the wave amplitude. Figure 4-60 shows a plasma with initial $T_e/T_i = 30$; the temperature ratio decreases rapidly with time due to ion heating and the reflection decreases rapidly as a consequence. The ions start off with such low energy that even a small absorption causes ion heating; thus the temperature ratio rapidly approaches the regime of fairly large ion Landau damping and hence decreased $\delta n/n$ and decreased reflection. Figure 4-60(a) shows some heating of electrons. This is not only due to numerical heating but also to Landau

Fig. 4-60. (a) Average electron and ion energy in the x direction vs time for Brillouin heating. (b) Poynting's vector of the transmitted light vs time for same run. The reflection decreases very rapidly as the ions heat. The initial parameters were: $T_e = 1$ keV, laser irradiance $= 10^{15}$, and $T_e/t_i = 30$.

damping on the ion waves by the electrons, which is artificially large since the mass ratio is so small ($M_i/m_e = 100$). With a realistic mass ratio, we would expect less electron heating due to ion Landau

damping. Figure 4-60(b) shows the rapid increase in the transmitted Poynting's vector in the case where there is little density steepening but an increase in ion Landau damping. The Brillouin in

Fig. 4-61. Ion heating rate vs power input to flat underdense plasma with reflecting boundary conditions. In all the runs, the plasma initially was $10 \lambda_D$ long and had initial $T_e = 1$ keV and $T_e/T_i = 3$. The dots indicate that the heating was averaged over about 300 laser periods for $M_i/m_e = 100$ and 600 periods for $M_i/m_e = 400$ (indicated by "400"). The squares indicate the fastest heating in the cases of irregular heating at high powers.

Fig. 4-62. Ion energy spectrum averaged over simulation region. Notice that the heated ions form a near-Maxwellian distribution. In this case, the initial plasma conditions were $T_e = 1$ keV, $T_e/T_i = 3$, laser irradiance $= 10^{16}$ W/cm², $n/n_{crit} = 0.5$, and the snapshot was taken at 500 laser periods.

these particular data was to some extent self-stabilizing in that the ions were heated to cause increased damping and less reflection.

Figure 4-61 is a plot of the ion heating rate in eV per laser cycle for plasmas that are 10 wavelengths long. Figure 4-62 shows a particular example of high v_{os}/v_{te} Brillouin in which the heated ions form a near-Maxwellian tail.

The problems of stimulated scatter in the underdense plasma and absorption near the critical surface by resonant absorption are inherently kinetic problems and have been studied by kinetic codes.^{110-115,118} However, since it is not economical

to use these codes on large regions long enough for macroscopic laser fusion studies, we are working on sets of empirical formulas for LASNEX to follow the time and space evolution of the laser light reflection dynamically as a function of laser light intensity, the self-consistent electron and ion temperature, density profile, and hydrodynamic motion. Additionally, since the fluid code can model the reflection, it can know the remaining light intensity and angle at the critical surface and therefore model the fraction of light absorbed by instabilities, resonant absorption and inverse bremsstrahlung, and the resulting electron distribution function.

References

109. C. S. Liu, M. N. Rosenbluth, and R. B. White, *Phys. Fluids* **17**, 1211 (1974).
110. D. W. Forslund, J. M. Kindel, and E. L. Lindman, *Phys. Rev. Lett.* **30**, 739 (1973).
111. W. L. Kruer, K. G. Estabrook, and K. H. Sinz, *Nuc. Fusion* **13**, 952 (1973).
112. D. W. Forslund, J. M. Kindel, and E. L. Lindman, *Phys. Fluids* **18**, 1002, 1017 (1975).
113. W. L. Kruer, E. J. Valeo, and K. G. Estabrook, *Phys. Rev. Lett.* **35**, 1076 (1975).
114. A. B. Langdon and B. F. Lasinski, in *Methods in Computational Physics* **16**, J. Killeen et al., Eds. (Academic Press, N.Y., 1976); *Laser Fusion Annual Report — 1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p. 309.
115. R. J. Faehl, *Numerical Simulation of Laser Fusion Plasmas Using a Reduced Description*, Ph.D. thesis, University of California, Davis, California (1976); Lawrence Livermore Laboratory, Rept. UCRL-52215 (1976).
116. R. E. Kidder, in *Proceedings of the Japan-US Seminar on Laser Interaction with Matter*, C. Yamanaka, Ed. (Tokyo International Book Co. Ltd., Tokyo, 1973), p. 331.
117. K. Estabrook, *Phys. Fluids* **19**, 1733 (1976).
118. K. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975), and references therein.

Author

K. G. Estabrook

4-6 THEORY AND SIMULATION: HEATED ELECTRON ENERGIES

4-6.1 Heated Electron Energies from Resonance Absorption

The absorption of laser light by resonantly driven electron plasma waves has been extensively reported.¹¹⁹⁻¹²³ This section extends the previous work by discussing the critical density scale length, lower density shelf height, pressure balance, fractional absorption, and heated electron distributions and temperature (T_{hot}) as a function of input power density, cold electron temperature (T_{cold}), and angle.

We have investigated resonant absorption with a two-dimensional, kinetic, relativistic, electromagnetic computer simulation program called ZOHAR.¹²⁴ A detailed description of how ZOHAR models resonant absorption is given in Ref. 123. Within the initial parameters of $0.3 < v_{os}/v_{te} < 3$ and $1 \text{ keV} < T_e < 32 \text{ keV}$, $T_e/T_i = 3$, $M_i/m_e = 100$, density gradient length = 1.8 vacuum wavelengths, $11^\circ < \text{angle of input light incidence} < 45^\circ$, we find that the energy spectrum of heated electrons by resonant absorption can be approximated fairly well as the sum of two Maxwellians (see Fig. 4-63). $v_{os} = eE/(mc\omega)$ where e is the electron charge, E is the laser peak electric field in vacuum, m is the electron mass, c is the speed of light, and ω

Fig. 4-63. Energy spectrum of electrons heated by resonant absorption. In this example, the initial conditions were: $v_{os} = 0.085$, $v_{ic} = 0.0885$, $T_e/T_i = 3$, angle of light to density gradient = 24° , periodic length = 2.5 vacuum wavelengths, density profile 0 to $1.7 n_{crit}$ in three vacuum wavelengths.

Fig. 4-64. Hot electron temperature heated by resonant absorption vs laser power flux. Crosses are for T_{cold} of 1 keV; dots are for 4 keV. The lines are drawn to show the respective slopes but are not fits to the data or theoretical interpretations. Most of the runs had an initial density gradient of 0 to $1.7 n_{crit}$ in three vacuum wavelengths and an angle of incidence of 24° . The lowest point at 10^{16} W/cm^2 is actually two points at 0 and 45° .

is the angular frequency of the laser light. $V_{te}^2 = T_e/(mc^2)$ where T_e is the electron temperature. The cold temperature is the initial Maxwellian loading and includes the oscillatory velocity; the hot temperature is directly heated by resonant absorption. In all these examples, profile steepening is allowed as described in Ref. 123. Just why the heated electrons form such a clear Maxwellian distribution is being actively studied. Figure 4-62 shows a particular example of Brillouin scattering that also heats as a Maxwellian. We have examined the energy spectrum from only the plasma region from 0.4 to 1.5 critical, over the whole region and through the high density wall (dividing the weight by the x velocity to convert flux into E distribution function), and have found nearly the same Maxwellian T_{hot} in cases with resonant absorption that we have run.

Figure 4-64 presents simulation data on the dependence of T_{hot} on the input power density for 1.06- μ m light. For 10.6- μ m light, the power density should be divided by 100 for an equivalent v_{os} . In each case, the plasma started from a linear density gradient: from 0 to $1.7 n_{crit}$ in three wavelengths, so the plasma reached a state where a density shelf was present. To learn how sensitive these data were to numerics, we re-ran the lower dot at 9×10^{15} with a factor of two higher spatial and temporal resolution and more particles and found about 10% higher T_{hot} (the higher dot). A similar study at low v_{os}/v_{te}

Fig. 4-65. Hot electron temperature vs cold electron temperature. The lines are drawn to show the respective slopes but are not theoretical interpretations. v_{os} was fixed at 0.085, the initial density gradient was 0 to $1.7 n_{crit}$ in three vacuum wavelengths, and the angle of light incidence was 24° .

Fig. 4-66. Critical density scale length vs input power density for resonant absorption for angles from 11 to 45° . The Debye length used the initial cold electron temperature. Initial conditions for the runs are described in Fig. 4-64.

showed a similar result. For power densities of 10^{16} W/cm^2 , 4 keV, and lower v_{os}/v_{te} , the plasma profile reached near equilibrium. However, at higher v_{os}/v_{te} , the points must be considered as not in equilibrium. To give an example of how important equilibrium is, the top point in Fig. 4-64 had an initial profile of 0 to $1.7 n_{crit}$ in three wavelengths, and the point below it had a step of $4 n_{crit}$. The high point is very much out of equilibrium; the lower point is nearer equilibrium. Experiments at LASL and at LLL show that T_{hot} as measured from the x rays does not increase as fast with v_{os} as the faster slope in the high power region. The translation from x-ray temperature to T_{hot} , however, is not trivial and depends on transport inhibition to the over-dense region, on whether the target is thick or thin, and on other factors. A target simulation code such as LASNEX is needed for each specific case.

Figure 4-65 presents simulation data for the heated T_{hot} vs T_{cold} , holding the input power density constant at 9×10^{15} W/cm^2 . Note the relatively weak dependence on T_{cold} .

We find that the absorption is not a strong function of T_{cold} for resonant absorption cases in which v_{os}/v_{te} is less than or equal to 1 for angles of 24° . Even for $v_{os}/v_{te} = 0.34$, there was local steepening

of the density profile near the critical surface. The absorption does increase for cases in which v_{os}/v_{te} is greater than 1, but in those cases that we have tried, the plasma was not in pressure equilibrium. In this ideal model (plane wave incident on a short slab) the absorption does depend strongly on angle, as described in last year's annual report and in Ref. 123.

The density gradient at the critical density is important to both resonant absorption and to inverse bremsstrahlung. The critical density gradient has been measured over a wide range of angles and has been found to be almost inversely proportional to v_{os} . It is presented as a function of power in Fig. 4-66. Note that at a fixed temperature, the scale length decreases with intensity. This decrease is one of the principal factors accounting for the weaker than square root dependence of T_{hot} on intensity.

The absorption due to inverse bremsstrahlung also depends on the density of the underdense shelf. The question immediately arises: is the shelf density purely a function of v_{os}/v_{te} , or does it depend on the hydrodynamic flow and history? The shelf heights shown in Fig. 4-67 are all found using an initial condition of a linear ramp from zero density to 1.7 critical in three vacuum wavelengths so that

Fig. 4-67. Shelf height n/n_{crit} vs v_{os}/v_{te} for resonant absorption. The initial conditions for the runs are described in Fig. 4-64.

Fig. 4-68. Phase space ($p_x - x$) for electrons heated by resonant absorption at time $\omega_0 t = 402$. The run is the same as that in Fig. 4-63.

there was a relaxation to quasi-equilibrium from that initial state. Equilibrium from other initial states is being actively studied. When the pressure balance at the critical density is being computed to determine the overdense height, one should remember to include the momentum component of the resonantly driven electrons down the density gradient as demonstrated by the phase space plot in Fig. 4-68 (actually, the electrons have an angle to the density gradient, but the largest component of the momentum is down the density gradient). The electrons that have gone around the ambipolar potential and through the critical surface are shown at the top of Fig. 4-68 and have no pressure difference across that region. However, the electrons driven directly out the bottom do have a pressure gradient. We could conjecture that a laser hot spot could cause an overdense filament or a bubble from the electron acceleration in the general direction of the reflected light as well as the ponderomotive pressure.

References

119. V. L. Ginzburg, *The Properties of Electromagnetic Waves in Plasmas* (Pergamon, New York, 1964), p. 260.

120. J. P. Freidberg, R. W. Mitchell, R. L. Morse, and L. I. Rudinski, *Phys. Rev. Lett.* **28**, 795 (1972).
121. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Lett. A* **49**, 109 (1974).
122. D. Forslund, J. Kindel, K. Lee, E. Lindman, and R. L. Morse, *Phys. Rev. A* **11**, 679 (1975).
123. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975).
124. A. B. Langdon and B. F. Lasinski, in *Methods in Computational Physics* **16**, J. Killeen et al., Eds. (Academic Press, N.Y., 1976); *Laser Fusion Annual Report — 1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p. 309.

Author

K. G. Estabrook

4-6.2 Wave-Breaking Amplitudes in Warm Inhomogeneous Plasmas

A problem of both basic interest and practical importance is the amplitude to which plasma waves can be resonantly driven in inhomogeneous plasma. For example, calculations of this amplitude are useful for understanding the scaling of the energy of the heated electrons produced in resonance absorption of intense laser light. It is well known^{125,126} that the plasma temperature has an important indirect effect on the wave-breaking amplitude in that it controls the amount of nonlinear steepening of the density profile near the critical density. We show that the temperature also has a significant direct effect on the wave-breaking amplitude; that is, an effect that persists even when the density scale length is held fixed. A simple theory of this effect is compared with simulation results, and some applications to laser fusion are given.

To investigate how the temperature affects the wave-breaking amplitude even in a fixed density profile, we have used a one-dimensional electrostatic particle simulation code to follow the evolution of an inhomogeneous plasma driven by

an oscillating electric field. This so-called capacitor model¹²⁷⁻¹²⁹ is the simplest model of resonance absorption and has been widely used in the past.

A plasma with a linear density gradient from 0 to $2n_{cr}$ (the critical density) is set up, and an oscillating field of the form $E_d \cos \omega_0 t$ is applied starting at time $\omega_0 t = 0$. Here ω_0 is the plasma frequency at $n = n_{cr}$. A vacuum region surrounds the plasma on the low-density side; on the high-density side, the heated electrons are re-emitted with their initial thermal temperature.

Figure 4-69 shows simulation results for the peak electric field amplitude at the time of initial wave-breaking as a function of the thermal velocity of the background plasma. For these results the density scale length and driver amplitude (E_d) are held fixed. Note the pronounced effect of plasma temperature. In the cold plasma limit (electron thermal velocity $v_e = 0$), the simulation results agree with the cold wave-breaking prediction¹²⁸ for the given scale length and driver amplitude. However, the wave amplitude becomes significantly reduced as the temperature increases.¹³⁰ We note that in all these cases, wave-breaking (electron "trapping") is occurring in the nonlinear state. One important consequence of the wave-breaking at lower amplitudes is that the transition to the purely thermal convection regime occurs at higher temperatures than previously estimated.

Some simple theoretical estimates can be given for wave-breaking in warm plasmas. The basic idea is to take the cold plasma model¹²⁸ (which is analytically tractable) to describe the initial wave growth, but then to estimate when the faster particles will undergo wave-breaking in this field. Hence, in this model, the wave is being built up and supported by the main body of slow electrons, and is being damped by a much smaller number of faster electrons.

In the cold plasma model, the wave amplitude peaks at the critical density (where it is most resonant) and grows linearly in time. As its amplitude increases, the field becomes more localized about its resonance point. Wave-breaking finally occurs when the field is sufficiently large in amplitude and narrow in spatial extent that electrons interact with it nonadiabatically; i.e., when electrons traverse the field in a time $\approx 1/\omega_0$. Then such electrons see a nearly constant field and are efficiently accelerated, thereby damping the field.

The cold plasma model gives

$$\ell \approx \frac{4L}{\omega_0 t}, \quad (59)$$

$$v_w = v_d \frac{\omega_0 t}{2}, \quad (60)$$

where ℓ is an effective width of the driven field, L is the density scale length at the critical density, and v_w (v_d) is the oscillation velocity of an electron in the driven (driver) field. Neglecting thermal effects, wave-breaking occurs when $\ell/v_w \approx \omega_0$. From Eqs. (59) and (60), we then obtain $v_w = \sqrt{2v_d \omega_0 L}$, which is the well-known cold plasma prediction.

The effect of plasma temperature can now be estimated. The point is that the wave-breaking condition is more readily satisfied by the faster particles in the thermal distribution. Since a Maxwellian distribution falls off so rapidly in velocity, we will take the fastest particles to have a velocity of $\approx 3v_e$. The modified wave-breaking condition becomes $\ell/(v_w + 3v_e) \approx \omega_0$. From Eqs. (59) and (60), we then obtain

$$v_w = \frac{-3v_e + \sqrt{9v_e^2 + 8L\omega_0 v_d}}{2}. \quad (61)$$

As shown by the dashed line in Fig. 4-69, this simple estimate is in reasonable agreement with the simulation results.

Let us now compare our predictions for the wave-breaking amplitude with some results from a two-dimensional simulation of resonance absorption published in Ref. 125. In that example, p-polarized, 1.06- μm -wavelength laser light with an intensity of 10^{16} W/cm^2 was incident at an angle of 24° onto a plasma slab. The plasma had an electron temperature of 4 keV and an initial linear density profile with scale length $k_0 L = 10$. The initial wave-breaking amplitude was observed to be $v_w/c = 0.29$. For this example, the corresponding parameters in the capacitor model are $v_d/c = 0.011$, $v_e/c = 0.088$ and $k_0 L = 10$. The cold plasma prediction for the wave-breaking amplitude is then $v_w/c = 0.47$, which is significantly larger than observed in the simulation. However, our simulation of the capacitor model including thermal effects for the given parameters yields $v_w/c = 0.3$, in quite good agreement. [The theoretical estimate in Eq. (61) gives $v_w/c \approx 0.35$.] Hence, warm plasma effects do significantly affect the wave-breaking amplitude as suggested in Ref. 125.

We note that relativistic effects do not significantly affect the above result, as has been recently claimed.¹³¹ Simulations of the capacitor model have been extended to include a relativistic equation of motion. The initial breaking amplitude in the example discussed above was found to be the same within a few percent. As a confirmation, the original two-dimensional simulation was then re-run with relativistic effects omitted.¹³² Again, the initial wave-breaking amplitude was the same within a few percent.

Fig. 4-69. Initial wave-breaking amplitude as a function of the thermal velocity of the background plasma. The points are simulation results; the dashed lines are theoretical estimates. The parameters are $L = 500 \delta$ and $v_d = 2 \omega_0 \delta$, where δ is the cell size.

One interesting consequence of these calculations has emerged. Although in a fixed profile the temperature decreases the amplitude of the resonantly-driven field, it does not strongly affect the heated electron energy. For example, the maximum energy gained by an electron is

$$\epsilon_{\max} \approx eE_w \ell,$$

where ℓ is again the distance over which an electron is resonant with the wave. Using Eq. (61) and $\ell = \omega_0(v_w + 3v_e)$, we obtain

$$\epsilon_{\max} \approx eE_d L,$$

which is the result for a cold plasma. Physically, because of thermal effects, the field is at a lower amplitude but broader in spatial extent; these two effects tend to compensate one another. The capacitor model simulations support this prediction. The maximum heated electron energy varied by less than about 10% when the background electron temperature was changed by a factor of 100.

This result indicates that the principal temperature dependence of the heated electrons arises from the temperature dependence of L , the local density scale length at the critical density. This explains why previous theoretical estimates¹²⁵ of the heated electron energies using the cold plasma prediction with the steepened scale length worked rather well.

Based on this result, we can now estimate some scalings of the hot electron energy due to resonance absorption (in the wave-breaking regime) in laser fusion applications. To relate E_d to the incident laser light intensity, we simply balance the absorbed energy flux with the energy flux predicted from the capacitor model

$$f \frac{cE_L^2}{8\pi} = \frac{\omega_0 L}{8} E_d^2,$$

where f is the fractional absorption, E_L is the electric field amplitude of the light (in vacuum), and ω_0 is the laser light frequency. This gives

$$E_d = E_L \sqrt{\frac{fc}{\pi\omega_0 L}}$$

The maximum heated electron energy then becomes

$$\epsilon_{\max} \approx eE_L L \sqrt{\frac{fc}{\pi\omega_0 L}}$$

Note that if E_L and f are held constant, $\epsilon_{\max}$ scales as $L^{1/2}$, so the heated energy scales more weakly with temperature than L does. Furthermore, if background temperature and f are held constant, $\epsilon_{\max}$ scales more weakly than the square root of the incident light intensity since L decreases with increasing intensity. Both these features have been observed in recent two-dimensional computer simulations.¹³³

In summary, we have found that plasma temperature plays a significant direct role in determining the wave-breaking amplitude of resonantly driven plasma waves. This temperature effect was calculated in simulations using the capacitor model, and a simple theory was developed. Our results were used to interpret some two-dimensional simulations of resonance absorption of laser light and to estimate some scalings of resonantly-heated electron energies. These model calculations are being extended to investigate the effects of slow pump-field turn-on.

References

125. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975).
126. D. W. Forslund, J. M. Kindel, K. Lee, E. L. Lindman, and R. L. Morse, *Phys. Rev. A* **11**, 679 (1975).
127. J. P. Freidberg, R. W. Mitchell, R. L. Morse, and L. F. Rudinski, *Phys. Rev. Lett.* **28**, 795 (1972).
128. P. Koch and J. Albritton, *Phys. Rev. Lett.* **32**, 1420 (1974).
129. J. DeGroot and J. Tull, *Phys. Fluids* **18**, 672 (1975).
130. T. P. Coffey, *Phys. Fluids* **14**, 1402 (1971).
131. J. F. Drake and Y. C. Lee, *Phys. Fluids* **19**, 1772 (1976).
132. K. G. Estabrook, Lawrence Livermore Laboratory, private communication.
133. K. G. Estabrook (this annual report); D. Forslund, *Bull. Am. Phys. Soc.* **21**, 1066 (1976).

Author
W. L. Kruer

4-7 THEORY AND SIMULATION: HEAT TRANSPORT

4-7.1 Polarization-Dependent Thermal Energy Transport

The possibility of inhibited transport of thermal energy in laser plasmas has been of great interest over the last few years. Results of a recent experiment suggest a polarization dependence of thermal transport.¹³⁴ Briefly, a thin (0.1 μm) plastic film was irradiated by obliquely incident 1.06- μm laser light. Faraday cups monitored the ion blowoff to the front (towards the laser) and to the back. At an intensity of $\sim 2 \times 10^{14}$ W/cm², an asymmetry in the front and back blowoff velocities was obvious in the p-polarization but not in the s-polarization. An interpretation of this observation is that the thermal flux is being inhibited, leading to lower temperatures in the back of the target.

Thus we have been led to consider mechanisms for polarization-dependent inhibition of thermal conductivity. These mechanisms apparently depend on the presence or absence of resonance absorption. This is the most obvious difference in the polarizations.

Resonance Absorption Magnetic Fields

We have shown¹³⁵ that large magnetic fields are generated by the momentum deposition concomitant with resonance absorption. These fields have been found in simulations to grow to the megagauss level, and have recently been observed experimentally.¹³⁶ To determine whether these fields can play a significant role in thermal transport, we must determine their magnitude and spatial extent. The magnitude may be estimated from Ampere's law,

$$\nabla \times \langle \mathbf{B} \rangle = \frac{4\pi}{c} \langle \mathbf{J} \rangle, \quad (62)$$

where the bracketed terms represent a time average. The time-average current is given to first order by

the correlation of the density fluctuation and the oscillating velocity,

$$\mathbf{v}_{os} = i \frac{e\mathbf{E}}{m\omega}; \quad (63)$$

$$\langle \mathbf{J} \rangle = -e \langle n \mathbf{v}_{os} \rangle.$$

Assuming a planar target, taking the plane of incidence to be the x-y plane and the plasma gradient to be in the x-direction, Eq. (62) gives

$$B_z \cong \frac{e}{mc\omega} \langle \text{Im } E_x E_y^* \rangle. \quad (64)$$

In nondimensional form, we may write Eq. (63) as

$$\frac{\Omega_c}{\omega} \cong \langle \text{Im } \frac{v_{osx}}{c} \frac{v_{osy}}{c} \rangle, \quad (65)$$

where Ω is the cyclotron frequency. The exact value of Ω_c/ω depends on the particular form of the plasma density gradient, but for short gradients, we may estimate Eq. (65) by

$$\frac{\Omega_c}{\omega} \cong \frac{v_{os}^2}{c^2} \frac{\sin\theta}{\nu/\omega},$$

where ν is an effective collision frequency at critical density. Putting in some values, $v_{os}/c \sim 0.1$ (10^{16} W/cm²), $\sin\theta \sim 0.2$, $\nu/\omega \approx 0.1$, we find $\Omega_c/\omega \approx 2 \times 10^{-2}$, which corresponds to 2 mg.

A strong magnetic field will limit the maximum thermal flux to well below classical values. We may show that the maximum energy flux may be written

$$\Gamma_E = f m \nu_T^3. \quad (66)$$

For zero magnetic field, $f \approx 1$. For a strong field,

$$f = 3/2 \frac{V_T \nu}{\Omega_c^2 L}$$

$$= 0.06 \frac{n/n_c}{B^2 L T} \quad (B \text{ in mg, } T \text{ in keV, } L \text{ in } \mu), \quad (67)$$

where ν is the collision frequency, and L is the gradient scale length. For example, if $n/n_c \sim 2$, $T \sim 1$ keV, $B \sim 2$ mg, $L \sim 10 \mu$, we find $f = 0.003$, a significant limitation.

However, the field generation is localized within a free-space wavelength of critical density. It must diffuse over several Larmor radii (say three) in order to affect particle motion. The time it takes to do this is

$$\tau = \frac{(3r_L)^2 \omega_p^2}{\nu c^2} = 100 \frac{T^{5/2}}{B^2} \quad (\text{in ps}). \quad (68)$$

For $T = 1$ keV and $B = 2$ mg, $\tau = 25$ ps, which is significantly shorter than most laser fusion experiments.

In conclusion, we find that resonance absorption magnetic fields may have a significant effect in intense, long pulse-width, planar laser-plasma experiments. For spherical targets, we expect a smaller maximum field value due to the increased symmetry. This has not yet been calculated.

Flux Limitation by

Ion Acoustic Turbulence

This subject is discussed in detail elsewhere in this report.¹³⁷ The basic idea is that heat deposition at the critical surface results in a skewed electron distribution function, because it must have a third moment, $Q = nm \langle V^3 \rangle$. If Q/nmV_T^3 exceeds a certain value, which depends on the ion-electron temperature ratio, T_i/T_e , an ion acoustic instability occurs. The resulting density fluctuations produce an effective drag force which tends to reduce the skewness factor and, thus, the heat flow. The main polarization dependence is that obliquely incident light in the p-polarization can be absorbed about twice as efficiently as s-polarized light. Thus the initial heat flux Q_0 is larger. The point is: if we are

near instability threshold levels, the additional energy absorbed in the p-polarization may not be efficiently transported.

Ponderomotive Potential at

Critical Density

Resonantly-excited fields have been shown to generate a strong nonlinear modification of the density profile via the ponderomotive force. The resulting cavities and sharp steps in density have been observed experimentally and are a good illustration of the importance of the ponderomotive potential, which can be written

$$e\phi = 1/2 m \langle V_\omega^2 \rangle, \quad (69)$$

where $\langle V_\omega^2 \rangle = e^2 \langle E_\omega^2 \rangle / m^2 \omega_{pe}^2$. Simulations show that intensities of $\langle V_\omega^2 \rangle \approx$ several V_{Te}^2 are readily obtained. Here, V_{Te} is the thermal velocity of the main body heating due to inverse bremsstrahlung ($T_e \sim 1$ keV).

We now focus on how the ponderomotive potential of the localized plasma waves affects electron transport. A small number of electrons are directly heated by transit-time acceleration if they have the proper speed and phase to interact non-adiabatically with the localized intense fields. This collective heating results in the generation of a low-density, hot plasma. However, the lower energy electrons heated by inverse bremsstrahlung cannot surmount the ponderomotive potential and transport energy into the overdense region. These lower energy electrons would have been the most effective in coupling their energy to a dense, thin target.

To illustrate this, consider a $0.1\text{-}\mu\text{m}$ -thick CH_2 foil. The mean free path of a 10-keV electron is $\sim 10 \mu$ (assuming $n \approx 5 \times 10^{22}$ and $z = 3$). Hence, such electrons are decoupled from the target. They pass back and forth through the target, gradually transferring their energy to the blowoff of a small number of very energetic ions. In contrast, the mean free path of a 1-keV electron is $\sim 0.1 \mu$. Thus, it couples to the overdense region very efficiently. However, these lower energy electrons which are heated by inverse bremsstrahlung may be confined to the underdense plasma by the ponderomotive potential.

On the basis of this simple model, one would expect to see a very fast group of ions on both sides of the target, followed by a slower group of ions. The fast speed would be the same on both sides, but the slow speed can exhibit a front-to-back asymmetry if the resonance absorption ponderomotive potential is sufficiently large. Of course, the energetic electrons which do surmount the potential lose some of their energy to the target, thereby heating it. So the target does disassemble, but slower than if the selective inhibition of the electrons is neglected. Both of these features have been seen in experiments with thin films.¹³⁴

References

134. J. S. Pearlman, private communication.
135. J. J. Thomson, C. E. Max, K. Estabrook, *Phys. Rev. Lett.* **35**, 663 (1975).
136. W. F. DeVergilio, A. Y. Wong, H. C. Kim, and Y. C. Lee, *Phys. Rev. Lett.* **38**, 541 (1977).
137. W. M. Manheimer, *Energy Flux Limitation by Tame Turbulence*, Lawrence Livermore Laboratory, Rept. UCRL-77149, Rev. 1, (1976).

Authors

J. J. Thomson
W. L. Kruer

4-7.2 Effect of Transport Inhibition on Ablation in a Spherical Laser Target

We have derived analytic solutions for steady spherical ablation in a laser target. Our description includes saturation of the electron heat conduction when the electron mean free path becomes comparable to the scale length for temperature variations. The solutions yield scaling laws for the Mach number of the flow and the ablation rate as functions of the amount of transport inhibition, laser intensity, and laser wavelength.

We find the ablation rate to depend sensitively on a parameter we call σ_0 , which measures the amount by which the electron heat flow is saturated:

$$\sigma_0 \approx \frac{\text{classical heat flux}}{\text{flux-limited heat flux}} \propto \frac{I^{4/3} \lambda^{14/3}}{\phi^{7/3}} \quad (70)$$

Here I is the laser intensity, λ the laser wavelength, and ϕ the flux limit as defined by

$$q_{\text{flux-limited}} = 5\phi \rho c^3 \frac{\text{ergs}}{\text{cm}^2 \text{s}},$$

where c = sound speed = $(p/\rho)^{1/2}$ and q is the electron heat flux. When σ_0 is large compared with unity, the heat flow is strongly saturated.

Our studies also show that, in the part of the overdense region where the heat flux is saturated, the flow Mach number $M = v/c$ is constant in space, depending only on the value of the flux limit ϕ . There are two regimes of interest in this regard. When $\phi > 1$ [or $f \equiv q_{\text{flux limited}}/(m_e n_e v_{te}) \lesssim 0.1$], the outflow is supersonic. Hence we would expect the flow to stabilize or slow down some types of plasma instabilities in the overdense region. On the other hand, for $\phi < 1$ [$f < 0.1$], the saturated outflow in the overdense region is subsonic. Thus strongly flux-limited flows should have less dramatic effects on plasma instabilities.

Much has been written¹³⁸⁻¹⁴⁴ about scaling laws for laser-driven ablation. The present work uses an approach first outlined in an astrophysical context by Cowie and McKee.¹⁴⁵

The basis for our solutions lies in the fact that, in many situations, electron heat conduction can be classical near the ablation front, yet flux-limited at larger radii. In particular, we consider flows where conduction is saturated at the critical density surface. We take the electron heat flux to be

$$\vec{q} = \min \begin{cases} -\kappa \vec{\nabla} T \\ -5\phi \rho c^3 \left(\frac{\vec{\nabla} T}{|\nabla T|} \right) \end{cases} \quad (71)$$

Here $\kappa = 0.98 (k_B T)^{5/2} / (m_e^{1/2} e^4 \bar{Z} \ln \Lambda)$ is the classical electron conductivity⁹ (for $Z \sim 1$), and $c = (p/\rho)^{1/2}$ is the sound speed. There are many different opinions about the correct value for the flux

Fig. 4-70. Temperature vs radius for a typical ablative implosion.

limit ϕ , ranging from $10 \lesssim \phi \lesssim 0.1$. Thus we leave ϕ as a parameter in our solutions. Generally, theoretical treatments^{146,147} have suggested larger values of ϕ , whereas laser-plasma experiments¹⁴⁸ suggest smaller values. A large theoretical effort is now aimed at explaining these experimental observations, which tend to indicate that $\phi \sim 0.1$. Whatever the ϕ value, our only requirement is that it be constant in space.

Figure 4-70 shows a schematic plot of a typical temperature profile $T(r)$. The temperature is very small near the ablation surface, $r = R_a$. Since κ , the classical conductivity, is proportional to $T^{3/2}$, the classical heat flux is very small and the conduction is classical near the ablation surface. By contrast, near the critical surface r_c , the temperature is high and the density low. Thus the saturated heat flux $5\phi\rho c^3$ can become smaller than the classical value, and conduction may be flux-limited.

Our system is described by the equations for steady flow in spherical geometry with $T_i = T_c$:

$$4\pi r^2 \rho v = \dot{m} = \text{constant}, \quad (72)$$

$$\rho v \frac{dv}{dr} = - \frac{dp}{dr}, \quad p = \rho c^2, \quad (73)$$

$$\frac{1}{r^2} \frac{d}{dr} r^2 \left\{ \rho v \left(\frac{1}{2} v^2 + \frac{5}{2} c^2 \right) + q \right\} = 1 \delta(r - r_c). \quad (74)$$

These three equations, respectively, express conservation of mass, momentum, and energy. Inverse bremsstrahlung is assumed to be unimportant, so the laser deposits all its energy at the critical surface $r = r_c$. The laser intensity is I . We do not consider effects of the ponderomotive force.

The corresponding jump conditions at the critical surface may be derived from Eq. (72) directly and by integrating Eqs. (73) and (74) over $4\pi r^2 dr$. We study the case where $[\rho] = [v] = [T] = 0$ at r_c . In this limit, Eq. (74) implies

$$[q]_{r_c} \equiv q(r_c + \delta r) - q(r_c - \delta r) = I. \quad (75)$$

It is straightforward to show that the temperature at r_c is determined by I , λ , and ϕ if r_c lies in the saturated regime. The saturated heat flow given by expression (71) can only jump discontinuously as required by Eq. (75) if the temperature gradient changes sign at r_c . We know that $dT/dr > 0$ for $r < r_c$, since the temperature is very low behind the ablation front. We conclude that $dT/dr < 0$ for $r > r_c$. Equation (75) then yields

$$[q]_{r_c} = 10 \phi \rho_c c^3 (r_c) = I, \quad (76)$$

$$c_c \equiv c(r_c) = \left(\frac{I}{10\phi\rho_c} \right)^{1/3} \quad (77)$$

Thus the temperature at the critical surface is determined by I , ρ_c , and ϕ . It can be shown from our solutions that r_c will fall in the flux-limited regime, as required by expression (76), if the saturation parameter defined by Eq. (70) satisfies

$$\sigma_0 = \frac{13}{\phi^{7/3} Z} \left(\frac{I}{10^{15} \frac{\text{W}}{\text{cm}^2}} \right)^{4/3} \left(\frac{0.1 \text{ cm}}{R_a} \right) \left(\frac{\lambda}{1 \mu\text{m}} \right)^{14/3} > 1. \quad (78)$$

(This expression assumes $\bar{A}/Z \cong 2$ and $\epsilon n \Lambda \cong 10$.) The above criterion is relatively easy to satisfy for parameters typical of present and planned laser-fusion systems.

A second important feature of the flux-limited regime, for $r < r_c$, is that the Mach number is constant, depending only on the flux limit ϕ . For $r < r_c$, the energy equation in the saturated region becomes

$$M_s(1 + 1/5 M_s^2) = 2\phi = \text{constant}. \quad (79)$$

The momentum equation then gives the temperature scaling

$$T = T_c (r/r_c) \left(\frac{4}{1+M_s^2} \right) \quad (80)$$

The solutions of Eq. (79) are shown in Fig. 4-71. For $\phi \ll 1$, $M_s \cong 2\phi$. For $\phi \gg 1$, $M_s \cong (10\phi)^{1/3}$. Thus, if $\phi < 0.6$, $M_s < 1$ and the flow may not affect plasma instabilities too strongly. The flow becomes supersonic for $\phi > 0.6$; its influence on instabilities in this regime must be carefully considered.

In the classical region, closer to the ablation surface, we obtain analytic solutions to the energy equation when the ablation front moves subsonically relative to the material in front of it. Thus, our solutions will apply to ablative implosions but

Fig. 4-71. Mach number in the saturated region, M_s , vs flux-limit parameter ϕ . The flow at the critical radius is supersonic for $\phi > 0.6$.

Fig. 4-72. Temperature profile from steady-state theory compared with dynamical calculation using LASNEX. There are no free parameters in the theoretical profile. Parameters are $\phi = 0.2$, $\sigma_0 = 2 \times 10^4$, $I = 1.6 \times 10^{14} \text{ W/cm}^2$, $\lambda = 5 \mu\text{m}$, and $R_a = 0.07 \text{ cm}$.

not to "exploding pusher" targets in which the electron thermal wave precedes the hydrodynamic motion. One can show that if the flow is classical and $\phi < 1$, then the energy equation and momentum equation decouple, because the Mach number satisfies $M < 2$. When this is the case, the solution to the energy equation satisfying $T \rightarrow 0$ at $r = R_a$ is

$$T = T_c \left(\frac{\dot{m}}{\dot{m}_{\text{class}}} \right)^{2/5} \left(1 - \frac{R_a}{r} \right)^{2/5}, \quad (81)$$

$$\dot{m}_{\text{class}} \equiv \frac{16}{25} R_a \frac{\kappa(r_c)}{k_b} \frac{\bar{A} m_p}{Z + 1}. \quad (82)$$

The global solutions for $T(r)$ are obtained by matching the temperatures given by Eqs. (80) and (81) at the point where the classical and saturated electron heat fluxes are equal.

We have compared our idealized, steady-state results with numerical calculations using the hydrodynamics code LASNEX.¹⁴⁹ We chose a time in the calculation when $\dot{m}$ was independent of radius, as required by the steady-state hypothesis. Figure 4-72 shows the analytic results and those

Table 4-12. Critical radius, ablation pressure, and ablation rate from theory and from LASNEX calculation. Parameters are described in Fig. 4-72

Ablation characteristic	Theory	LASNEX
r_c (cm)	0.25	0.20
P_A (dynes/cm ²)	0.7×10^{13}	1.0×10^{13}
$\dot{m}$ (g/s)	0.9×10^4	1.5×10^4

from a sample one-dimensional, one-temperature computer calculation with parameters $I = 1.6 \times 10^{14}$ W/cm², $R_a = 0.07$ cm, $\phi = 0.2$, $\lambda = 5.0$ μ m, and $\sigma_0 = 2. \times 10^4$. Numerical and theoretical values of the Mach number at r_c , the mass loss rate, the critical radius, the ablation pressure, and the sound speed at r_c are shown in Table 4-12.

The completed analytic solution yields scaling laws for the ablation rate and critical radius. These are obtained by matching the classical and flux-limited temperatures, Eqs. (80) and (81), at the radius where $q_{\text{classical}} = q_{\text{saturated}}$. The basic parameter in the scaling laws is σ_0 , the ratio of classical to saturated heat flux at r_c , given by Eq. (78). The present theory is valid for $\sigma_0 > 1$. Apart from factors of order unity, which are described by the function $H(\phi)$ in Ref. 145, the critical radius is given by

$$r_c \sim R_a \sigma_0^{\frac{1}{2}} \left(\frac{1+M_s^2}{6+M_s^2} \right) \quad (83)$$

M_s is obtained from Eq. (79) or Fig. 4-71. When $\sigma_0 \gg 1$ and the flow is highly saturated, the critical surface must move farther from the ablation surface. This is because the relatively inefficient saturated conduction needs a longer distance to sustain the required temperature drop

$$T(r_c) - T(R_a) = \frac{I}{k_b} \left(\frac{\bar{A}m_p}{\bar{Z} + 1} \right) \left(\frac{I}{10\phi\rho_c} \right)^{2/3} \quad (84)$$

between the critical surface and the ablation surface.

The ablation rate is

$$\dot{m} \sim \left[4\pi R_a^2 \rho_c \left(\frac{I}{10\phi\rho_c} \right)^{1/3} \right] \sigma_0 \left(\frac{1+M_s^2}{6+M_s^2} \right) \frac{g}{s} \quad (85)$$

This is simply $(4\pi r_c^2 \rho_c M_s c_s)$, with expression (77) substituted for c_s and Eq. (83) for r_c . Noting the scaling of σ_0 from Eq. (78), we conclude that the mass loss rate is enhanced by using shorter wavelength lasers so that ρ_c is higher.

Finally, we note that our analysis implicitly requires the range of hot electrons created at the critical surface to be less than the thickness of the saturated region. Otherwise, the hot electrons could penetrate into the inner classical zone, where we have explicitly taken the mean free path to be small. The condition that this not occur is

$$\sigma_0 \leq \frac{7 \times 10^3}{(\phi Z)^{3/2}}, \quad \phi \ll 1 \quad (86)$$

If inequality (86) is satisfied, corona-core decoupling¹⁵⁰ will be prevented.

In summary, we have found analytical solutions describing steady spherical ablation. The ablation rate is found to depend sensitively on the parameter σ_0 , which represents the ratio of classical to flux-limited electron heat flux and scales as $\sigma_0 \propto (I^{4/3} \lambda^{14/3} \phi^{-7/3})$. The outflow in the flux-limited regime for $r < r_{\text{flux-lim.}}/(n_e m_e v_{te}^3) \gtrsim 0.1$. Such supersonic flows may have a strong effect on plasma instabilities in this regime.

References

138. J. L. Bobin, *Phys. Fluids* **14**, 2341 (1971).
139. F. Floux, *Nuc. Fusion* **11**, 635 (1971).
140. J. Nuckolls, *Laser Induced Implosion and Thermonuclear Burn*, Lawrence Livermore Laboratory, Rept. UCRL-74345 (1972).
141. R. E. Kidder, *Nuc. Fusion* **14**, 797 (1974).
142. K. A. Brueckner and S. Jorna, *Rev. Mod. Phys.* **46**, 325 (1974).
143. K. Lee, D. Forslund, J. Kindel, and E. Lindman, *Phys. Fluids* **20**, 51 (1977).
144. S. J. Gitomer, R. L. Morse, B. S. Newberger, *Phys. Fluids* **20**, 234 (1977).
145. L. L. Cowie and C. F. McKee, *Astrophys. J.* **211**, 135 (1977).
146. L. Spitzer, Jr., *Physics of Fully Ionized Gases* (Wiley Interscience, N.Y., 1962), p. 144.

147. R. L. Morse and C. W. Neilson, *Phys. Fluids* **16**, 909 (1973); W. M. Manheimer and H. H. Klein, *Phys. Fluids* **18**, 1299 (1975).
148. R. C. Malone, R. L. McCrory, and R. L. Morse, *Phys. Rev. Lett.* **34**, 721 (1975); W. C. Mead et al., *Phys. Rev. Lett.* **37**, 489 (1976).
149. G. Zimmerman, *Numerical Simulation of the High Density Approach to Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCR!-74811 (1973).
150. R. E. Kidder and J. W. Zink, *Nuc. Fusion* **12**, 325 (1972).

Authors

C. E. Max

C. F. Mc Kee

W. C. Mead

4-7.3 Energy Flux Limitation by Ion Turbulence

Distribution functions that transport heat can be unstable to the ion acoustic instability,¹⁵¹⁻¹⁵⁴ and the resulting ion turbulence can significantly reduce the thermal conductivity of the plasma. Previous estimates of this anomalous thermal conductivity have not self consistently taken into account the concomitant effects of the ion turbulence on other transport coefficients, such as the resistivity or the ion heating rate. These concomitant effects may play an important role. For example, the ion heating will modify the instability threshold. Our goal here is to derive a set of anomalous transport coefficients that are internally self-consistent and that can readily be incorporated into fluid codes.

To achieve this ready input to fluid codes, some rigor was sacrificed. In a future publication we will more rigorously examine anomalous flux limitation in the limit of no time dependence and compare the more accurate results with the simpler results presented here.

The basic features of our treatment may be summarized as follows:

- The distribution function is modeled as the sum of a Maxwellian with density, velocity, and temperature (n, u, T) and an additional piece with heat flux Q and vanishing density, temperature, and velocity.^{155,156}
- The equations for the first four moments (for

Fig. 4-73. Schematic of an electron distribution that carries a heat flux but no current: (a) the distribution function versus v_x and (b) contours of this distribution in v_x, v_y space.

n, v, T , and Q) are calculated assuming a quasi-linear collision term on the right side of the Vlasov equation.

- Anomalous transport coefficients are calculated in terms of fluctuation spectra that assumes an ion acoustic instability generated by the return current.

- Important anomalous effects are thermal flux limitation, ion heating, electron cooling, current generation, and anomalous absorption of the laser light due to enhanced inverse bremsstrahlung on the ion density fluctuations:

- Ion acoustic fluctuation amplitudes are calculated by now standard arguments concerning ion trapping.

Formulation of the Model

A typical electron distribution that has a heat flux in the x direction but no net particle current is shown in Fig. 4-73(a). Figure 4-73(b) shows contour lines of f in the v_x, v_y plane. The return current drives an ion acoustic instability with a three-dimensional spectrum of unstable wave numbers k . Since the unstable wave spectrum is not one dimensional, we expect that quasi-linear theory will be

valid for the electrons.¹⁵⁷ We model the electron distribution function as

$$f(u) = \frac{n}{(2\pi v_e)^{3/2}} \exp \left\{ -\frac{(u_x - v)^2 + u_y^2 + u_z^2}{2v_e^2} \right\} \times \left[1 + \frac{Q}{3nmv_e^3} \left\{ \left(\frac{u_x - v}{v_e} \right)^3 - 3 \frac{u_x - v}{v_e} \right\} \right] \quad (87)$$

assuming that the hydrodynamic velocity and heat flux are in the x direction.

This model for $f(u)$ is clearly somewhat arbitrary. It is the simplest extension of a Maxwellian distribution to include a heat flux, and it allows us a simple and tractable description. As a flux limit, we will insist that

$$Q < \frac{3}{2} nmv_e^3, \quad (88)$$

which is approximately a condition that $f(u) > 0$ for positive ($\parallel$ to Q) u .¹⁵⁸

As is clear from Fig. 4-73, the return current, which is carried by the main body electrons, may drive unstable ion acoustic waves. If the ion velocity is v_i , the growth rate of ion acoustic waves whose wave vector k is parallel to the return current (i.e., antiparallel to Q) is given approximately by

$$\gamma(k) \approx \sqrt{\frac{\pi}{8}} \frac{m}{M} \left[k(v_e - v_i) - \omega - \frac{kQ}{nmv_e^2} - \omega \left(\frac{M}{m} \right)^{1/2} \left(\frac{T_e}{T_i} \right)^{3/2} \exp \left(-\frac{\left(\frac{T_e}{2T_i} + \frac{3}{2} \right)}{1 + k^2/k_0^2} \right) \right] - \nu_{ii}/2 \quad (89)$$

where we have assumed the sound speed is given by $v_s^2 \approx (T_e + 3T_i)/M$, $T_i \ll T_e$. Also we have allowed for ion collisional damping since the ions can be much colder than the electrons. However, if

$\nu_{ii} \ll \omega_{pi}$, the ion collisional damping terms should be unimportant.

One can easily show that the first three moments of Eq. (87) are n, v, T where $T = mv_e^2$, and the heat flux,

$$\int d^3 u \frac{1}{2} m(u_x - v)^3 f = Q.$$

The collision term in the Vlasov equation, Cf , is taken to be the standard quasi-linear term

$$Cf = \sum_k \frac{1}{2} \frac{\partial}{\partial u} \cdot \underline{k} \left(\frac{e\phi(k)}{m} \right)^2 \quad \text{Im} \frac{1}{\omega - \underline{k} \cdot \underline{u}} \underline{k} \cdot \frac{\partial f}{\partial \underline{u}} \quad (90)$$

where the potential fluctuations are taken to be

$$\phi(\underline{r}, t) = \sum_k \phi(k) \cos(\underline{k} \cdot \underline{r} - \omega t).$$

Taking the first four moments of the electron Vlasov equation, then, gives the following equations for n, v, T , and Q :

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x} nv = 0, \quad (91)$$

$$nm \frac{\partial v}{\partial t} + nmv \frac{\partial v}{\partial x} + \frac{\partial}{\partial x} nT_e + neE = C_{ve}, \quad (92)$$

$$\frac{\partial}{\partial t} \frac{3}{2} nT_e + \frac{\partial}{\partial x} \frac{3}{2} nvT_e + nT \frac{\partial v}{\partial x} + \frac{\partial Q}{\partial x} = C_{Te}, \quad (93)$$

$$\frac{\partial Q}{\partial t} + \frac{3}{2} nT \frac{\partial v}{\partial t} + \frac{3}{2m} \frac{\partial}{\partial x} nT^2 + \frac{\partial}{\partial x} vQ + \frac{3}{2} Q \frac{\partial v}{\partial x} + \frac{3}{2} nTv \frac{\partial v}{\partial x} + \frac{3}{2} n \frac{e}{m} ET_e = C_{Qe}, \quad (94)$$

where

$$C_{ve} = \int d^3u \, m u_x C_f, \quad (95)$$

$$C_{Te} = \int d^3u \, \frac{1}{2} m (u_x - v)^2 + u_y^2 + u_z^2 C_f, \quad (96)$$

$$C_{Qe} = \int d^3u \, \frac{1}{2} m (u_x - v)^3 C_f. \quad (97)$$

To accurately determine the C_e 's, we need to know $\text{Im}[1/(\omega - k \cdot u)]$. There are two contributions: the resonant and nonresonant parts. To get the nonresonant part, we must know how the waves are growing both in space and time.

We will now make one of the approximations that allow us to put our final results into a form that can easily be incorporated in fluid codes. That is, we will neglect all nonresonant contributions to $\text{Im}(\omega - kv)^{-1}$ and keep only the resonant parts in all electron equations. This is certainly a valid approximation near marginal stability. Since the instability does drive the plasma towards marginal stability, neglect of nonresonant diffusion is probably a reasonable assumption. Furthermore, even if the plasma is far from marginal stability (for instance $T_i \approx 0$), one can show that the nonresonant contributions to the C_e 's are either much less than or roughly equal to the resonant contributions, depending on which moment equation one considers. Thus, keeping only resonant contributions to the C_e 's will at worst be qualitatively correct.

Before calculating the C_e 's, let us consider the C_i 's, the analogous terms in the ion fluid equations. In taking moments of the quasi-linear term in the ion Vlasov equation one has the same problem of how to deal with resonant and nonresonant ion velocity space diffusion. It is more complicated than for electrons because either resonant or nonresonant diffusion can dominate. If the ion temperature is very low, there is virtually no resonant diffusion and the nonresonant diffusion dominates; on the other hand, if the ion temperature is higher so the wave is near marginal stability, resonant diffusion dominates.

Whichever does dominate, energy and momentum must be conserved between electrons and ions

since the electrostatic contributions to wave energy density and wave momentum flux are very small for an ion acoustic wave with $k\lambda_{De} \ll 1$. Thus, we will use in the ion equations collision integrals that conserve energy and momentum, or

$$C_{Ti} = -C_{Te} - (\underline{v} - \underline{v}_i) \cdot \underline{C}_{ve}, \quad (98)$$

$$C_{vi} = -C_{ve}, \quad (99)$$

where $\underline{v}_i$ is the ion velocity. We will neglect ion heat transport since, at least in laser-produced plasmas, it is negligible compared to electron heat transport.

To obtain a qualitatively correct result that can easily be incorporated into a fluid code, we will reduce the wave spectrum to a single unstable wave of wave number k antiparallel to Q (parallel to the return current). Then one can easily calculate

$$C_{ve} = \frac{\pi m k}{2\sqrt{2\pi} |k|} \left[\frac{n(\omega - kv)}{v_e^3} + \frac{kQ}{mv_e^5} \right] \left(\frac{e\phi(k)}{m} \right)^2 \quad (100)$$

$$C_{Te} = \left(\frac{\omega}{k} - v \right) C_{ve}, \quad (101)$$

$$C_{Qe} = \frac{3}{2} \left(\frac{\omega}{k} - v \right)^2 C_{ve}, \quad (102)$$

assuming $\omega/k \ll v_e$. The frequency of an ion acoustic wave is taken as $\omega = |k| v_s$, v_s being the sound speed.

Anomalous Transport Coefficients

Let us now show how Eqs. (91-94) can relate the thermal flux to the temperature gradient in the limit of

$$\left\{ \begin{array}{l} mn v_e^2 v \\ mn v_e^2 v_s \end{array} \right\} \ll Q \ll mn v_e^3. \quad (103)$$

The right side of Eq. (103) simply says that the flux is strongly limited. The left side says that even

though limited, the thermal flux is still the dominant energy transport process. If Eq. (103) is satisfied, Eqs. (92) and (94) can be combined to

$$\frac{\partial Q}{\partial t} + \frac{3}{2m} n T_e \frac{\partial T_e}{\partial x} = C_{Qe} - \frac{3}{2m} T_e C_{ve} \\ \approx \frac{3\pi |k| n T^3}{4m\sqrt{2\pi}} \frac{Q}{nmv_e^3} \left(\frac{e\phi(k)}{T_e} \right)^2 \quad (104)$$

Assuming that the velocity defined by $(\partial/\partial t)/(\partial/\partial x)$ from the left side of Eq. (104) is less than the thermal flux velocity Q/nmv_e^2 , the ratio of these two terms is less than $Q^{-1/2} (nmv_e^2)^2 \ll 1$ so that the time-derivative term may be neglected. Thus, Eq. (104) is reduced to a relation between the temperature gradient and thermal flux

$$Q = K_{an} n \frac{\partial T_e}{\partial x} \quad (105)$$

where

$$K_{an} = \frac{2\sqrt{2}\pi}{\pi |k|} v_e \left(\frac{e\phi(k)}{T_e} \right)^{-2} \quad (106)$$

Notice that the flux is proportional to the temperature gradient exactly as in the classical case. If there are also classical collisions, one can simply add the reciprocals of the classical and anomalous thermal diffusion coefficients to get the reciprocal of the total diffusor coefficient

$$K_T^{-1} = K_{an}^{-1} + K_{cr}^{-1} \quad (107)$$

A simple estimate can be given to show that a modest level of fluctuations will strongly reduce the heat transport. Denoting $\partial/\partial x$ by $1/L$ and approximating k by $0.5\lambda_{De}$, we have

$$Q = n\theta_e v_e f \quad (108)$$

where

$$f \approx \frac{3\lambda_{De}}{L} \left(\frac{e\phi}{T} \right)^{-2}$$

Here f is the anomalous flux limit defined as the reduction of the heat flux from its free streaming value. Assuming some typical values for recent laser plasma experiments ($\theta_e = 1$ keV, $n = 10^{22} \text{ cm}^{-3}$ and $L = 10 \mu$) and a modest fluctuation level ($e\phi/T = 0.1$), we obtain $f \approx 10^{-1}$.

Now let us examine some of the other features of the fluid equations. If there is no hydrodynamic velocity and if $\omega \ll kQ/nmv_e$, Eq. (100) shows that C_{ve} has the same sign as Q so that an electric current is generated with the electrons drifting parallel to Q and the ions traveling antiparallel. As is apparent from Eq. (89), this electric current opposite to the return current lowers the growth rate and brings the system toward marginal stability. Another way to view current generation is as the plasma's attempt to reduce the energy flux and transport the energy by hydrodynamic motion of the electrons instead. Of course any net current generated will produce a magnetic field that will be azimuthal if the plasma is produced by a focused laser.

Another important effect of the instability is to produce electron cooling if there is no net relative velocity between the ions and electrons and if $\omega \ll kQ/nmv_e^2$. As is apparent from Eq. (101), the sign of C_{Te} is negative since k and Q have opposite signs. This result, which may appear surprising, is actually quite reasonable. In a current-driven ion acoustic instability, the ions are always heated and the electrons lose energy. However, the electrons are heated nevertheless since they lose more drift energy than they gain in thermal energy. For an ion acoustic instability driven by a return current, however, there is no drift energy to lose; therefore the electrons must lose thermal energy to balance the thermal energy the ions gain. The electron cooling can also be viewed as the plasma's attempt to stop the heat flux (and bring the electrons closer to a Maxwellian distribution) by taking particles out of the nonthermal tail and putting them into the body of the distribution function. This electron cooling and ion heating also tend to drive a collisionless plasma towards marginal stability. Note that our one-temperature model for the electrons is rather ideal.

A better description would allow at least two electron temperatures—one for the cold particles providing the return current and one for the heated particles.

If the laser light is present in the region where the ion acoustic instability is occurring, another important effect is anomalous inverse bremsstrahlung from the ion density fluctuations.¹⁵⁹⁻¹⁶² That is, an ion density fluctuation at wave number k can scatter laser light at frequency Ω into a plasma oscillation at (Ω, k) . Since k for an ion acoustic instability is roughly $k_D/2$, the plasma oscillation is strongly damped and the laser energy is deposited in electrons moving at roughly twice the thermal velocity. Thus, this anomalous absorption process will not give rise to a very high energy tail on the electron distribution function.

Taking a simple Lorentzian model for D_L ,

$$D_L(k, \omega) = 1 - \frac{\omega_{pe}^2}{(\omega + ikv_e)^2} \quad (109)$$

assuming the ion acoustic spectrum vanishes outside a 45° half-angle cone about the direction of the return current and has a flat spectrum inside from $k = 0$ to $k = k_D/2$, we find that the ratio of anomalous to classical collision frequency is

$$\frac{\nu_{an}}{\nu_{cl}} \approx \frac{1.5 \pi^2 (n\lambda_D^3) \left(\frac{e\phi}{T_e}\right)^2}{\ln(4\pi n\lambda_D^3)} \quad (110)$$

where for an ion acoustic wave we have made use of the fact that $n(k)/n_0 = e\phi(k)/T$. The anomalous damping of the wave, of course, gives rise to an anomalous electron heating rate

$$\nu_{an} \frac{E_0^2}{8\pi} \quad (111)$$

which should be added to the right side of the electron temperature equation. As we remarked earlier, this electron heating does not produce a long non-thermal tail, but rather heats principally the electrons with velocities $\sim$ few v_{Te} . Also, it is worth noting that the electron heating, since it increases

T_e/T_i , drives the plasma toward instability rather than toward greater damping.

Now we have all anomalous transport coefficients for a fluid code in terms of e/T (assuming $k \approx k_D/2$). Although the transport coefficients are approximate, they are at least internally self consistent with one another. To determine $e\phi/T_e$, one can now use the great number of theories and simulations of the ion acoustic instabilities.¹⁶³⁻¹⁷¹ Theories and simulations both indicate that the instability stabilizes by ion trapping. Hence the level can be estimated on the basis of simple trapping arguments to be

$$\frac{e\phi_{tr}}{kT} \approx \frac{1}{4} \left(\frac{1}{\sqrt{1 + k^2\lambda_D^2}} - \sqrt{3} \frac{T_i}{T_e} \right)^2 \quad (112)$$

Incorporation into a Fluid Code

Let us now discuss how to incorporate these results into a fluid code. At a particular time, let us say that all fluid parameters are known as a function of x . We then want to determine $e\phi/T$ so as to get the anomalous transport coefficients. To do so, first assume $\phi = \phi_{tr}$ at each x , that is assume the plasma is unstable. Then calculate the heat flux

$$Q = \left(K_{cl}^{-1} + K_{an}^{-1} \right)^{-1} n \frac{\partial T_e}{\partial x} \quad (113)$$

Inserting the calculated value of Q into the expression for the growth rate, Eq. (89), then tells whether the plasma is in fact unstable and whether the choice $\phi = \phi_{tr}$ is consistent. If it is, then retain the calculated value of the total heat flux and the chosen value of $e\phi/T_e$. All other anomalous transport coefficients are calculated with this value of $e\phi/T_e$.

For the values of x which the plasma turns out to be stable with Q determined by $\phi = \phi_{tr}$, try $e\phi/T_e = 0$ (i.e., classical transport). Then the heat flux is $Q = K_{cl} n(\partial T_e/\partial x)$. Insert this expression for Q into Eq. (89). If the plasma is stable, the value of $e\phi/T_e$ is consistent, and there is no anomalous transport. If Eq. (89) shows that for certain values of x , the plasma is unstable for $\phi = 0$, but stable for ϕ_{tr} , then

Q is determined here by the marginal stability condition. That is, Q is determined by setting the right side of Eq. (89) equal to zero. Then the value of $e\phi/T_e$ is found by setting

$$Q = \left[K_{an}^{-1} \left(\frac{e\phi}{T_e} \right) + K_{cl}^{-1} \right]^{-1} n \frac{\partial T}{\partial x}. \quad (114)$$

Once $e\phi/T_e$ is found (which will always be between 0 and $e\phi_u/kT_e$), all anomalous transport coefficients are thereby determined. Of course, if the relative electron-ion velocity and the return current are in opposite directions, the sign of k is chosen so that

$$k(v_e - v_i) - \frac{kQ}{nmv_e^2} > 0. \quad (115)$$

That is, the wave-phase velocity is in the direction of whichever current dominates.

Although it is difficult to assess the effects of flux limitation and the associated anomalous transport without numerical fluid code studies, one can envision the following sequence. Laser energy is absorbed and transported to the core of the slab or pellet. The transport generates an ion acoustic instability that tries to set up an electric current, heat the ions, and cool the electrons. Because of the presence of the laser light, however, the electrons are heated by enhanced inverse bremsstrahlung, and the laser light continues to be absorbed. Since the ion acoustic instability has $k \sim k_D/2$, the absorption of laser light does not produce a long tail of superthermal electrons. This sequence of events can now be readily tested with present codes.

References

151. R. C. Malone, R. L. McCrory, and R. L. Morse, *Phys. Rev. Lett.* **34**, 721 (1975).
152. D. Forslund, *J. Geophys. Res.* **75**, 17 (1970).
153. E. J. Valeo and I. B. Bernstein, *Phys. Fluids* **19**, 1348 (1976).
154. W. M. Manheimer and H. H. Klein, *Phys. Fluids* **17**, 1889 (1974).
155. M. Z. Caponi and N. A. Krall, *Phys. Fluids* **18**, 699 (1975).
156. W. M. Manheimer, D. Colombant, and R. Flynn, *A Theory of Anomalous Energy Flux and Deposition in a Laser Produced Plasma*, NRL Memorandum 3119, also *Phys. Fluids*, to be published.
157. W. M. Manheimer, *Phys. Fluids* **16**, 945 (1973).
158. Other possible ways of determining the flux limit are $f > 0$ for all u , or f has only a single maximum. The former is not reasonable for our model distribution functions since for $Q \neq 0$, $f < 0$ for sufficiently large, negative u . The latter does not seem reasonable either since double peaks, if they exist at all, are right near the electron thermal velocity. Such electron distribution functions are not generally unstable.
159. J. M. Dawson, "Radiation from Plasmas," in *Advances in Plasma Physics*, Vol. 1 (John Wiley and Sons, New York, 1968) p. 1.
160. J. M. Dawson and C. Oberman, *Phys. Fluids* **5**, 517 (1962).
161. J. M. Dawson and C. Oberman, *Phys. Fluids* **6**, 394 (1963).
162. R. J. Faehl and W. L. Kruer, *Phys. Fluids* **20**, 55 (1977).
163. M. Lampe, W. M. Manheimer, J. McBride, J. Ohrens, K. Papadopoulos, R. Shanny, and R. Sudan, *Phys. Fluids* **15**, 2652 (1972).
164. W. Manheimer and R. Flynn, *Phys. Rev. Lett.* **27**, 1175 (1971).
165. W. Manheimer and R. Flynn, *Phys. Fluids* **17**, 409 (1974).
166. J. H. Ohrens and J. M. Dawson, *Anomalous D.C. Plasma Resistivity Due to Ion Acoustic Turbulence*, NRL Memorandum 2850.
167. M. Z. Caponi and R. C. Davidson, *Phys. Rev. Lett.* **31**, 86 (1973).
168. J. P. Borsi, J. M. Dawson, J. H. Ohrens, and K. V. Roberts, *Phys. Rev. Lett.* **25**, 706 (1970).
169. D. Biskamp and R. Chodura, *Phys. Rev. Lett.* **27**, 1553 (1971).
170. D. Biskamp, K. U. von Hagenow, and H. Welter, *Phys. Letters* **39A**, 351 (1972).
171. A. M. Sleeper, J. Weinstock, and B. Bezzerides, *Phys. Fluids* **16**, 1508 (1973).

Author

W. M. Manheimer*

4-7.4 Growth of Current Filaments in Laser Fusion Plasmas

In laser-driven, inertial-confinement fusion schemes,¹⁷² the useful hydrodynamic work is done at the ablation surface, which has a density many times greater than the maximum density (n_{cr}) to which the laser light propagates. The transfer of absorbed energy between the critical surface—a sphere of radius r_c where the electron density $n(r_c) = n_{cr}$ —and the ablation surface of radius r_a is

*LLL consultant from Naval Research Laboratory, Washington, D.C.

presumed to smooth any small irregularities in the absorbed energy so that a very nearly uniform energy flux and pressure are maintained at the ablation surface. This uniformity is essential since the ablation surface is Rayleigh-Taylor unstable.¹⁷³ Impression there of even slight pressure nonuniformities can result in large asymmetries, and thus much lower compressions, in the final state.

The presumption that the transfer process acts to smooth inhomogeneities in energy flux is based on the use of the diffusion approximation to describe the thermal conduction. In many cases, collective absorption processes¹⁷⁴ generate a significant number of high-energy electrons whose collisional mean free path can be greater than r_a . These electrons are not correctly described by the diffusion approximation. Nevertheless, inhomogeneities in the flux carried by these "free-streaming" electrons are also expected to be reduced as the ablation surface is approached, in this case by phase mixing.

The finite mean free path of the energetic electrons allows the possibility of collisionless plasma instabilities associated with the energy transfer. It has already been pointed out¹⁷⁵ that the (colder) electron current that flows from r_a to r_c , in order to preserve charge neutrality, may excite electrostatic-ion-acoustic turbulence. If this occurs, the enhanced level of ion fluctuations resulting from this turbulence will increase the electron-ion collision frequency and possibly reduce the electron thermal conductivity.

We discuss here another source of free energy implicit in the transfer process that can drive an electromagnetic instability by velocity-space anisotropies. This instability may ultimately result in the formation of energy conduction channels. The model is as follows: Consider the spherical shell of plasma between r_a and r_c as shown in Fig. 4-74(a). Decompose the plasma electrons into a cold, collision-dominated component whose principal

Fig. 4-74. (a) Conduction region geometry showing ablation surface ($r = r_a$), critical surface ($r = r_c$), and cone angle $\theta_0(r) = \sin^{-1}(r_a/r)$. The hot electron distribution function is assumed to vanish for $\cos \theta = \hat{r} \cdot \hat{r} > \cos \theta_0$. (b) Cartesian space and cylindrical velocity-space coordinates. The cylinder axis and the $\hat{z}$ axis both lie in the direction of $\hat{r}$.

source is the ablation surface, and into a hot electron component whose principal source is the absorption surface. A hot electron that hits the ablation surface is absorbed, and a cold electron is emitted. Let the hot-electron mean free path $\lambda_{h,mfp}$ be much greater than r_a . We show below that the ambipolar potential drop in a distance $\lambda_{h,mfp}$ can be much less than the hot electron temperature T_h . Under these conditions, and for radii $r < \lambda_{h,mfp}$, the hot electron velocity distribution f vanishes within the cone-shaped region in velocity space:

$$\cos \theta \equiv \hat{v} \cdot \hat{r} > \cos \theta_0 \equiv 1 - \left(\frac{r_a}{r} \right)^2 \quad (116)$$

by virtue of the "shadow" cast by the ablation surface. For θ greater than θ_0 , the distribution is affected by the uniformity of energy deposition since the electrons comprising this portion of velocity space have contact with the absorption region. We consider here only anisotropies intrinsic to the geometry (i.e., we assume f isotropic for θ greater than θ_0).

The "loss cone" in the hot electron distribution results in a temperature anisotropy, with the azimuthal temperature exceeding the radial temperature. Such a distribution is susceptible to the electromagnetic Weibel^{176,177} instability. We have obtained the dispersive properties of this instability for the two-component plasma described above.

Dispersion Relation

The cold electrons of density n_c and velocity u_c satisfy the continuity and momentum conservation equations

$$\frac{\partial n_c}{\partial t} + \nabla \cdot n_c u_c = 0, \quad (117a)$$

$$m n_c \left(\frac{\partial u_c}{\partial t} + u_c \cdot \nabla u_c \right) = -q n_c E - T_c \nabla n_c - \nu m n_c u_c. \quad (117b)$$

The isothermal equation of state $T_c = \text{constant}$ has been employed. The drag term $-\nu m n_c u_c$ describes collisions with the background (immobile) ions.

The hot electrons are described by the Vlasov equation

$$\frac{\partial f}{\partial t} + v \cdot \nabla f - \frac{q}{m} \left(E + \frac{v}{c} \wedge B \right) \cdot \frac{\partial f}{\partial v} = 0. \quad (118)$$

The Maxwell field equations

$$\nabla \wedge E = -\frac{1}{c} \frac{\partial B}{\partial t}, \quad (119a)$$

$$\nabla \wedge B = \frac{4\pi}{c} j + \frac{1}{c} \frac{\partial E}{\partial t}, \quad (119b)$$

$$\nabla \cdot B = 0, \quad (119c)$$

complete the description.

The modes of interest have wave vector magnitudes $|k|$ much larger than $1/r_a$, so that the plasma may be assumed locally homogeneous. Cartesian coordinates, with $\hat{z} = \hat{r}/r$ in the direction of the cone axis, will be employed. The wave vector will be taken to lie in the $(\hat{x}, \hat{z})$ plane. Lowest (first-order) quantities will be designated by a zero (1) subscript where necessary for clarity. The hot electron current in lowest order,

$$j_{h,0} = -q \int dv v f_0(v, \theta) = q n (1 - \cos^2 \theta) \int_0^\infty dv v^3 f_0(v) \hat{z} \quad (120)$$

is balanced by an oppositely directed cold electron current

$$j_{c,0} = q n_{c,0} u_{c,0} = \frac{q^2 n_c}{\nu m} E_0, \quad (121)$$

which requires the electric field $\underline{E}_0$ to maintain it. In writing the second form of Eq. (120), the explicit form

$$f_0(v, \theta) = f_0(v) U(\cos \theta_0 - \cos \theta) \quad (122)$$

with U , the Heaviside step function, has been introduced.

Assuming perturbations of the form $\exp(i\mathbf{k} \cdot \mathbf{x} - i\omega t)$, the first-order cold-particle current is

$$\underline{J}_{c,1} = \frac{\omega_{pc}^2}{4\pi(\nu - i\Omega)} \left\{ \underline{E} - \frac{\mathbf{k} \cdot \underline{E}}{D_1 \Omega} \left[\frac{i\mathbf{k}T}{m(\nu - i\Omega)} - \underline{u}_{c,0} \right] \right\}, \quad (123a)$$

where we have made the definitions

$$\Omega \equiv \omega - \mathbf{k} \cdot \underline{u}_0, \quad (123b)$$

$$D_1 \equiv 1 + \frac{ik^2 T_c}{m\Omega(\nu - i\Omega)}. \quad (123c)$$

The ambipolar potential drop across a mean free path $\Delta\phi = E_0 \lambda_{h,mfp}$ may be estimated from Eq. (121) by using $n_h v_{Th} = n_h (T_h/m)^{1/2}$ for $n_c u_c$ there, with the result

$$\frac{q\nabla\phi}{T_h} \sim \frac{n_h}{n_c} v_c \left(\frac{m}{T_h} \right)^{1/2} \lambda_{h,mfp} \sim \frac{n_h}{n_c} \left(\frac{T_h}{T_c} \right)^{3/2}$$

Therefore, if

$$\frac{n_h}{n_c} \left(\frac{T_h}{T_c} \right)^{3/2} \ll 1, \quad (124a)$$

the effect of the ambipolar potential on the hot electron trajectories may certainly be neglected. This is a very conservative estimate. Actually, since we will

find real and imaginary frequencies can both be comparable to $k v_{Th}$, we need only satisfy the milder restriction $qE_0/T_h k \ll 1$, which may be rewritten in the form

$$\frac{v_c}{\omega_{ph}} \frac{c}{v_{Th}} \frac{n_h}{n_c} \ll 1, \quad (124b)$$

where k has been estimated by the hot electron skin depth ω_{ph}/c .

With neglect of the zeroth-order ambipolar potential, the linearized Vlasov equation may be solved for the hot-particle current with the result

$$\underline{J}_{h,1} = \frac{iq^2}{m} \int d\mathbf{v} \underline{v} \frac{[\mathbf{k} \cdot \underline{v} \cdot \underline{E} - \mathbf{E} \cdot \underline{v}]}{\omega(\mathbf{k} \cdot \underline{v} - \omega)} \cdot \frac{\partial f_0}{\partial \mathbf{v}} + \int d\mathbf{v} \frac{\underline{v} \cdot \underline{E}}{(\mathbf{k} \cdot \underline{v} - \omega)} \frac{\partial f_0}{\partial \underline{v}}. \quad (125)$$

Faraday's law, Eq. (119a), has been used to eliminate the magnetic field in Eq. (125). Substituting $\underline{J}_{c,1} + \underline{J}_{h,1}$ for $\underline{J}_1$ in Eq. (119b), rearranging terms, and again using Eq. (4a), we get the homogeneous vector equation

$$\left(\frac{c}{\omega} \right)^2 \left[\mathbf{k} \cdot \underline{E} - \kappa^2 \underline{E} \right] - \underline{v} \cdot \underline{E} + \frac{i\omega_{pc}^2}{(\nu - i\Omega)\omega} \left\{ \underline{E} - \frac{\mathbf{k} \cdot \underline{E}}{D_1 \Omega} \left[\frac{i\mathbf{k} T_c}{m(\Omega - i\nu)} - \underline{u}_0 \right] \right\} = 0 \quad (126)$$

where the dispersion tensor

$$\underline{\chi} \equiv \int d\mathbf{v} \frac{\underline{v} \underline{v} \cdot \mathbf{k}}{(\mathbf{k} \cdot \underline{v} - \omega)} \cdot \frac{\partial f_0}{\partial \mathbf{v}}. \quad (127)$$

The solutions of Eq. (126) decompose into a purely transverse mode for which $\underline{E} \times \underline{v} = 0$, and into two modes of coupled longitudinal-transverse character for which $\underline{E} \cdot \underline{v} = 0$. If $\mathbf{k} \times \underline{\hat{z}} = 0$, then the longitudinal and transverse modes become

decoupled. In this case, the two transverse modes satisfy the same dispersion relation

$$\epsilon_{\perp} = -\left(\frac{ck}{\omega}\right)^2 + 1 - \left(\frac{\omega_{ph}}{\omega}\right)^2 (1 + \chi_{\perp}) + \frac{i\omega_{pe}^2}{\omega(\nu - i\Omega)} = 0, \quad (128a)$$

while the longitudinal mode frequency satisfies

$$\epsilon_{\parallel} = 1 - \left(\frac{\omega_{ph}}{\omega}\right)^2 (1 + \chi_{\parallel}) + \frac{i\omega_{pe}^2}{\omega(\nu - i\Omega)} \left\{ 1 - \frac{k}{D_1 \Omega} \left[\frac{kT}{m(\nu - i\Omega)} - u_0 \right] \right\} = 0. \quad (128b)$$

Here, we have introduced transverse and longitudinal susceptibilities

$$\chi_{\perp} = \int d\mathbf{v} \frac{v_z^2 k_z}{(k_z v_z - \omega)} \frac{\partial f_0}{\partial v_z} \quad (129a)$$

and

$$\chi_{\parallel} = \int d\mathbf{v} \frac{v_z^2 k_z}{(k_z v_z - \omega)} \frac{\partial f_0}{\partial v_z}, \quad (129b)$$

respectively.

Solution

A numerical solution of the dispersion relation for $n_e = 0$ but including ion motion has been previously obtained¹⁷⁷ for the case of an anisotropic, bi-Maxwellian electron-distribution function. The growth rate of the transverse mode was found to have a single maximum as a function of k and to approach zero as $k \rightarrow 0$ and as $k \rightarrow k_{\max} \sim \omega_{ph}/c$. When $k_{\perp}/k_z \ll 1$, the quasi-transverse mode was found to behave in much the same way as

did the purely transverse mode except as $k \rightarrow k_{\max}$, where coupling to the longitudinal mode was found to be qualitatively important. The growth rate of the quasi-longitudinal (acoustic) mode was found to be much smaller than the maximum transverse-mode growth rate.

Because there are several parameters in Eq. (126), we consider here only the transverse mode, first for $k_{\perp}^2 = 0$ and then for $(k_{\perp}/k_z)^2 \ll 1$. Since the most unstable waves are shown to have wave vectors $k \gtrsim c/\omega_{ph}$, corresponding to wavelengths somewhat larger than 1μ if we equate n_h to n_{cr} for $1.06\text{-}\mu$ laser radiation, the potentially most dangerous modes (those for which $k_{\perp} \sim r_{\perp}^{-1}$) do indeed have a small perpendicular wave vector. Additionally, we find that, except for k near $k_{\max}$, the growth rate (for fixed k_z) has a local maximum at $k_{\perp}^2 = 0$.

Before presenting the numerical results for finite θ_0 , we analytically solve the dispersion relation for $\theta_0 \ll 1$, $k_{\perp} = 0$.

- $\theta_0 \ll 1$.

When θ_0 is small compared to unity, the eigenfrequency is also small, and only the small argument expansion of the dispersion function is needed. When $k_{\perp} = 0$, it is convenient to perform the velocity integral in cylindrical coordinates with perpendicular velocity, $v_{\perp}$, defined so that $\mathbf{v}_{\perp} \cdot \hat{\mathbf{z}} = 0$, as shown in Fig. 4-74(b). The dispersion function is then expressible in terms of the reduced distribution function

$$g(v_z) \equiv \pi \int_{v_{\perp, \min}}^{\infty} dv_{\perp} v_{\perp}^3 f(v_{\perp}^2, v_z^2) \quad (130)$$

with

$$v_{\perp, \min} = v_z \tan \theta_0, \quad v_z > 0, \\ 0, \quad v_z < 0.$$

If $\omega/kv_{Th} \ll 1$, then

$$\chi_{\perp} \sim \pi i \frac{d^2 g(0)}{dv_z^2} \frac{\omega}{k} + \chi_r \quad (131)$$

where χ_r is the principal value integral

$$\chi_r = \oint dv \frac{dg}{v} \quad (132)$$

For $\theta_0 \ll 1$, χ_r becomes, dominantly,

$$\begin{aligned} \chi_r &= 2\pi \int_{-\infty}^{\infty} dv_z \frac{d}{dv_z^2} \int_0^{\infty} dv_{\perp} v_{\perp}^3 f(v_{\perp}^2, v_z^2) \\ &= \pi \theta^4 \int_0^{\infty} dv_z v_z^2 f(0, v_z^2) \end{aligned} \quad (133)$$

Specializing to the case of a Maxwellian distribution

$$\begin{aligned} f(v_{\perp}^2, v_z^2) &= \left[(2\pi^3)^{1/2} v_{Th}^3 (1 + \cos \theta_0) \right]^{-1} \\ &\exp \left[- (v_{\perp}^2 + v_z^2) / 2v_{Th}^2 \right] \end{aligned} \quad (134)$$

we obtain explicitly

$$\begin{aligned} \chi_1 &\sim \left[i \left(\frac{\pi}{2} \right)^{1/2} \frac{\omega}{kv_{Th}} + 1 + \theta_0^4 \right] \\ &\times \left(\frac{\omega}{kv_{Th}}, \theta_0 \right) \ll 1 \end{aligned} \quad (135)$$

Substitution of Eq. (135) into the dispersion relation, Eq. (128a), yields the growth rate

$$\omega_i = \frac{\left[\theta_0^4 - \left(\frac{kc}{\omega_{ph}} \right)^2 \right] \frac{2}{\pi}^{1/2} kv_{Th}}{\left[1 + \frac{n_c}{n_h} \frac{kv_{Th}}{\nu} \left(\frac{2}{\pi} \right)^{1/2} \right]} \quad (136)$$

• $\theta_0 \sim 1$.

When θ_0 is finite, recourse must be made to a numerical solution. For this purpose, the hot electron distribution function was chosen to be Maxwellian for $\theta > \theta_0$ and zero otherwise. The temperature $T_h = mv_{Th}^2$ was set equal to $0.02 mc^2 = 11$ keV, a value representative of those obtained in computer simulation studies¹⁷⁴ of collective heating. The reduced distribution function g is shown in Fig. 4-75(a) for several values of θ_0 . When ν_c is greater than $(|ku_0|, |\omega|)$, the cold electrons are characterized completely by their conductivity $\theta = \omega_{pe}^2 / 4\pi\nu_c$, which enters through the combination $\mu \approx 4\pi(\sigma/\omega_{ph})(v_{Th}/c)$.

Solutions for $\omega = \omega_0(k_z) + i\omega_i(k_z)$ are shown in Fig. 4-76 for several values of μ . Figure 4-77 shows the variation of $\omega(k)$ with θ_0 for $\mu = 100$, which occurs, for example, if $n_h = 10^{21} \text{ cm}^{-3}$, $T_c = 0.1$ keV, and ion charge $Z = 1$. As suggested by Eq. (136), when $\mu kc/\omega_{ph} \ll 1$ the dispersion function is

Fig. 4-75. (a) Reduced velocity distribution function g defined in Eq. (15), which enters into the transverse susceptibility $\chi_{\perp}$, is shown for several values of θ_0 (radians). (b) Reduced velocity distribution function g_1 defined in Eq. (25), which enters into the second derivative $\partial^2 \chi_{\perp} / \partial k_{\perp}^2$ of the transverse susceptibility.

Fig. 4-76. Instability growth rate (a) and real frequency (b) vs k_z for several values of the normalized cold-electron conductivity $\mu = (qn_c/m\nu\omega_{ph})(V_{Th}/c)$. Perpendicular wave vector $k_\perp = 0$, hot-electron temperature $T_h = mv_{Th}^2 = 0.02mc^2 = 11$ keV, and cone angle $\theta_0 = 1.25$ radians.

needed only for small argument. In this case, the growth rate is well approximated by

$$\omega_i = \frac{\nu n_h}{n_c} \left[\operatorname{Re} \chi(i\delta \downarrow 0) - 1 - \left(\frac{kc}{\omega_{ph}} \right)^2 \right]. \quad (137)$$

The function $\operatorname{Re} \chi(i\delta \downarrow 0) - 1$ is plotted in Fig. 4-78.

Finally, we estimate the maximum $k_\perp^2$ for which instability occurs by calculating

$$\frac{\partial \omega}{\partial k_\perp^2} = - \left(\frac{\partial \epsilon_\perp}{\partial \omega} \right)^{-1} \left(\frac{\partial \epsilon_\perp}{\partial k_\perp^2} \right) \quad (138)$$

for $k_\perp^2 = 0$. In computing the derivatives, the additional functions

$$\frac{\partial \chi_\perp}{\partial \omega} = - \frac{1}{k_z} \int \frac{dv}{\left(v - \frac{\omega}{k_z} \right)} \frac{\partial^2 g}{\partial v^2}, \quad (139a)$$

$$\frac{1}{2} \frac{\partial^2 \chi_\perp}{\partial k_\perp^2} = - \frac{1}{k_z^2} \left[\chi_\perp + \int \frac{dv}{\left(v - \frac{\omega}{k_z} \right)} \frac{\partial^3 g_1}{\partial v^3} \right] \quad (139b)$$

are needed. Figure 4-75(b) shows the additional reduced distribution function

Fig. 4-77. Instability growth rate (a) and real frequency (b) vs k_z (again for $k_\perp = 0$) for several values of θ_0 (radians). Normalized cold electron conductivity $\mu = 100$; and hot electron temperature is 11 keV.

Fig. 4-78. $\text{Re } \chi_{\perp} (i\delta; 0)$ vs θ_0 , which can be used in Eq. (22) to evaluate the growth rate when $\mu kc/\omega_{ph} \gg 1$.

Fig. 4-79. Logarithmic derivatives of ω_i (a) and ω_r (b) with respect to $k_{\perp}^2$ evaluated at $k_{\perp} = 0$. Since $k_z^2 (\partial \ln \omega_i / \partial k_z^2) \approx -1$ except as k_z approaches the maximum unstable wave ($\partial \ln \omega_i / \partial k_{\perp}^2$) vector $k_{z, \max}$, the instability is expected to persist even for $k_{\perp} \sim k_z$. The change in sign of $\partial \ln \omega_i / \partial k_z^2$ as k_z^2 approaches $k_{z, \max}^2$ indicates that the growth rate maximizes for $k_{\perp} \neq 0$ there. Parameters are $\mu = 1$, $\theta_0 = 1.25$, and $T_h = 0.02 mc^2$.

$$y_1(v_z) \equiv \int_0^{2\pi} d\phi \int_{v_{1,\min}}^{\infty} dv_1 v_1^5 \sin^2 \phi \cos^2 \phi f(v_1^2 v_z^2) \quad (140)$$

for several values of θ_0 . The derivatives of ω_i and ω_r are shown in Figs. 4-79(a) and (b), respectively. These results indicate that the transverse mode continues to be unstable but with a reduced growth rate, even for $k_{\perp}$ comparable to k_z . Note that as k_z approaches the maximum unstable wave vector, $\partial\omega_i/\partial k_{\perp}^2$ changes sign, i.e., the growth rate maximizes for nonzero $k_{\perp}^2$.

Conclusions

We have shown the existence and examined the properties of an electromagnetic instability driven by velocity-space anisotropies that may occur in laser fusion targets. The instability is expected to play a role in the heat transfer process within a mean free path of the ablation surface. Previous studies¹⁷⁸⁻¹⁸⁰ of the nonlinear evolution of similar instabilities suggest that current and heat flow channels may form and impose pressure asymmetries on the ablation surface.

References

172. J. Nuckolls, L. Wood, R. Thiessen, and G. Zimmerman, *Nature* **239**, 139 (1972); J. S. Clarke, H. N. Fischer, and R. J. Mason, *Phys. Rev. Lett.* **30**, 89 (1973); K. A. Brueckner, *IEEE Trans. Plasma Sci.* **1**, 13 (1973).
173. J. D. Lindl and W. C. Mead, *Phys. Rev. Lett.* **34**, 1273 (1973).
174. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975), and references therein; D. Forslund, J. Kindel, K. Lee, E. Lindman, and R. L. Morse, *Phys. Rev. A* **11**, 679 (1975).
175. D. W. Forslund, *J. Geophys. Res.* **75**, 17 (1970); R. J. Bickerton, *Nucl. Fusion* **13**, 457 (1973).
176. E. W. Weibel, *Phys. Rev. Lett.* **2**, 83 (1959).
177. G. Kalman, C. Montes, and D. Quemada, *Phys. Fluids* **11**, 1797 (1968).
178. R. Lee and M. Lampe, *Phys. Rev. Lett.* **31**, 1390 (1973).
179. R. C. Davidson, D. A. Hammer, I. Haber, and C. E. Wagner, *Phys. Fluids* **15**, 317 (1972).
180. R. L. Morse and C. W. Nielson, *Phys. Fluids* **14**, 830 (1971).

Author

E. J. Valeo

4-7.5 Effect of Laser Electric Fields on Plasma Transport Coefficients

It is well known that a high-frequency laser electric field exerts a time-averaged force on a plasma. This is the so-called ponderomotive force. We have considered an analogous but more general effect in which the laser electric field modifies low-frequency plasma properties such as resistivity, thermal conductivity, and the plasma pressure tensor, as well as exerting force on the plasma. The goal of these studies is to facilitate more accurate calculations of the generation and evolution of dc magnetic fields and heat flow in the presence of laser radiation pressure.

Our general approach is to express the electron and ion distribution functions and electromagnetic fields as sums of low- and high-frequency components. First, considering the low-frequency plasma behavior, we derive moments of the time-averaged Vlasov equation, describing the plasma in terms of fluid variables such as the average center-of-mass velocity, density, and pressure. In the limit of strong collisions we assume that the low-frequency distribution functions do not deviate greatly from local Maxwellians. A description of the fluid-like properties of the plasma is then obtained.

These low-frequency equations determine the plasma's hydrodynamic behavior, but the transport coefficients and pressure tensor are now expressed as functions of the high-frequency electron distribution function. Thus we must solve simultaneously for the high-frequency plasma response to the laser fields. We do so by appropriate linearization and iteration of the high-frequency Vlasov equation.

In pertinent limits, useful closed-form expressions are derived for the way in which low-frequency plasma properties are modified by the laser's oscillating electric field. These provide tools for studying the growth of laser-generated dc magnetic fields and the resulting effects on transport.

Authors

J. Bernstein

C. E. Max

J. J. Thomson

4.8 THEORY AND SIMULATION: OTHER STUDIES

4-8.1 Mechanisms of the Plasma Spatial Filter for High-Power Lasers

Small-scale self-focusing appears to be a serious limitation on the performance of high power laser systems. Vacuum pinhole spatial filters have previously been suggested and used for ameliorating this problem.¹⁸¹ Recently a plasma spatial filter (PSF) has been developed at KMS Fusion¹⁸² as an attempt to reduce small-scale inhomogeneities that exponentiate down the laser chain. Here, we describe a quantitative analysis of mechanisms of the PSF.

The idea of a PSF is that a partially amplified laser beam is focused onto a plastic slab, part way down the $\lambda = 1.06\text{-}\mu\text{m}$ Nd:glass laser chain. About 20% of the light incident on the slab is reflected back through the lens. This reflected light is recollimated, and then amplified through the remainder of the laser chain. Near-field photographs show the time-integrated final beam to contain fewer small-scale inhomogeneities than in the absence of the PSF.

We discuss two kinds of processes operating in the PSF. The first involves the outward curvature of the critical density surface ($n_c = m_e \omega^2 / 4\pi e^2 \text{ cm}^{-3}$), at which the laser light is reflected. The critical surface is locally flat near the axis of the laser beam, but at larger radii, it curves away from the lens. Low spatial frequency components of the incident beam are focused near the axis, hit the flat part of the critical surface, and are thus reflected back into the lens. Higher spatial frequency components hit the target at larger radii, where the critical surface is tilted. They are given a significant angular deviation upon reflection, and thus are not efficiently recollimated by the collecting lens. Hence, the curvature of the critical surface preferentially selects the lower spatial frequencies to be amplified by the remainder of the laser chain.

The second process derives from the motion of the critical density surface, causing time variation in the reflection of the incoming rays. There is a

decoherence time associated with the time it takes a ray to sweep across the scale length of a beam inhomogeneity. Since the near-field photograph is time-integrated over the whole pulse, it appears smoother than an instantaneous picture would. This dynamical effect does not actually decrease small-scale self-focusing in the remainder of the laser chain since the latter depends only on the instantaneous local intensity.

The analysis presented here is based on computer simulations using the two-dimensional fluid-dynamics code LASNEX. Parameters were chosen to be relevant to the recent KMSF plasma spatial filter experiments.¹⁸² The calculation discussed here assumed 2.0 J of 1.06- μm light focused by an $f/3.4$ lens onto a CH_2 slab. The beam was spatially Gaussian with a FWHM of 32 μm , and temporally Gaussian with 35-ps FWHM. Figure 4-80 shows a snapshot of the calculation at the time of peak laser power. The z -axis is an axis of rotational symmetry, and the solid lines show the boundaries of the Lagrangian mesh. The critical surface contour is shown as the dashed line. Two rays are shown, representing a central ray, which is recollimated by the focusing lens, and a ray at the half-intensity point, which is deflected by reflection from the curved critical surface.

The development of a curved critical surface is seen only in the simulations that include thermoelectric magnetic field generation, and is a result of spatially localized transport inhibition. The magnetic field source term proportional to $\nabla n_e \times \nabla T_e$ maximizes near the beam edge, creating a toroidal region of megagauss-level magnetic field, as shown in the figure by the dotted contour representing 1.0 MG. The field significantly inhibits transport into the denser part of the slab. This in turn reduces the outward mass flow rate in the overdense region. Simultaneously, the inhibition raises the temperature just outside the critical surface, increasing the mass flux there. The net outward velocity of the critical surface is determined by the difference between the mass flux, ρv , on the overdense side and that on the underdense side of the critical surface. Magnetic fields at the spot edge thus

Fig. 4-80. Shape of critical density surface. The z-axis is an axis of rotation; R is the cylindrical radius. Dotted line shows n_c surface. Dashed line is 10^6 G magnetic field contour. Parameters are described in the text. Two representative laser rays are shown.

decrease the critical surface velocity at the spot edge, relative to that at the spot center. A curved critical surface results.

A related effect is the steep temperature gradient at the side of the spot due to sharply reduced thermal conductivity. The cooler material outside the primary beam tends to expand more slowly. This also contributes to the curvature of the critical surface.

We now calculate the effects of the critical surface curvature on the reflected laser light. Following an analysis by Hunt,¹⁸³ we take the scalar electric field just after the focusing lens to be

$$E = A(\vec{r}) \left[1 + \sum_{\vec{\kappa}} \alpha_{\vec{\kappa}} \exp(i\vec{\kappa} \cdot \vec{r}) \right] \times \exp[-ik(z - r^2/2R)] \quad (141)$$

$A(r)$ is the primary beam profile, and $(z - r^2/2R)$ is the diffraction-limited phase, with R the lens focal length. The vacuum wavenumber is k . The summation in Eq. (141) describes the superposition of components $\alpha_{\vec{\kappa}}$, having spatial frequency $\vec{\kappa}$, on the primary beam. The spatial frequency $\kappa \cong 2\pi/d$, where a typical beam inhomogeneity scale length d may be determined from the near-field photograph.

In the target plane, it can be shown that the focused beam consists of a central circular region

corresponding to the primary beam, plus similar regions whose centers are displaced by distances $\ell_s \sim \lambda D/d$ from the axis. These displaced spots represent the contribution of higher spatial frequencies κ . Here f is the lens f-number, and D is the lens diameter. The higher the spatial frequency κ , the farther the corresponding spot is from the axis.

To investigate the reflection of higher spatial frequencies κ , we computed the ray trajectories of spots shifted by distances $\ell_s \cong \lambda D/d$ from the axis. Figure 4-81 shows the percentage of three different spatial frequencies that are re-collected by the lens as a function of time. Numerical values are from the LASNEX computer run described above. Curve (1) represents the primary beam, while curves (2) and (3) represent higher spatial frequency components having sizes 17% and 8.5% of the beam diameter at the lens, respectively. The re-collimated intensity of the highest spatial frequency is reduced by a factor between 0.3 and 0.7 relative to the intensity of the primary beam. Thus the relative amplitudes of higher spatial frequency components are reduced by the PSF.

Next, we evaluate the effect of critical surface motion on the time-integrated near-field photograph. Suppose that the incident beam at the lens is described by Eq. (141) and that the critical surface is locally tilted at an angle ϕ relative to the beam normal, with $\phi \ll 1$. At the plane of the near-field photograph, the space-dependent part of the time-integrated reflected intensity is proportional to

Fig. 4-81. Time dependence of the percentage of three different spatial frequencies re-collected by the lens. Curve (1) represents the primary beam. Curves (2) and (3) describe near-field structures having sizes 17% and 8.5% of the beam diameter at the lens, respectively.

$$\bar{T} \equiv 1/T \int_0^T dt \cos(\psi_0 + \Delta\psi). \quad (142)$$

Due to reflection from the tilted critical surface, there is an extra phase factor $\Delta\psi \cong 2\phi k\Delta r$, relative to the accumulated phase ψ_0 for a flat critical surface ($\phi = 0$).

Taking $\phi(t) = \dot{\phi}t$, as suggested by the computational results, Eq. (142) becomes

$$\begin{aligned} \bar{T} &= 1/T \int_0^T dt \cos[\psi_0 + 2k\Delta r \dot{\phi}t] \\ &= \frac{\sin[\psi_0 + 2k\Delta r \dot{\phi}T] - \sin \psi_0}{2k\Delta r \dot{\phi}T} \end{aligned} \quad (143)$$

This expression becomes small compared to the zero frequency contribution in the limit $2k\Delta r \dot{\phi}T_{\max}$

$\gg 2\pi$, or $\phi_{\max} \gg \pi/(k\Delta r)$. A typical value of Δr is $\Delta r \cong 2\ell_c = 2f\lambda D/d$.

Putting these pieces together, we find that the time-integrated near-field picture should show little relative contribution from a spatial frequency $\kappa = 2\pi/d$, if the maximum tilt angle of the critical surface satisfies

$$\phi_{\max} \gg (\pi/2f) (d/D). \quad (144)$$

Here D is the lens diameter, f is its f -number, and d is a typical size for small-scale beam structures. For the example $f = 3.4$, we only require $\phi_{\max} \gg 2^\circ$ in order for beam inhomogeneities on the order of one tenth of the beam diameter to appear to be washed out on the time-integrated near-field photograph.

Figure 4-82 shows the mean tilt angle of the critical density surface as a function of time. Curve (2) represents the tilt angle near the edge of the laser spot. Curve (1) is the mean tilt near the spot center. Half of the laser energy is deposited in the interval between about 40 and 60 ps. During this period, the mean critical surface angles are about 6° and 15° for curves (1) and (2), respectively. Thus the inequality in Eq. (144) is well satisfied, as is the requirement $\phi_{\max} \ll 1$ assumed in our analysis.

Fig. 4-82. Mean tilt angle of critical density surface as a function of time. Curves (1) and (2) represent tilt angle near the center and edge of laser spot, respectively.

Therefore, for this numerical example, we expect all near-field structures smaller than about a tenth the beam diameter to be washed out on the time-integrated near-field photograph.

Motion of the critical surface also modifies the spectrum of the back-reflected laser light. For the interval between 40 and 60 ps, where about half the laser energy is deposited, the outward velocity of the critical surface varies from about 1×10^7 cm/s to 4×10^7 cm/s, as seen in the LASNEX calculation. The corresponding instantaneous Doppler shift of the laser light varies from 3.5 to 14.1 Å to the blue. On a time-integrated spectrum, the superposed Doppler shifts produce an overall spectrum broadening. In the current numerical example, the broadening would be roughly 14 Å, and the centroid of the back-reflected spectrum would be shifted to the blue by about half this value, or 7 Å. We expect the spectral broadening and shift to be quite sensitive to the amount of laser prepulse since our calculations show that the magnitude and even the direction of critical surface motion can vary, depending on prepulse conditions.

The PSF mechanisms discussed thus far have not included turbulent or disordered plasma processes. Rather, they have relied on the curvature and on the laminar motion of the plasma's critical surface. We find the latter mechanisms to be sufficient to explain many PSF features, including spectral broadening and spatial decoherence. It is nevertheless probable that random (or turbulent) plasma processes are also occurring. Likely candidates are beam filamentation, critical surface rippling, and stimulated scattering processes. These effects would act to enhance the spatial decoherence and spectral broadening produced by the PSF.

The PSF's ability to reject moderate spatial frequencies presents an interesting contrast to the operation of the vacuum pinhole spatial filter. A pinhole has a lower limit on its size, which is dependent on pulse length and power, because pinholes that are too small will be damaged and closed by laser energy deposition. Thus a pinhole spatial filter can only reject spatial frequencies above a cutoff frequency determined by its size. The PSF creates its own pinhole of the proper size to accept mainly the primary beam.

These mechanisms suggest scaling behavior of the plasma spatial filter. Curvature of the critical surface will be stronger for higher intensity light. Beam spatial profile has a somewhat more subtle effect on

critical surface curvature. Once the spatial profile is sharp enough to produce strong $\nabla n \times \nabla T$ de magnetic fields, lateral gradients are enhanced and critical surface curvature is produced. Thus the beam spatial profile should affect critical surface curvature only when the profile is so shallow that $\nabla n \times \nabla T$ B fields are suppressed. A detailed study of the effect of beam profile on thermoelectric B-field generation will be published elsewhere.¹⁴

If too large a fraction of the incoming light is contained in high spatial frequencies, so much energy will be focused near the edge of the main spot that the curvature of the critical surface will no longer be maintained. Once this occurs, the ability of the PSF to reject high spatial frequencies is reduced. This suggests that the PSF may be most effective if placed early in the laser chain, before the beam quality has been degraded too severely.

In summary, we believe the following effects are operating in the plasma spatial filter. First, curvature of the critical density surface causes the collecting lens to reject high spatial frequencies, relative to lower ones. Second, the time dependence of the plasma blowoff washes out some of the remaining high spatial frequency structures, when the latter are viewed on a time-integrated photograph. Curvature of the critical surface can degrade the focusability of the re-collected light, and the time-integrated spectrum of back-reflected light will be broadened because of time-dependent critical surface motion.

References

181. J. A. Glaze, *Opt. Eng.* **15**, 136 (1976); W. W. Simmons, S. Guch, Jr., F. Rainer, and J. E. Murray, *A High Energy Spatial Filter for the Removal of Small Scale Beam Instabilities in High Power Solid State Lasers*, Lawrence Livermore Laboratory, Rept. UCRL-76873 (1975) and *IEEE J. Qu. Elect.* QE11, 30D (1975).
182. S. Thomas, K. Moncur, and F. Mayer, as reported in Monthly Progress Reports 7, 8, and 10, KMS Fusion, Ann Arbor, MI, Report Nos. KMSF-U459 (1975), KMSF-U467 (1976), KMSF-U494 (1976), respectively.
183. J. Hunt, *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976).
184. G. Dahlbacka, C. E. Max, and J. J. Thomson, *Calculations of Self-Generated Magnetic Fields in Polyene Disc Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-77150 (1975).

Authors

C. E. Max
W. C. Mead
J. J. Thompson

4-8.2 Plasma Profile Steepening Due to Normal Incidence of Strong Microwaves

When strong microwaves are normally incident onto a gently inhomogeneous plasma (inhomogeneous scale length $L/\gamma_{De} \approx 10^3$), absorptive parametric instabilities¹⁸⁵ are excited near the critical surface (where the microwave frequency, 1.2 GHz equals the plasma frequency). We have observed¹⁸⁶ the spatially resolved time evolution of the wave and the plasma density profile (see Fig. 4-83). The ponderomotive force of the localized waves [curve (a)] blows the plasma out of the region near the critical density (n_c) and pushes the critical surface toward the plasma core; this is accompanied by simultaneous expansion of the instability region

[curve (b)]. The plasma densities continue to steepen with time until a density plateau is produced [curves (e) to (h)] adjacent to a sharp step in which the density changes from sub- to supercritical ($0.6n_c$ to $1.4n_c$). After this density profile is generated, the wave amplitude is greatly reduced ($\langle E^2 \rangle$ can be as small as 20% or less of the peak value) due to the steep density gradient. The plasma pressure then prevails over the ponderomotive force so that the plasma density profile begins to relax [curve (i)]. The waves are pushed back toward the initial region, and the wave amplitude again increases [curve (d)]. Thus the system shows a relaxation oscillation.

By solving the hydrodynamic equations in the steady state, we can obtain a simple formula for the jump size $\Delta n/n_c \propto \eta/2$ when η^2 is small ($\Delta n = n_2 - n_1$, n_1 and n_2 are the plasma densities of the sub- and supercritical regions and $\eta^2 = E^2/4\pi n_c k T_e$).

Fig. 4-83. Space/time evolution of wave energies (a) and plasma densities (b) at a microwave power of 1 kW. In plot (b), the dotted curve is the initial plasma density profile.

Fig. 4-84. Density jump size ($\Delta n/n_2$) vs microwave power. Solid circles represent experimental data; solid curve represents theory.

The experiments show that the jump size is proportional to η for $P_0 < 0.2$ kW in agreement with the theory (Fig. 4-84). The power absorption coefficient increases linearly with microwave power for weak microwave powers. The absorption coefficient is roughly constant (~ 0.2) in the high-power regime where the plasma density is strongly modified.

References

185. K. Mizuno and J. S. De Groot, *Phys. Rev. Lett.* **35**, 219 (1975).
186. K. Mizuno and J. S. De Groot, *Nonlinear Evolution of Parametric Instabilities in Inhomogeneous Plasma*, University of California-Davis, Rept. PRG-R-16 (1976).

Authors

K. Mizuno
J. S. De Groot

4-8.3 Experimental Observation of Finite-Bandwidth Effects on Parametric Instabilities Near the Critical Density

We have studied the effect of a broad band pump on parametric instabilities.¹⁸⁷ The pump power spectrum has a Lorentzian distribution and hence, a single sample of the time history of pump power has a stochastic nature [Fig. 4-85(a)]. By observing the

ensemble average for over 100 samples, we can remove the stochastic component [Fig. 4-85(b)]. The single samples of the time history of the parametrically excited, high-frequency waves also exhibit the expected stochastic nature [Fig. 4-85(c)].

However, the time history of the ensemble-averaged, high-frequency waves shows clear exponential growth as if the waves are excited by a coherent pump wave [Fig. 4-86(a)]. The growth rate decreases with the increasing pump bandwidth, $\Delta\omega$. In Fig. 4-86(b), we give the measured exponential growth rates vs bandwidth and compare them to theoretical predictions.¹⁸⁸

Experimental results agree with the theory for small bandwidths. However, for larger bandwidths and when the pump power is close to threshold, the high-frequency wave energy grows linearly in time (Fig. 4-86 inset). In contrast to the growth rate, the saturation level of the high frequency wave energy is almost independent of bandwidth for pump powers well above the coherent threshold (Fig. 4-87, curve 1), but it decreases rapidly with bandwidth for pump powers near threshold (Fig. 4-87, curves 2 and 3).

Fig. 4-85. (a) Time histories of pump power: single traces of the pump wave vs time ($2 \mu\text{s}/\text{div}$); (b) ensemble-averaged (>100 samples) pump wave vs time, ($1 \mu\text{s}/\text{div}$); and (c) single traces of the parametrically excited instabilities vs time ($2 \mu\text{s}/\text{div}$).

Fig. 4-86. Time history of the parametrically excited, high frequency waves ensemble averaged for more than 100 samples (2 μ s/div). In (a), we see exponential growth [pump power $P_0 = 6 \text{ W}$, $\Delta\omega/2\pi = 0.1 \text{ MHz}$ for curve (2)]. In (b), the growth is linear with time. The normalized effective growth rate γ_{eff}/γ is given vs $\Delta\omega$. The estimated γ using narrow bandwidth pump wave ($\Delta\omega/2\pi = 0.05 \text{ MHz}$) is $7.5 \times 10^{-4} \text{ s}^{-1}$. The solid line. The inset shows the time evolution of the ensemble-averaged instabilities for $\Delta\omega/2\pi = 1.4 \text{ MHz}$ and $P_0 = 3W$.

Fig. 4-87. Saturated high-frequency wave energy vs $\Delta\omega$. The wave energy is normalized by the wave energy for a narrow band pump ($\Delta\omega/2\pi = 50$ kHz). Curve (1) is for $P_0 = 6$ W, curve (2) for $P_0 = 4$ W, curve (3) for $P_0 = 3$ W.

These results have direct consequences for the production of suprathermal electrons. We also find that the suprathermal electron production is not a function of $\Delta\omega$ at high power (up to the highest available bandwidth, $\Delta\omega/\omega_0 \approx 3 \times 10^{-3}$). This is in agreement with computer simulations. The growth rate of the instability decreases with $\Delta\omega$ as theoretically predicted; however, wave saturation energy and suprathermal electron production are almost independent of $\Delta\omega$.

References

187. K. Mizuno and J. S. DeGroot, *Finite Bandwidth Effects on Parametric Instabilities*, University of California-Davis, Rept. PRG-R-11 (1976).
188. J. J. Thomson, *Nucl. Fus.* 15, 237 (1975).

Authors

K. Mizuno
J. S. De Groot

4-8.4 Effect of Instability of the Critical Surface on Laser Absorption

We have investigated the stability of a plasma supported by the ponderomotive force due to obliquely incident electromagnetic waves. The wave polarization can be in (p) or out of (s), the plane of incidence which is defined by the plasma density gradient and the direction of electromagnetic wave propagation. In laser fusion, the ponderomotive force can be so strong that the density-gradient scale length near the critical density (where the laser frequency equals the plasma frequency) is only a few Debye-lengths or less. The light can parametrically decay into waves that propagate perpendicular to the density gradient and ripple the critical surface. The length of this light-plasma interaction region where parametric instabilities can occur plays an essential role in determining the instability thresholds and growth rates. This length is determined by treating the field structure and density profile self-consistently.

This problem is investigated with theory as well as with one- and two-dimensional fluid computer codes. In the theory, the usual W.K.B. and saddle point methods do not apply because the density profile is so steep and must be determined self-consistently.

Instead, perturbation theory is used. The spatially averaged properties of the zero-order variables are taken by integration over the critical surface region to determine the dispersion relation for the overall surface. The zero-order equations are solved numerically.

The results from both theory and two-dimensional fluid computations indicate that decay and oscillating two-stream instabilities (both of which have electromagnetic characteristics) occur along the critical surface. For angles of incidence larger than a certain value, the decay type dominates and has a maximum growth rate near the backscatter angle. The width of the unstable k-spectrum is broader than that for a homogeneous density profile.

For smaller angles of incidence, shorter wavelength oscillating-two-stream waves grow more rapidly. The threshold is higher for p-polarization because the density profile is steeper due to the ponderomotive force of the resonantly

Fig. 4-88. Density contours for s-polarization at $\omega_0 t = 280$ in (a) and for p-polarization at $\omega_0 t = 200$ in (b). The contour lines increase from the left ($0.6 n_c$ to $1.4 n_c$). The parameters are $v_0/c = 0.2$, $v_e/c = 0.1$, $M/m = 25$, and $\sin \theta = 0.4$ in (a) and 0.2 in (b).

excited electrostatic waves paralleling the density gradient. The growth rate does not increase rapidly with laser power because higher power results in a steeper density profile.

The nonlinear stage, studied using the two-dimensional fluid code, is quite different for the two polarizations. For p-polarization, the instability saturates when the inhomogeneity along the critical surface is so large that large amplitude electrostatic waves are saturated by wave-particle effects. No saturation mechanism was discovered in two-dimensional computations of s-polarization. The surface is strongly and increasingly rippled.

Typical results are shown in Fig. 4-88. The plasma-density contour plots are given at a time late in the computer run. The initial perturbation is $1\lambda_{De}$ in amplitude. In Fig. 4-88(a) for the s-polarization case, we find that the instability does not saturate. However, in Fig. 4-88(b) for the p-polarization case, we find that the instability saturates with the generation of electrostatic waves. As a result of this instability, laser absorption is increased by as much as 15%.

Authors

W. Woo

J. S. De Groot

4-8.5 Suprathermal Electron Production During Resonant Absorption

We have studied the suprathermal electron production that occurs during resonant absorption following three approaches: experiments with a plasma-filled capacitor, a theoretical model based on single-particle orbit calculations, and a particle-simulation computer code.

A diagram of the experimental apparatus used in the first approach is shown in Fig. 4-89. An unmagnetized plasma with a density gradient ($n^{-1}dn/dx = 0.16 \text{ cm}^{-1}$) is created by a hot-cathode discharge at one end of the vacuum chamber. A 470-MHz signal is applied to the capacitor (a 15-cm diameter screen disk and the vacuum chamber wall) so that the oscillating electric field has a component along the plasma-density gradient. Where the electron plasma frequency approximately equals the applied frequency, this field resonantly excites an enhanced field. The electrons accelerated parallel to the density gradient by this enhanced, localized field are sampled with an energy analyzer that is located far enough from the resonant region so that it does not perturb the enhanced field.

Fig. 4-89. Apparatus for experiments with the plasma-filled capacitor.

Our principal goal for 1976 was to model the electron acceleration process based on single-particle orbit computations.¹⁸⁹ This model develops a relation between the temperature of the suprathermal tail and the strength and width of the resonantly driven, high-frequency electric field. In Fig. 4-90, the calculated temperature of the tail, T_h , normalized to the temperature of the unheated distribution, T , is plotted as a function of the scaled ratio of the field strength to field width, $\eta\lambda_D/D$. Here, $\eta = E_0/(4\pi nkT)^{1/2}$, $2D$ is the width of the field, and λ_D is the Debye length.

This model also predicts the time-averaged distribution function of the accelerated electrons. In Fig. 4-91 we show a comparison between the distribution function obtained with a particle-simulation computer code¹⁹⁰ to model resonant absorption (thin jagged line) and the calculation based on single-particle orbits (thick smooth line). The field parameters used in the calculations were obtained entirely from the self-consistent fields that developed in the simulation.

References

189. C. P. DeNeef and J. S. DeGroot, *Phys. Fluids* (to be published, 1977).
190. J. S. DeGroot and J. E. Tull, *Phys. Fluids* **18**, 672 (1975).

Authors

C. P. DeNeef
J. S. DeGroot

Fig. 4-90. Calculated temperature of the nonthermal electron distribution, T_h , normalized to the temperature of the incident distribution, T , vs the scaled ratio of field strength to width, $\eta\lambda_D/D$.

Fig. 4-91. Distribution function, $f(v)$, calculated with the simple model is compared with the result of a numerical simulation of resonant absorption. Velocities, $\bar{v}/v_0$, are scaled to the initial thermal velocity in the simulation.

4-8.6 Absorption of a Focused Laser Beam by a Nonspherical Plasma

We have extended the work of Erkkila¹⁹¹ to include plasma motion. Erkkila developed a code to calculate the absorption of a focused laser beam by a spherical plasma, solving the full three-dimensional electromagnetic equations. He found that even for an initially spherical plasma, the ponderomotive force would introduce asymmetries.

We have added a hydrodynamics code to follow this asymmetrical plasma response. We also have written a new electromagnetic field solver that permits the predicted nonspherical plasma density profiles. We assume that the laser beam is circularly polarized because the ponderomotive force then is axially symmetric and the plasma motion is essentially two-dimensional. Many important plasma effects—inverse bremsstrahlung, resonant absorption, profile steepening, deformation of the critical surface, Brillouin scattering, bubble formation, and filamentation—are described by our code.

Our preliminary results indicate that resonant absorption can be an important absorption mechanism for high-intensity focused laser beams ($v_{os}/v_{th} \approx 1$, where v_{os} is the electron quiver velocity and v_{th} is the electron thermal velocity), even if the beam is normally incident onto the plasma. The plasma in the underdense region is expelled laterally to form a trough. The marginal rays of the beam are gently diffracted by the sides of the trough to make broad sweeps across the critical surface at the trough's end. The resonant absorption of these rays is very efficient and a 15 to 20% increase is realized in the absorption of the beam. Parametric instabilities that ripple the critical surface increase the absorption still further. We find overall absorption efficiencies of about 35% for this state, which we believe to be the asymptotic one for this laser intensity. In many cases, the initial spherical plasmas had absorption efficiencies less than 10%.

Reference

191. J. H. Erkkila, *Laser Light Scattering and Absorption in Dense, Spherically Symmetric Plasmas*, Lawrence Livermore Laboratory, Rept. UCRL-51914 (1975).

Authors

C. Randall
J. De Groot

4-8.7 Anomalous DC Resistivity

We have studied the mechanisms which produce anomalous dc resistivity in those current-carrying plasmas in which the relative electron drift equals or exceeds the electron thermal speed. In laser fusion, this current is required to balance the inward flux of hot electrons created near the critical surface. We have discovered a new mechanism for anomalous dc resistivity which obtains for drifts greater than the electron thermal speed.

Using one- and two-dimensional computer models, we have simulated anomalous dc resistivity in a uniform plasma by applying an external uniform electric field to the plasma to maintain the drift velocity constant. For large electron-to-ion temperature ratios, the resistivity increases dramatically as the electron drift velocity is increased beyond the electron thermal speed (Fig. 4-92). The resistivity results from large amplitude ion

Fig. 4-92. Simulation results for the maximum effective collision frequency. The effective collision frequency is given by $\nu_{eff} = -eE_e/mV_d$, where E_e is the external electric field required to maintain constant current. ● represents $L = 50\lambda_{De}$; ○ and X represent $L = 141\lambda_{De}$, from 2D simulations with $T_e/T_i = 20$. ■ from 1D simulations, □ from 2D simulations, and $T_e/T_i = 1$. The larger resistivity values are determined with less accuracy since we were not able to hold V_d/v_{th} strictly constant, due to the large electron heating rates for those cases. Also we found that the maximum resistivity depends on the densities lining up. The alignment was complete for the largest ν_{eff} shown (X). The spread in values at $V_d/v_{th} = 1.4$ (○, ●) is due to incomplete alignment. The collision frequency due to the numerical model is less than any shown.

Fig. 4-93. Self-consistent potential surfaces (time-averaged over one plasma period) at $\omega_{pe} = 1225$ from the 2D simulation shown in Fig. 4-94. The total potential (sum of self-consistent plus external) is nearly constant to the left of the densiton.

turbulence which results in nearly isotropic electron heating.

Results from one-dimensional simulations show that a solitary structure grows out of the ion turbulence. This structure has associated with it a narrow density spike upstream of a shallower and wider ($>20 \lambda_{De}$) density depression. Across this structure appears a large (several kT_e/e) potential jump; the electron distribution function is strongly double-humped, leading to an electron-electron two-stream interaction which thermalizes the accelerated electrons. The heating is anisotropic, favoring the drift direction.

In two-dimensional calculations with electron cooling so that the system comes to steady state, the solitary structures grow out of the ion turbulence (Figs. 4-93 and 4-94). They are formed at random locations but later line up perpendicular to the electron drift, becoming nearly one-dimensional. In

Fig. 4-94. Time history of electron and ion phase in the direction of the drift ($y, v/a_\alpha$; where $a_\alpha = \sqrt{2kT_{\alpha}/m_\alpha}$ and $\alpha = e, i$ for electrons and ions). From a 2D simulation with parameters $V_d/v_{the} = 1.4$, $L_x = L_y = 256$ cells $= 141 \lambda_{De}$, $M/m = 1000$, $T_e/T_i = 20$, $N_e = N_i = 160$ K, and $\Delta t \omega_{pe} = 0.5$. The system is periodic in the drift (y) direction and has conducting, particle-reflecting transverse boundaries. The x direction is divided into 16 segments (each of width $9 \lambda_{De}$), and the ninth segment is shown at (a) $\omega_{pe} = 540$, (b) $\omega_{pe} = 780$, and (c) $\omega_{pe} = 1260$. A densiton is forming in (a). The resistivity is maximum at a time close to (c).

long systems, multiple structures appear (the spacing is $\leq 60 \lambda_{De}$). Since most of the external potential drop falls in the potential jump, the external potential is essentially excluded from the bulk of the plasma.

We have shown that these structures are triggered by ion perturbations. The plasma initially had a density trough of 15 to 30%, extending perpen-

dicular to the drift direction. The solitary structures grew out of the density depression before the ion turbulence was formed.

Authors

C. Barnes

J. DeGroot

4-9 TARGET FABRICATION: OVERVIEW

Laser-fusion target fabrication can be separated into two major tasks: first, to produce "research targets" designed for reaching established research milestones such as significant thermonuclear burn and scientific breakeven; and second, to develop, simultaneously with the first task, a set of techniques and methods for producing reactor-class targets ("production targets") at high rates (one per second) and low cost (50¢ per target). Research targets are often produced on a "few-of-a-kind" basis and may cost several thousand dollars each when research and development expenses are taken into account. During 1976 more than 1000 research targets of various designs were fabricated for testing in the three laser systems—Janus, Cyclops, and Argus. These targets included thin disks (0.25-10 μm) of glass, metal, and plastic; hollow spheres filled with gas; solid spheres of glass, tungsten, gold, copper, and plastic; and various other complicated glass and metal assemblies. In addition, multiple-shell spherical assemblies such as those discussed by Nuckolls in another section of this report have been studied and subjected to design calculations. Techniques to fabricate such targets are discussed later in this section.

Achievement of high neutron yield (more than 10^9 neutrons), proof of thermonuclear burn, and other goals were made possible by having targets specifically designed and fabricated for the experiments performed, with target parameters maintained to the requisite accuracy. The overall process of target fabrication is shown in the flow chart in Fig. 4-95. The target design is a result of many iterations between concept, calculation, and physical reality. After a design decision has been made and

material parameters are chosen (often during the design phase), a choice of materials is made or a study is begun to find materials whose properties fit the target parameters. This phase may require in-depth materials research or, in some cases, merely a "handbook" search. Specific material is acquired or made for the purpose at hand, and the physical and chemical properties of interest are experimentally measured.

Fabrication of research targets can be divided into three areas: parts production, target assembly, and target characterization. Within these broad categories are fuel sphere production, DT (deuterium-tritium) fuel filling, thin film coating and layer deposition, production of large spherical shields and shells, research and development on cryogenic targets, levitation of target parts, laser machining, parts manipulation and handling, production of special parts, target assembly techniques, optical and electron microscopy, optical interferometry, DT fill characterization, computer control of shell manipulation, and studies on generation of liquid fuel drops.

Parts fabrication techniques are developed for the particular target being produced. In some instances, the parts are produced by means which have been used for previous targets or which have been used in other unrelated fields, e.g., manufacture of solid-state integrated circuits. As techniques are developed to make parts, methods of characterizing the parts must be originated or devised from existing techniques.

As parts become available, methods for assembling complete targets are applied. Often new tools, techniques, and materials must be developed. During the assembly processes, various characterization

Fig. 4-95. Flow chart showing the broad processes involved in fabrication of laser fusion targets.

steps must be accomplished; dimensions, mass, surface finish, and material properties of all parts of the target and fuel must be measured to accuracies required by the design specifications.

When the target has been completely assembled and characterized, it is mounted on a suitable support and delivered for experimental use, i.e., irradiation by a laser.

The block diagram in Fig. 4-96 shows the technical steps in the process of building laser fusion targets. The steps and details of the processes are elaborated on in the following articles. It should be recognized that, for completeness, every step shown in the block diagram would have to be surrounded by many blocks showing materials research, electronics development, organic and inorganic chemistry research and development, optics studies, development of specialized electron microscopy techniques, glass physics and chemistry development, and many others.

Lawrence Livermore Laboratory has extensive

facilities for target fabrication work. A tritium-handling laboratory and high pressure facility are used to fill targets with deuterium-tritium fuel mixtures. Other resources are highly developed capabilities in chemical analysis, precision machining, materials research, electronics, mechanical fabrication, and computation. Highly skilled people in many fields required for target fabrication are available for assistance and consultation.

Because of the exacting surface finish tolerances and materials homogeneity required in target designs, special problems must be solved for materials employed in target fabrication. Local density or surface variations present because of crystal structure or voids in the materials may prove disastrous to the operation of the target by causing fluid instabilities during the implosion. As the various layers of material are compressed, conditions occur in which high density material is being "pushed" by lower density material, thus giving rise to possibly unstable configurations. Many of the hardest problems to solve in target fabrication arise

Fig. 4-96. Steps required for the production of complex, noncryogenic targets. Above the dashed line, the operations are generally batch processes; below the line, the items are handled individually.

from attempts to minimize the possibility of physical irregularities which can grow and destroy an otherwise symmetrical implosion.

It is perhaps not widely perceived that the "target factory" for a reactor must perform more or less the same complex operations shown in Fig. 4-96 to produce targets of high enough quality to avoid fluid instability problems. The factory will use automated, computer-controlled batch or serial processes, with real-time computer sensing for characterization and measurement. Since the targets will probably be cryogenic, with the fuel in either gaseous, liquid, or solid form at a few tens of degrees Kelvin, the factory will be an integral part of the laser reactor complex. In addition, while development of the various target-fabrication processes may be done at widely separated locations, all the steps for the actual production of complicated cryogenic targets under "real time" conditions (i.e., the targets being used immediately after being made), whether for research purposes or for production reactors, must take place near the laser target chamber.

With the many complicated processes necessary for the production of laser fusion targets, how can we expect to reduce the cost of the targets from several thousand dollars each to less than one dollar? As a possible analogy, let us consider the cost reduction of a solid state device from as recent a time as the early 1950's to the present time. In the early 1950's, a "high quality" transistor (with a frequency cutoff of perhaps a few megahertz) might cost as much as \$50-100. In 1977 a better transistor (in terms of cutoff frequency, power handling capability, etc.) costs at most a few cents. An entire intermediate-frequency fm system fabricated as a silicon-chip integrated circuit containing 89 transistors, 67 resistors, 14 capacitors, 5 diodes, 2 voltage regulators, all the interconnecting conductors, output and input terminals, and packaged in a $1.9 \times 0.6 \times 0.4$ -cm, 16-lead, dual in-line plastic package, cost \$3.83 in 1974. The reduction in cost per transistor from 1954 (about \$50) to 1974 (4¢) is more than a factor of 1000. In 1976, one could purchase an entire microcomputer on a wafer containing several hundred thousand transistors for a few hundred dollars or about 1¢ per transistor with the resistors, capacitors, diodes, connectors, etc., thrown in free. Compared to 1954, we see a reduction in price per transistor of 5×10^4 .

Integrated circuit technology is currently able to

produce conductor strips a few microns wide, edge definition of hundredths of microns, surface qualities of a few hundred angstroms, and multilayered structures. The quality and tolerances of the structures in solid-state integrated circuits are of the same order of magnitude as those currently required and anticipated for future inertial-confinement fusion targets.

While the analogy between solid state devices and laser targets cannot be carried too far, we can safely say that with the utilization of automated production and characterization techniques, quality control, etc. as practiced by the solid-state industry, we can reasonably expect a several-thousandfold reduction in costs of production quantities of reactor targets as compared to one-of-a-kind manufacture.

During the past year the Target Fabrication Group has provided targets which have successively given yields of 10^6 , 10^7 , 10^8 , and 10^9 neutrons with proof of thermonuclear burn. The targets have also provided the opportunity to begin high density and higher yield experiments.

Means of characterizing targets to higher accuracies than previously considered possible have been developed. Techniques such as optical microscopy, optical interferometry, x-ray micrography, and electron microscopy are providing extremely accurate surface and volume characterization displays of target parts and completed targets.

Production of target-quality hollow glass spheres has begun. A wide range of size and thickness of these spheres can be selected.

Techniques have been developed for coating spheres with compounds such as boron nitride, boron, polymerized fluorocarbon compounds, and various other organic, inorganic, and metallic materials. The purpose is to enable us to build up multilayer target spheres with ablator and pusher shells. To avoid the surface irregularities that occur in most batch-process coatings of small particles, means have been devised for levitating the target parts during deposition of the layers. This allows the coating of one target at a time, eliminating the irregularities caused by particle-particle collisions. These achievements and others are described in detail in the following articles.

Techniques have been developed for coating spheres with compounds such as boron nitride, boron, polymerized fluorocarbon compounds, and

various other organic, inorganic, and metallic materials. The purpose is to enable us to build up multilayer target spheres with ablator and pusher shells. To avoid the surface irregularities that occur in most batch-process coatings of small particles, means have been devised for levitating the target parts during deposition of the layers. This allows the coating of one target at a time, eliminating the irregularities caused by particle-particle collisions. These achievements and others are described in detail in the following articles.

Author
C. D. Hendricks

manufactured by droplet generation. So can spherical metal particles.

In 1976, we extended our studies on the disintegration of liquid jets, investigating the properties of molten metals and alloys, molten salts and aqueous solutions, inks, organic materials, and cryogenic fluids.¹⁹² Also studied were the interactions of colliding liquid drops of equal and differing masses.

Basic Procedure

Basically, experimental systems for studying the production of liquid drops of controlled diameter and mass must have the following:

- A source of liquid, usually a reservoir.
- A means for applying pressure to the liquid in the reservoir.
- An orifice through which the liquid is forced to create a smooth, nonturbulent jet.
- A means for stimulating the jet into the desired disintegration mode.
- A mechanism for charging and extracting the desired droplets.
- Diagnostic and control equipment with which to monitor and control the droplet downstream trajectory.

4-9.1 Droplet Generation

During the past several years we have developed and studied droplet methods for producing the small, uniformly sized particles of fusion fuel needed for magnetic and inertial confinement experiments. Hollow and solid glass spheres can be

Fig. 4-97. Apparatus for studying droplet behavior in collisions.

Fig. 4-98. Collision between a large drop (diam $530\ \mu\text{m}$, velocity $3.7\ \text{cm/s}$) and a small drop (diam $180\ \mu\text{m}$, velocity $6.7\ \text{cm/s}$). Both drops are water. The time between frames is about $0.1\ \text{ms}$. In (a) the classical impact parameter is about $40\ \mu\text{m}$; and (b) it is about $5\ \mu\text{m}$. This difference in impact parameter is responsible for the differences in the collisions.

● For cryogenic fluids (e.g., hydrogen and its isotopes, oxygen, argon), a refrigeration system to liquify the gas and maintain it in liquid form.

With proper apparatus, particles of equal mass can be separated from the smooth jet. The first step is to stimulate the jet by applying a periodic disturbance, using perturbations of either large or small amplitude.¹⁹³ Then one adjusts such parameters as the orifice diameter, jet velocity, reservoir pressure, and amplitude and frequency of the perturbations

to obtain the correct particle size and prevent formation of small satellite droplets between the main drops.

Once the jet disintegrates, the drops are charged and extracted. We have successfully used several charging techniques: induction charging, ion-beam or gas-discharge charging, injection or contact charging. Static dc electric fields are then applied to the charged particles, permitting separation and trajectory control of the drops.

Computer diagnostics with sensing and feedback capabilities can be incorporated into the system to provide downstream correction and control of the droplet trajectories.

Normal jet and drop velocities in air range from 2 to 30 m/s. In high-vacuum environments, however, charged particles can be accelerated to the much higher velocities needed for reactor fuel injection, impact and collisional studies, and other applications.

Collisional Interaction of Liquid Drops

We have conducted a set of room-temperature experiments⁹⁴ to study collisions of liquid drops of equal and unequal sizes. The drops for these studies were formed by a droplet generating system similar to those described in some earlier articles in this report (see Fig. 4-97). By controlling the drop tra-

jectories, we can cause tangential (grazing) impacts, head-on impacts, or any variation between. Figure 4-98 is a sequence of photographs showing collisions between water drops of unequal size for two different impact parameters (the impact parameter is the closest approach between the extended trajectories of the two particles).

These collisional studies have been helpful for simulating liquid drop models of nuclear interactions as well as for studying the behavior of colliding macroscopic particles.

Copper Particle Generation

Room temperatures suffice for producing uniformly sized spheres of many materials. Some, however, require temperatures that are either very low or very high. Our work with particle generation from cryogenic materials such as hydrogen isotopes

Fig. 4-99. High-temperature system for producing uniformly sized spheres of copper and other high-melting-point materials.

is discussed in Section 3. We have also produced particles from molten copper at temperatures exceeding 1100°C, presenting some difficult operating problems as described below.

The copper particle generating system consists of fused quartz cylinders assembled in the double-wall arrangement shown in Fig. 4-99. The inner vertical cylinder—1 cm in diam and 75 cm long, sealed at the bottom except for an orifice—is the fluid reservoir. This unit replaces easily if the orifice clogs or an aperture of different size is required. A piezoelectric or electromagnetic transducer attaches to the "flat" formed at the 90° bend at its upper end. The outer cylinder, 4 cm in diam and 2.5 m long, protects, isolates, and supports the inner cylinder. The bottom end of the outer cylinder terminates in a closed, removable "catcher" filled with quartz wool to cushion the fall of the soft, solid-copper spheres. The two cylinders are secured by clamps and ground joints at their upper ends. They can be individually evacuated and filled with various desired gases.

During operation, a clamshell cylindrical furnace surrounds the outer cylinder so that the orifice is approximately centered and opposite the observation window in the furnace wall. The cylinders are evacuated and backfilled with the selected gases. Then the furnace temperature is raised to the copper melting point. When the metal is molten, the pressure differential between the inner and outer cylinders is adjusted to form a jet of liquid copper through the orifice. Simultaneously, the transducer is energized by a periodic signal. The jet disintegrates into uniform drops that cool as they fall and are collected as solid spheres in the quartz wool of the "catcher."

The system works well. We find, however, that the inner cylinder must be replaced often because the molten copper wets the quartz, leaving a copper residue after the system cools. As the temperature decreases, the difference in contraction between copper and quartz pulls fragments out of the quartz wall, destroying the cylinder.

References

192. J. M. Schneider, N. R. Lindblad, and C. D. Hendricks, "An Apparatus to Study the Collision and Coalescence of Liquid Aerosols," *J. Colloid. Sci.* **20**, 610 (1965).
193. C. D. Hendricks and J. L. Dressler, "Production of Glass Balloons for Laser Targets," *Bull. Am. Phys. Soc.* **22**, 113 (1976).

194. C. D. Hendricks, R. J. Galliger, and K. S. Robinson, *Examination of Fluid Droplet Collisions*, Lawrence Livermore Laboratory, Rept. UCRL-78493 (1976).

Author

C. D. Hendricks

Major Contributors

J. L. Dressler

J. F. Wengert

4-9.2 Hollow Glass Sphere Production

Commercial sources^{195,196} do not provide hollow glass spheres of the size, wall thickness, composition, or quality for the targets needed to achieve present or future laser fusion milestones. The available commercial glass spheres are produced in a spectrum of sizes but are limited both in wall thickness and diameter. Fuel compressions to one hundred times the liquid density require a fuel ball that is much thicker than any available from the present vendors. In addition, to demonstrate significant thermonuclear burn, we need fuel balls larger in diameter than those which can be purchased.

Commercially available glass spheres are available in only a few compositions. This is a twofold handicap. The current sphere-filling method involves the diffusion of hydrogen or other gases through the walls at high temperature and pressure. The gas is trapped when the targets are stored at low temperature where the diffusion is greatly decreased. The alkali metal content of the commercial glass spheres makes it almost impossible to diffuse several desirable gases through the walls. This greatly limits the range of experiments that we can perform. The composition of the glass also plays an important role in the absorption of the laser pulse and the dynamics of the resulting implosion. Experiments in implosion dynamics thus are hindered by the limited selection of available glasses.

We have developed a process to manufacture glass spheres, combining a glass-particle-blowing process and a modified solid-particle generator that is similar to one originated by Hendricks and Babil.¹⁹⁷

Fig. 4-100. Hollow-glass-sphere production facility at I.I.I.

Our apparatus (see Fig. 4-100) consists of two subsections—a droplet generator mounted on a drying-firing oven. The droplet generator forms uniformly sized drops of a solvent, usually water, in which the glass constituents and, if necessary, a blowing agent are dissolved. Identical drops of glass-forming solution fall through the oven where most of the water is evaporated, leaving a solid particle of the glass constituents. The solid particle then falls into a hotter zone of the oven where it melts into a glass. The remaining water vaporizes and the blowing agent decomposes. The gas from these decompositions blows the molten glass droplet into a bubble.

Fig. 4-101. Droplet generator showing its three basic components: the resonant stub (top), the orifice plate mounted to its holder (middle), and the deflector-catcher electrodes (bottom).

Fig. 4-102. Satellite-free stimulated jet breakup. This process of stimulated breakup was observed in the 19th century and the first adequate theoretical treatment was given by Raleigh in 1897¹⁹⁸—hence the name, Raleigh breakup.

Producing target balls this way offers several advantages over the commercial process. The droplet generator precisely controls the volume of glass solution released. This control greatly reduces the size distribution of the resulting particles and thus, it is easier to produce a glass sphere of a specified size. Also, spherical particles of solid glass are formed as an intermediate step in the process. By using spherical glass particles rather than irregular particles made by crushing, the uniformity of wall thickness of these hollow spheres is more easily controlled.

Droplet Generator

Glass solution droplets of a precisely controlled volume are produced by the droplet generator (see Figs. 4-100 and 4-101). This droplet generator consists of three basic components. The top component, the resonant stub, forms the ultrasonically

stimulated jet; the second, the charge ring, selectively charges the resulting liquid drops; and the third component, the deflector-catcher electrodes, captures the charged drops of liquid and allows uncharged drops to fall into the oven.

The resonant stub produces a jet of the glass-forming solution through an orifice plate. The pressure in the manifold behind the orifice plate is varied at an ultrasonic frequency by a piezoelectric crystal. These pressure fluctuations cause velocity fluctuations of the jet which, in turn, cause the jet to break up into a stream of uniformly sized and spaced drops (see Fig. 4-102).

To provide efficient coupling of the ultrasonic energy to the liquid jet, the manifold that holds the liquid is also a resonant structure (see Fig. 4-103). Two stainless steel cylinders are bolted so that they squeeze the piezoelectric transducers between them. The lower steel cylinder is threaded, allowing the orifice-plate mounts to be screwed in place. This feature permits the easy removal and exchange of orifice plates. This lower cylinder is also tapered to amplify the sonic vibrations at the orifice plate. The upper steel cylinder has two inlet ports; one for the glass solution and one for a pressure transducer.

Fig. 4-103. Orifice plate is attached to the resonant stub to obtain high-amplitude jet stimulation.

Fig. 4-104. A single drop is being ejected by the droplet generator.

The glass solution is channelled through the center of the cylinder.

An oscillator that locks onto the resonant frequency of the liquid manifold drives the piezoelectric crystals. When the droplet generator is operating, the heat from the oven causes the resonant frequency to drift. Because the oscillator is controlled by the manifold, it also drifts in frequency. As a result, the amplitude of the oscillating pressure in the liquid is maintained at a nearly constant level. Thus, when the liquid jet is disrupted, satellite-droplet formation is prevented (see Fig. 4-102).

The charge electrode or charge ring is located just below the jet-forming orifice. The cylindrical electrode is situated so that the breakup of the jet occurs inside the cylinder. When a voltage is placed on the charge ring, the drops are inductively charged with the opposite charge. During operation, the voltage on the charge ring switches between ground and positive; thus, the drops are either neutral or negatively charged.

Beneath the charge ring are the deflector-catcher

electrodes. The deflector electrode is maintained at a high negative voltage; the catcher electrode is held at ground potential. When the jet breaks up, the charged drops are repelled by the deflector onto the catcher and are removed by a vacuum line. The uncharged drops are unaffected by the electric field and pass into the oven.

During normal operation, one out of every 32 drops is uncharged. Thus, most of the drops are caught and only the few uncharged ones pass into the oven; there is a large space between the drops falling into the oven. Because the drying drops are far apart, there is a minimum chance of a coalescing collision between two drops and the resulting particle size is kept uniform.

Figure 4-104 is a photograph of the droplet generator in operation. The stream of charged drops being deflected into the catcher electrode can be seen on the right side of the photograph. In the lower part of the picture, an uncharged drop near the catcher has not been deflected by the electric field and will pass into the oven.

For proper operation of the droplet generator, the charging pulse must be synchronized with the droplet breakoff. Improper timing can result in two drops being pulsed out of the stream and sent into the oven or possibly in all drops being charged. Without uncharged drops, no glass spheres would be produced. When two adjacent drops are pulsed out of the stream, they coalesce to form an oversized drop and the resulting glass sphere has double the desired mass.

Two parameters can significantly affect the time lag between the stimulation signal and the drop separation—the static (average) pressure of the glass solution in the manifold and the oscillating (stimulation) pressure of the solution. A change in the stimulation pressure affects the initial amplitude of the disturbance on the jet and requires a corresponding change in the time necessary for this disturbance to reach the separation value.

A change in the static pressure affects the separation in two ways. First, the pressure change alters the jet velocity. This varies the wavelength of the applied disturbance and, in turn, affects the growth rate. Secondly, the ratio of the jet's stimulation velocity to the steady velocity is altered and this also changes the breakup time.

Pressure variations may be eliminated by placing a strain-gage pressure transducer on the liquid manifold to measure the gage pressure adjacent to

the orifice plate. This signal then controls the pressure at the supply tank. As the filters clog with accumulated particles, the supply pressure is increased to maintain a constant pressure at the orifice plate. Also, if the elevation of the droplet generator is changed (i.e., moved from a workbench to the top of the oven), the supply pressure is changed to keep the pressure drop across the orifice constant. In addition, the synchronism of the charging-pulse timing may be altered as the liquid height is changed. The changes in stimulation pressure are caused primarily by fluctuations in the temperature of the piezoelectric crystals. This is alleviated with the resonance tracking oscillator, described above.

Drying-Firing Oven

The drying-firing oven has three temperature zones with a large temperature gradient running from the cooler top of the oven to the hotter bottom zones. When a droplet enters the top zone, it is warmed just enough to evaporate the water in the glass-forming solution. Temperature must be carefully controlled because if it is too hot, the droplet may explode as the solution boils. With the water evaporated, there remains a shell of silica gel that also contains boric oxide, sodium oxide, and other

Fig. 4-105. Optical microscope photograph of solid glass spheres made with the LLL hollow-glass-sphere production facility. Note that the diameters of these spheres are almost identical.

Fig. 4-106. Hollow glass spheres made at the LLL facility. As a result of oven temperature fluctuations, these spheres do not all have identical diameters; those with smaller diameters have thicker walls.

alkali oxides from the various constituents in the glass-forming solution. These shells are very flexible and can be easily redissolved in a basic solution.

Once the droplet has lost most of its water and can no longer explode, it is heated rapidly. The middle oven zone is kept as hot as possible without thermally affecting the upper "cool" zone and causing the droplets to explode. As the shells of silica gel fall into the middle high-temperature zone, the boric oxide melts and acts as a solvent for the silicon dioxide and sodium oxide. The gas trapped inside the silica-gel sphere is lost by diffusion, resulting in a molten glass sphere with few voids (see Fig. 4-105).

The glass droplets become hotter still as they fall into the hottest zone of the oven ($\sim 1350^{\circ}\text{C}$). A gas, either water vapor or the decomposition products of a blowing agent, is released in the glass, forming a bubble inside the liquid drop. This bubble expands and blows the glass droplet into a thin-shelled glass balloon (see Fig. 4-106). In this figure it is apparent that all the glass spheres do not have the same diameter. This variation possibly is a result of temperature fluctuations in the oven. Because all the

Fig. 4-107. Target spheres with centered (a) and uncentered (b) gas bubbles. The sphere in (a) is 103 μm in diameter with a wall thickness of 1.4 μm . The sphere in (b) was made from a droplet released from a 100- μm orifice; its diameter is 216 μm and its average wall thickness is 5 μm . These pictures were taken with an interference microscope and the concentricity of the interference rings is an indication of the uniformity of wall thickness.

spheres are made from the same amount of material, those with smaller diameters most obviously have thicker walls.

Below the last air inlet to the oven, a fritted glass disk collects the glass spheres as they come out of the oven. Air can pass through the frit but the target spheres are larger than the voids in the disk and are caught. The glass frit is then removed and the hollow spheres can be gently tapped out and collected for characterization and inspected for defects.

A frequent defect in commercial fuel balls is that the center of the gas bubble and the center of the exterior glass surface are not the same. This causes a nonuniform wall of the sphere and the wavelength of the nonuniformity is equal to the circumference of the hollow sphere. However, uncentered gas bubbles do not occur as frequently in the glass spheres produced by the LLL technique.

Photographs of glass spheres produced at LLL by the above technique are shown in Fig. 4-107. These pictures were taken with an interference microscope and the concentricity of the interference rings indicates the uniformity of the wall thickness. For the sphere in Fig. 4-107(a), the interference pattern shows that the wall thickness variation is practically unmeasurable. In Fig. 4-107(b), we see the interference pattern indicates that there is some variation in wall thickness, approximately 13%. Although this figure is not negligible, it is considerably smaller

than any variation measured on commercially obtained glass spheres of similar diameter.

Glass Solution

The composition of a sample glass-forming solution used in the droplet generators is presented in Table 4-13. These components are mixed in water to form a solution, which, when dried and fired, will produce the desired glass.

To determine the amount of water needed, several constraints must be considered, including the desired mass of the glass sphere and the diameter of the drops of glass-forming solution. The mass of the target sphere can be computed from its desired size and the density of the glass;

$$M_T = \rho/3\pi (R_o^3 - R_i^3), \quad (145)$$

where ρ is the glass density, R_o is the radius of the target's outer surface, and R_i is the target's inner radius. For many desired targets, the wall thickness is small compared to the target radius and thus, target mass can be approximated by

$$M^T = \pi \rho D_T^2 \delta, \quad (146)$$

Table 4-13. Composition and quantity of a typical glass-forming mixture to yield 1 litre of solution

Component	Mole weight	Mole %	Weight %	Mass, g
SiO ₂	60	71.9	70.7	121.9
Na ₂ O	62	21.9	22.2	38.3
B ₃ O ₃	70	6.2	7.1	12.2
Total			100.0	172.4

where D_T is the target diameter and δ is the sphere thickness.

The volume of solution available to produce the sphere can be calculated from data given by Chandrasekhar.¹⁹⁹ If we assume that the jet is stimulated at a frequency near its most unstable frequency, then the length, L , of the piece of liquid jet that forms one drop is

$$L = 4.51 D_j, \quad (147)$$

where D_j is the orifice diameter and hence the diameter of the jet. This length of jet then breaks up to form a drop of liquid with a volume

$$V = \frac{4.51 \pi D_j^3}{4}, \quad (148)$$

This volume of liquid forms a sphere of a diameter

$$D_s = 1.89 D_j, \quad (149)$$

where D_s is the diameter of the solution droplet.

For a unit volume of solution, the mass (grams) of required glass material is

$$M_s = \frac{4 \pi D_j^2}{4.51 D_j^3}, \quad (150)$$

One target size which we have produced is a 100- μm -diameter sphere with a 1- μm -thick wall. The orifice to form the jet is 50 μm in diam. The density of the glass, ρ , should be 2.43 g/cm³ (see Ref. 200, Table 7). The mass needed for a unit volume of solution for these targets is then

$$M_s = 0.1724 \text{ g/cm}^3. \quad (151)$$

Thus, we can determine the weight of each component for the glass to obtain 1 litre of the glass-forming solution (see Table 4-13). As this solution is formed into droplets that fall through the oven and are fired into glass, a small amount of the water is retained by the solutes when the particle becomes molten. This trapped water must be released and the water vapor blows the molten glass into a water-vapor-filled hollow sphere. For this particular solution the water vapor blows the sphere to the desired size; however, in some cases, an additional blowing agent is needed.

References

195. W. R. Beck and D. L. O'Brien, *Glass Bubbles Prepared by Reheating Solid Glass Particles*, U.S. Patent 3,365,315 (Jan. 23, 1968).
196. F. Veatch, H. E. Alford, and R. D. Croft, *Hollow Glass Particles and Method of Producing the Same*, U.S. Patent 3,030,215 (Apr. 17, 1962).
197. C. D. Hendricks and S. Babil, "Generation of Uniform 0.5 to 10 Micron Solid Particles," *J. Phys. E5*, 905 (1972).
198. J. W. S. Rayleigh, *Proc. London Mathematical Soc.* 10, 4 (1878).
199. S. Chandrasekhar, *Hydrodynamic and Hydromagnetic Stability*, (Oxford University Press, London, 1961), Ch. 12.

200. P. C. Souers, R. T. Tsugawa, and R. R. Stone, *Fabrication of the Glass Microballoon Laser Target*, Lawrence Livermore Laboratory, Rept. UCRL-51609 (1974).

Author
J. L. Dressler

Major Contributor
C. D. Hendricks

4-9.3 Grinding and Lapping Glass Microspheres

To fabricate targets for laser fusion experiments, it is often necessary to grind and lap glass spheres. For example, two glass shells, matched for diameter and wall thickness, can be lapped down to hemispheres and then mated together to form a layer for a multilayer spherical target. The hemispheres can also be used as molds for hemispherical foam targets. Two procedures are available for grinding and lapping glass spheres—the single-sphere and the batch-sphere method.

Single-Sphere Method

The single-sphere grinding and lapping method

Fig. 4-108. Acrylic cement must be applied to the microsphere/chuck joint for a strong bond. The vacuum chuck and sphere are shown before (a) and after (b) cement is applied.

Fig. 4-109. A 100- μ m-diam glass microsphere attached to a vacuum chuck and ready for grinding.

was developed by S. J. Perry of LLL's Nuclear Explosives Engineering Division. Essentially, a sphere is selected, cemented to a vacuum chuck, and lapped on a very smooth and accurate grinding wheel. In detail, the procedure is as follows.

After upward-sieving to segregate the microspheres by diameter, a glass shell is selected and characterized interferometrically for diameter, wall thickness, sphericity, and lack of significant defects. The selected sphere is then picked up on a vacuum chuck that has an opening approximately half the sphere diameter. The size of the vacuum chuck must be selected with care. If the chuck is too small, the sphere may be pulled off in the cementing step; also, the cemented joint or chuck may break in lapping. On the other hand, if the vacuum chuck is too large, it may not be flexible enough, preventing a proper preload on the grinding wheel.

The microsphere and chuck tip are dipped into an acrylic cement that dissolves away easily at the end of the lapping-grinding process. The cement is diluted either with ethylene dichloride, chloroform, or acetone (approximately three parts cement to one part solvent) to reduce the viscosity and surface tension. The chuck is dipped repeatedly in the cement until a layer of acrylic is built up at the microsphere/vacuum chuck interface (see Fig. 4-108). The cementing is checked under a microscope because the cement must be thick enough at the

Fig. 4-110. Jewelers' lathe showing the grinding wheel, vacuum chuck, and microscope eyepiece.

joint to support the microsphere during grinding but thin enough (about $3\ \mu\text{m}$) at the sphere surface to permit a reasonably short lapping time. Sometimes it is necessary to apply cement directly to the joint to ensure adequate strength. A microsphere properly cemented to the chuck and ready for grinding is shown in Fig. 4-109.

A jewelers' lathe with a 20-mm-diam brass grinding wheel is used for the actual lapping process. After the wheel is rough-faced on a lathe, it is lapped further with a 1900-grit abrasive and then with $0.3\text{-}\mu\text{m}$ alumina-grit until the grinding-wheel flatness can be measured against an optical flat to within a single fringe. The wheel is then charged with diamond grit, first by sprinkling the grit onto the face of the wheel and then by hand-loading the grit onto the wheel with a plate. Coarse $3\text{-}\mu\text{m}$ grit is used to grind spheres $200\ \mu\text{m}$ in diam and vacuum chucks about $100\ \mu\text{m}$ in diam. A finer $1\text{-}\mu\text{m}$ grit is used for smaller spheres and vacuum chucks. When the wheel is mounted on the lathe, the total indicated runout is within $3\ \mu\text{m}$. A wetting agent (e.g., soapy water) is used for a cooling and cutting medium. (We first tried a 95% alcohol solution but found that it did not lubricate as well.)

Next, the vacuum chuck with the glass sphere properly attached is inserted in a plastic sleeve and this sleeve is placed in a brass holding assembly. The plastic sleeve prevents damage to the vacuum chuck from the holding screws. The holding assembly is mounted on the lathe bed at a 30° angle to the grinding wheel to ensure the proper preload on the microsphere.

The application of the proper preload is extremely important. If there is too much pressure, the chuck or sphere will break. If there is not enough pressure, the lapping time will be too long. For a proper preload, the vacuum chuck and sphere are pushed against the grinding wheel so that the chuck bends just perceptively. If the chuck is too large and inflexible, the sphere will be crushed against the grinding wheel. Therefore, the taper at the end of the chuck should be long enough to be flexible (about $10\ \text{mm}$) and so that the microsphere can travel on the grinding wheel for a total distance of about $20\ \mu\text{m}$.

A wheel speed of about 850 rpm is used and grinding is stopped every 5 min to measure the opening. The holding assembly can be moved along the lathe bed and away from the grinding wheel to view the sphere through a stereo microscope. Although this does provide some measure of the lapping progress, it is still very difficult to approximate the opening size. If the hole is not yet large enough, the preload must be reset and the grinding continued. This grinding operation usually takes from 1 to 3 h. The lapping assembly with the microsphere and chuck are shown in Figs. 4-110 and 4-111.

Fig. 4-111. Photograph of a partially lapped microsphere against the diamond-charged grinding wheel.

Fig. 4-112. Lapping-grinding process: (a) a 100- μ m-diam hemisphere in a vacuum chuck, (b) two hemispheres ready for mating, and (c,d) the two lapped hemispheres after mating.

After lapping, the vacuum chuck is removed from the plastic sleeve and holding assembly so that the lapped microsphere can be released and cleaned. This is not a trivial task because the microsphere is fragile and can be easily contaminated.

The vacuum chuck is placed in a high-quality micromanipulator and a single drop of chloroform is placed on a clean glass microscope slide. The microsphere at the end of the vacuum chuck is carefully dipped in and out of the chloroform drop. The chloroform evaporates quickly but this first drop removes much of the acrylic cement. Thus, considerable residue is left behind on the slide. If the microsphere is freed from the chuck in this first drop, it becomes severely contaminated with the acrylic residue. However, if no other contaminants are present, the acrylic sometimes can be removed by oxidation in an oven at 540°C. It is best if the glass sphere remains on the chuck at least until it is

dipped into the third drop of chloroform. Each chloroform drop is placed on a clean spot on the slide and the slide is repositioned each time.

When the sphere is released into the third drop, there is very little acrylic residue to contaminate the sphere. The slide and microsphere are then placed in an oven at 540° and baked for approximately 1 h. A finished microhemisphere is shown in Fig. 4-112. Even though this procedure is performed with great care, the microspheres can be easily lost in the cement, destroyed in lapping, or contaminated by the acrylic residue. However, with careful and experienced handling, the yield can be as high as 90%.

Batch-Sphere Method

The batch method for grinding and lapping glass microspheres was developed by A. Ulrich of the Metallurgy and Ceramics Division at LLL.

For this process, a glass microscope slide is sprayed with a mold-release agent. Then, a lucite potting resin that has been mixed with an accelerator and then degassed is applied in a thin coat on top of the mold-release agent. Several thousand glass microspheres are sprinkled in a monolayer onto the lucite. A ring mold is placed on top of the slide around the microspheres and is filled with lucite. An epoxy plug is set on top of the lucite and a weight is added on top of the plug. The potted resin hardens in several hours.

The lucite disk and microspheres are lapped by a 100-rpm polishing wheel that is covered with a diamond-impregnated cloth; kerosene is used as a lubricant. Thick-walled spheres (2 to 4 μm) are ground with 1- μm diamond paste for about 4 h whereas thin-walled spheres (0.75 to 1 μm) are ground with 0.25- μm diamond paste for 16 to 24 h. The lucite disk is lapped until most of the spheres have the desired opening. However, because the microspheres are of different diameters and are imbedded at different depths in the lucite, many different size wall openings result.

Removing the spheres from the lucite and cleaning them usually takes about 24 h. The lapped lucite disk is placed on a 40- to 60- μm -pore glass frit which, in turn, is placed in a Soxhlet-type extractor. Stripper MS-111 for cured epoxy resins is refluxed through the system at about 80°C for 6 h. This dissolves most of the lucite. The glass frit is then transferred to a second Soxhlet-type extractor. Glacial acetic acid is refluxed through for 6 h at 118°C. The frit is then washed twice for 1 min in deionized water with an aspirator. It is washed a third time in 95% ethyl alcohol. The frit is drained thoroughly with an aspirator and allowed to dry for 10 min. It is baked in one oven at 100°C for 2 h and then in a second oven at 550°C for 6 to 24 h.

At the end of this process, the glass shells can be gently tapped out of the frit and onto a glass slide in a petri dish. The yield of acceptably lapped hemispheres is less than 1%. These good shells must be sorted under a low-power light microscope and then characterized individually in the interferometer for diameter, wall thickness, and lack of defects.

Conclusions

These two methods accomplish the same results. The main difference between these techniques is the

way the spheres themselves are handled and the techniques used. The single-sphere method produces a high yield of good hemispheres but an operator is required essentially throughout the process. In contrast, the batch method needs less operator attention except during the characterization step; however, the yield of good hemispheres is very low. Thus, when glass microspheres are lapped for a particular laser fusion experiment, a decision must be made whether constant operator attention or low yield is more tolerable.

Author

R. M. Singleton

4-9.4 Laser Machining of Parts

Laser machining has already proved useful in fabricating laser fusion targets. As previously reported,²⁰¹ many materials can be drilled with a single pulse from a ruby laser.

The ruby laser has a pulse width of a millisecond. By controlling the charging voltage and introducing various apertures in the laser cavity, we can vary its energy from a few millijoules to about one joule, providing power settings from 1 W to 1 kW. By selecting appropriate power settings and choosing focusing lenses that focus to a known spot size, we can control the size of the pulsed hole. Using this system we have drilled holes in silicon glass, quartz glass, lead glass, tungsten glass, gold, copper, aluminum, carbon, tantalum, Parylene, and diamonds in thicknesses from 0.5 to 50 μm . We have found that the minimum hole size is limited by the thickness of the sample until the thickness is less than 5 μm . From 0.5 to 5 μm , the limiting factor is the focal spot size produced by the lens. The smallest hole we have been able to drill is 2 μm in 0.5- μm -thick tungsten glass. On the other hand, we can drill 250 μm holes easily in most samples with a single pulse of the laser.

To cut a line in a given material, we overlap successive pulses. The manual alignment of each shot and the slow pulse rate of the ruby laser (about 2

pulses/min) make this technique tedious and time-consuming. Typically, cutting a 500- μm -diam glass disk takes about 45 min. Furthermore, the edge of the finished disk is ragged and shows the marks of the separate shots used to cut it out (see Fig. 4-113). To speed the cutting process and produce more un-

Fig. 4-113. Tungsten glass disk (250- μm -diam cut with pulsed ruby laser.

iform parts, we have used the cw laser machining arrangement described below.

Laser Machining Arrangement

A 5-W argon ion laser operated in a cw mode is used with a broad-band mirror tuned to maximum power output. As shown in Fig. 4-114, the beam is directed vertically by an adjustable turning prism through a beamsplitter and then focused with an ordinary microscope objective lens onto the material to be cut. The beamsplitter and a standard microscope illuminator allow a telescope and television camera to view the cutting process through the same lens that focuses the laser. A filter is used in front of the telescope to protect the television camera from backscattered laser light. The object to be cut is mounted on a micromanipulator that moves the object in two dimensions in the focal plane of the laser. This micromanipulator is mounted on an x-y platform positioner that steps in 2.5- μm increments on each axis. By controlling the drives to this axis, we can make the platform and the material move in a circular pattern.

Results

Using this arrangement with the cw laser, we have found we can cut certain glasses (such as tungsten

Fig. 4-114. Continuous wave laser machining arrangement.

Fig. 4-115. Disk partially cut from tungsten glass sample.

glass), plastics, and carbon films, but we cannot cut metal foils. Lasers of higher power should permit improvements in the process. Using a 40-power objective lens as the focusing lens, the smallest hole we have been able to drill in 10- μm glass (75% WO_3 , 25% P_2O_5) is 7 μm . Figure 4-115 shows a 250- μm -diam disk partially cut from a piece of 10- μm -thick tungsten glass; Fig. 4-116 shows the same piece after separation from the stock glass. This piece took 20 s to cut compared with 45 min for the disk in Fig. 4-113; moreover, the edge has a smoother finish. These pieces can be produced in large numbers with no significant differences in size or shape. Different dimensions can be dialed into the controller, and a production run of disks can be cut in a matter of minutes.

Shapes other than disks are also possible. For example, Fig. 4-117 shows a 50- $\times$ 100- μm rectangle cut from 1- μm -thick carbon film by manually controlling the x-y platform stepping motors. The piece took about 1 min to cut. Random shapes can also

Fig. 4-116. Same disk as shown above completely cut out.

Fig. 4-117. 1- μm -thick carbon film 50 $\times$ 100 μm .

be cut using only the micromanipulator and cutting the desired shape while viewing it on the TV screen.

In summary, our cw laser micromachining system is more limited than the single-pulse ruby system in the materials it can cut, but it offers advantages in time, uniformity, and smoothness of the finished cut.

Reference

102. B. W. Weinstein, C. D. Hendricks, and J. T. Weir, *Laser Microdrilling in the Fabrication of Laser Fusion Targets*, Lawrence Livermore Laboratory, Rept. UCRL-77406 (1975).

Author

J. T. Weir

4-9.5 Thin Films

To meet the next milestones of the laser fusion program, especially reaching compressions of 100 and 1000 times hydrogen liquid density, we will need multilayer targets that are much more advanced than today's simple glass spheres filled with DT fuel. The layers being considered range from ele-

ments of low atomic number and density to those of high atomic number and density. Also being considered are organic polymers and several inorganic materials including various glasses and metal-like alloys.

So that the required techniques will be available when needed, we have been developing the specialized equipment and processes for fuel pellet coating. At present this equipment is being used routinely for other laser program tasks, such as preparing thin gold disks for pinhole cameras, gold-coated alignment balls, and gold-and-plastic disks for diagnostic targets.

Radiofrequency Plasma Coaters

The rf plasma coater shown in Fig. 4-118 is being used to develop methods for coating by converting various organic monomers into polymeric materials at the surface of the fuel pellet. An electrical discharge creates an activated species in the vapor phase of the monomer. The activated species condenses on the surface of the object to be coated — such as a spherical copper mandrel or glass mandrel — which has been placed in or near the glow discharge. The activated monomeric species then polymerizes with other monomer molecules on the surface of the mandrel.

Fig. 4-118. Radiofrequency plasma coater.

Currently, our emphasis is on developing techniques for depositing fluorine-substituted compounds such as tetrafluoroethylene, octafluoro-2-butene, and copolymers of these materials. In our system, two electrodes are placed in a vacuum system capable of maintaining pressure at 1 to 10 μm . One electrode consists of a wire mesh fitted into a hemispherical cavity fitted with a tube for bleeding either gas or monomer through the mesh into the chamber. The other electrode is a planar aluminum plate containing fixtures for holding the mandrels to be coated. The mandrel is generally cleaned by charging either argon or oxygen into the chamber and applying the rf field to the electrodes to produce a glow discharge. The chamber is evacuated to about 10 μm , and then the monomer of interest is bled into the chamber through a needle valve, the rate being controlled to produce a pressure of approximately 200 μm . The high-frequency signal (30 to 50 W, 13.56 MHz) is applied to the electrodes during introduction of the monomer and is maintained for the duration of the coating process. The rate of polymer deposition is from 0.1 to 5 $\mu\text{m}/\text{h}$.

The following factors are being investigated to determine their effect on the surface quality and rate of deposition: temperature of the substrate surface, concentration of the monomer, power delivered to the electrodes, and type of monomer used. Figure 4-119 is a scanning electron micrograph of the surface finish obtained by depositing an octafluoro-2-butene,

Fig. 4-119. Scanning electron micrograph of surface of glass mirror coated with tetrafluoroethylene-octafluoro-2-butene copolymer deposited by plasma discharge.

Fig. 4-120. Ball-on-stalk target coated with octafluorobutene.

tetrafluoroethylene copolymer on a glass mirror to a thickness of 7 μm . Figure 4-120 shows a plastic ball-on-stalk target after coating with about 60 μm of octafluoro-2-butene.

Parylene Coating

Parylene is produced by the vapor phase deposition and polymerization of para-xylylene ($-\text{CH}_2-\text{C}_6\text{H}_4-\text{CH}_2-$). The process, performed under license to Union Carbide Corporation, starts by heating a dimer of the above molecule to vaporize the dimer, which is then pyrolyzed, producing a reactive monomer vapor. When this vapor passes over an object at room temperature, it coats the object with a very uniform layer of parylene (poly-para-xylylene). This process is not line-of-sight-limited as are some other deposition methods. Figure 4-121 shows the equipment used to coat articles with parylene.

We employ the parylene coating process routinely to produce such diversified materials as 500- $\text{\AA}$ support films, freestanding spherical shells, and 1- to 20- μm wafers used for various other targets.

Fig. 4-121. Parylene coating process.

Direct Current Sputtering

Direct current (dc) sputtering is a valuable tool. The basic equipment (Fig. 4-122) is a hollow-sleeve cathode system using argon gas at a pressure of 10 μm to form the energetic ions. The ion generation is improved by using the field of a permanent magnet to constrain the emitted electrons in a spiral pattern. The argon ions attracted to the cathode target have enough energy to dislodge an atom of the target material. The sputtered particles are ejected from

the target in random directions, so that a large area of coverage is generated by the sputter pattern. This system is especially useful for target materials of relatively low resistivity.

The dc sputtering method is used for coating alignment balls with gold (Fig. 4-123) to produce gold disks for use as laser targets or as pinhole cameras and to coat various mandrels.

In addition to the standard coatings, the sputtering equipment has been utilized for reactive sputtering of materials such as carbon, aluminum, and

Fig. 4-122. Direct current sputter system.

Fig. 4-123. Gold alignment target, a hollow glass sphere coated with gold.

Fig. 4-125. Scanning electron micrograph of 0.5- μm -thick boron film with particulate inclusion deposited by electron-beam method.

Fig. 4-124. Electron beam evaporator system.

Fig. 4-126. Ion-beam etch-deposition system.

Fig. 4-127. Scanning electron micrograph of ion-deposited Teflon film showing electron-beam damage site.

boron to produce $(CH_x)_n$, aluminum nitride, and boron nitride coatings. Although these materials have been successfully deposited, the surface characteristics are not yet satisfactory for our applications. Difficulties with arc breakdown prevented the generation of surfaces of sufficient quality. Further investigations were temporarily discontinued when other equipment became available for producing the same types of coatings.

Physical Vapor Deposition

Physical vapor deposition is generally carried out by thermally vaporizing a material in a vacuum and depositing the vapor on a line-of-sight basis on materials at a lower temperature. Although this method has not been used extensively, it has proved valuable in one area. For calorimetry, it was necessary to coat the inside of 3-cm-diam glass shells with a thin layer of aluminum. This was accomplished by inserting a small coil of resistance wire, containing a loop of aluminum wire, through an opening to the center of the shell. This method was quite successful in coating the entire inner surface of the glass bubble.

Electron Beam Vapor Deposition

The electron beam system shown in Fig. 4-124 provides a means for depositing many materials. A beam of electrons focused on a material of interest vaporizes the material, which is then deposited on a

mandrel. This apparatus is being used to evaluate methods for applying coatings of standard materials, such as gold, copper, and aluminum, as well as materials more difficult to apply, such as boron. Figure 4-125 shows a $0.5\text{-}\mu\text{m}$ coating of boron deposited on a glass slide by the electron-beam system.

Ion Beam Milling/Deposition

Figure 4-126 shows the ion beam milling/deposition system that recently became operational at LLL. Basically, the system consists of a low-voltage ion beam that can be impinged on a substrate to remove material or directed at a target from which atoms or molecules are to be removed for redeposition on a substrate. The system produces only minor temperature increases, because there is no electron bombardment of the deposition substrate. The types of materials that can be deposited by the system, are virtually unlimited, so many different materials are being evaluated. Included among those so far tested are teflon, fluorinated ethylene propylene polymer, aluminum nitride, boron nitride, silicon dioxide, and boron carbide. Figure 4-127 shows a scanning electron micrograph of a teflon coating deposited by the equipment.

Author

C. W. Hatcher

Major Contributors

S. F. Meyer
H. G. Redmond
L. E. Lorensen
K. L. Montgomery
W. E. Johnson

4-9.6 Electron Microscopy Applications to Laser Fusion

In 1976, the LLL Laser Program activated a research scanning electron microscope to serve target fabrication and other aspects of the program. The scanning electron microscope (Fig. 4-128) is a highly versatile tool and is able, with minimum sample preparation, to provide quantitative topographical and elemental information on a wide

Fig. 4-128. Cambridge S-180 scanning electron microscope.

variety of samples in a form that can be readily interpreted. This instrument has developed into a major tool in the on-going attempt to produce better fusion targets and to analyze glass damage sites on laser amplifier components.

There are three basic versions of the electron microscope, the conventional transmission electron microscope (CTEM), the scanning electron microscope (SEM), and the scanning transmission electron microscope (STEM). The first two instruments both have distinct advantages and disadvantages while the third microscope is an attempt to exploit the advantages of the first two and eliminate their disadvantages.

Conventional Transmission Electron Microscope (CTEM)

The CTEM is a high-resolution instrument with a long history of application to material and biological science. Point-to-point transverse resolutions better than $3 \text{ \AA}$ have been obtained on very high contrast objects such as crystal lattices and metal droplets on carbon films. However, thin $1000\text{-\AA}$ samples or surface replicas are required for observation. This requirement, coupled with the thick low-contrast nature of our target materials, limits the applicability of the CTEM on laser program samples.

Scanning Electron Microscope (SEM)

In contrast to the CTEM, the highly adaptable SEM with its basically simple sample preparation has found many applications in the laser program. A SEM employs a triode electron gun with a tungsten hairpin, lanthanum hexaboride (LaB_6), or a tungsten point-field emitter as the electron source. The source image is demagnified through an electromagnetic lens system and is focused onto the specimen as a sharp rastered beam.

Electrons interacting at the surface of the sample produce a variety of usable effects. The most commonly exploited signal is the flux of low-energy secondary electrons, created through ionization of the sample by the high-energy (1- to 50-keV) primary electrons. Escape depths of 0- to 50-eV secondaries range up to $500 \text{ \AA}$, depending on Z . Thus, image resolution is close to the beam diameter; $50\text{-\AA}$ resolutions are attainable on high-density, high-secondary-yield materials such as gold or tungsten. In low- Z materials characteristic of laser fusion targets, the primary beam broadens farther due to scattering before it falls below the escape depth of the secondaries. As a result, without a high- Z coating such as gold, material considerations limit resolution to about a couple hundred angstroms.

Secondary electrons are collected on one side of the sample and are electronically detected with a scintillator-photomultiplier detector. The apparent angle of illumination comes from one direction and thus, this single-point detection gives the viewed sample a definite visual relief. Additionally, secondaries are actually being produced throughout the penetration depth of the primary beam. Therefore, where the topography allows the beam to strike the sample at a grazing angle, more secondaries escape and the area is highlighted; the bright side of the feature generally oriented toward the detector.

As a result, SEM images appear quite similar to obliquely illuminated optical views and are thus readily subject to interpretation. Figure 4-129 illustrates this point. The micrographs are equivalent to what is expected optically and only after a second examination does the increased resolution and depth of field become evident. Conversely, a homogeneous material with low-aspect-ratio surface structure greater than about 1:10 and without obvious boundaries is difficult to detect because of the lack of contrast.

Fig. 4-129. SEM micrographs of gold plated copper mandrels illustrating the need for careful contamination control where smooth surface finishes are required. In (a), a copper mandrel after cleaning in trichlorethylene before coating shows large residual contamination. In (b), the mandrel in (a) after 10- μm sputtered gold coating. The mandrel has been rotated 150° counterclockwise and large growths are apparent, generally corresponding to the previous contamination. In (c), a copper mandrel after cleaning in trichlorethylene and before coating shows essentially no contamination. In (d), the mandrel in (c) after 10- μm sputtered gold coating. Although the mandrel was clean initially, the deposition-system cathode had just been reinstalled, introducing contamination from the deposition system and resulting in large gold growths on the mandrel.

Backscattered electrons provide another useful signal, being sensitive to atomic number. However, because they scatter a long distance in the sample relative to beam diameter, they come out of a larger material volume ($\sim 1 \mu\text{m}^3$) and do not offer as much resolution. The angular dependence of the backscatters can be used to increase contrast, whereas characteristic fluorescence x rays (generated by the high-energy primary and scattered electrons) can be used to detect and image all elements from

beryllium up the periodic table with sensitivities in the 100 $\mu\text{g/g}$ range. Auger electrons produced in the ionization process can also be used for elemental identification and for imaging the top 10 to 50 Å of the surface. However, to prevent contamination problems and to provide stable surfaces, pressures in the 10^{-9} Torr (10^{-7} Pa) are needed and dictate a special Auger surface-analysis instrument system.

Because of the up to 5-cm working distance and the typical 200- μm illuminating aperture, the SEM

possesses great depth of field (over 100 times that of the light microscope, i.e., 1 mm at 10,000 $\times$). This represents a major advantage for SEM images taken in the optical microscope range and makes the SEM extremely useful for observing very rough, three-dimensional surfaces (Fig. 4-130). In addition, the large depth of field can be further increased by dynamically focusing the beam as it sweeps, obtaining complete focus across the field of steeply sloped, flat samples (Fig. 4-131).

With matched pairs of photographs of different viewing angles, stereo images can be constructed both for viewing and for quantitative three-dimensional measurements (Fig. 4-132). However, because each point must be individually measured on both images, stereo pairs are a time consuming and tedious way of obtaining surface-roughness information. As an alternative technique, the surface can be viewed at an oblique angle between 80 and 89 $^\circ$ to the normal and the height variations can be measured directly (Fig. 4-133). Although this second method is simpler, it has a serious flaw; pits are essentially impossible to measure and are extremely difficult to locate. As a result, both techniques are routinely used for three-dimensional measurements.

Fig. 4-130. Damage site on a flash-lamp shield, viewed at 83 $^\circ$ to the normal. The depth of field available on the SEM is used effectively to image the entire site, even though it is greater than 0.5 mm in diameter.

Fig. 4-131. SEM image of a vacuum-evaporated carbon film, viewed at 83 $^\circ$ to the normal. With dynamic focus, the depth of field is greater than 2.3 mm. A graphite structure is forming with numerous contaminants on the surface.

The secondary-electron image has high noise-free contrast only on high-Z samples with large topographical variations. Thus, most modern SEM's include some form of image processing, including differentiation of the signal, digital expansion of the contrast, conversion to grey levels, contour mapping, and Y modulation (Fig. 4-134). None or any of these may be necessary to display the area of interest on a given sample. Generally, the lower the sample contrast, the greater the need for such image-processing techniques. These techniques find great use on low-contrast laser fusion materials.

Limitations to SEM Applicability. The limitations are (1) size and vacuum compatibility, (2) contamination and sensitivity to e-beam damage, (3) sample conductivity, and (4) secondary yield.

Size and Vacuum Compatibility. The SEM specimen is examined in a vacuum system at 10^{-6} Torr (10^{-4} Pa). Therefore, any specimen must fit within the confines of the sample chamber and must be vacuum compatible. Because resolution is a function of working distance, the sample area to be analyzed ideally should be within 10 mm of the lens for maximum resolution.

Contamination and Sensitivity to e-beam Damage. Currents up to 20 μ A at 60 keV (10^5 W/cm 2) are possible in the instrument, and can cause severe damage to some materials. Even normal operating currents (10^{-10} to 10^{-12} A at 20 keV) are sufficient to decompose some plastics when they are scanned

Fig. 4-132. Stereo pair of a damage site on a flash-lamp shield. Stereo angle is $\pm 5^\circ$ at about a 40° tilt. Sharp fractured areas and fused areas are visible in the crater. The height of most points within the crater can be determined with parallax measurements.

Fig. 4-133. A 90° edge view of a $3\text{-}\mu\text{m}$ direct current sputtered carbon film showing the columnar grain structure and surface height variations.

over a $10\text{ }\mu\text{m}^2$ area. Furthermore, the electron beam tends to deposit an organic film on most samples during operation as a result of the polymerization of surface organics and residual gasses in the vacuum system. This film generally is only angstroms thick but it can greatly reduce secondary emission and severely impair bonding characteristics. In addition, traces of greases, oils, or other volatile organics contained in the sample itself tend to increase the severity of the contamination, and thus, sample cleanliness is always an important consideration.

Sample Conductivity. Samples that are good insulators become charged where the beam impinges. The resulting electric fields around the sample can actually deflect the beam. This problem is most severe with large bulk insulators such as alumina

Y modulation

Unprocessed image

Two contour levels

Four gray levels

Light micrograph

Two expanded contrast levels

Fig. 4-134. SEM micrographs of a ball-on-stalk target illustrating the various image-processing techniques. The ball is uncoated and epoxied to a glass stem. Electrostatic charging causes the banding and background variations; however charging is not severe enough in even this instance to preclude micrographs at 30,000X of the surface.

Fig. 4-135. Surface of an uncoated glass shell using expanded contrast imaging. Even though the sample is insulative and of low atomic number, resolutions of approximately 300 Å are evident with a number of visible sub-1000-Å defects. Artifacts this size, including the 8000-Å-wide hill in the center, are below the spatial resolution of an interferometer and are only visible on the SEM.

ceramics and on long filamentary insulators like fiberglass cloth.

Laser fusion targets are often good insulators and thus would be expected to experience charging problems. In general, however, when a glass shell is placed on and in good electrical contact with a conductive mount, the charging problems are actually quite small. The path length to ground followed by the charge is quite short, accumulated charge dissipates rapidly, and after exposure to air, the shells are somewhat conductive (Fig. 4-135).

Where charging is a problem, the most common solution is to coat the surface of the laser target with approximately 200 Å of evaporated gold or aluminum. In cases where this is not desirable, the beam current can be reduced and the sweep rate can be increased (although this results in an increase of noise and a decrease in resolution). Alternatively, the beam voltage can be reduced to a few kiloelectron volts so that the secondary and backscatter emissions exceed the absorbed electron current, also at the expense of noise and resolution.

Secondary Yield. The ultimate resolution of a SEM generally is determined by the noise limita-

tions of the secondary generation and collection system. The beam currents required to produce a usable image dictate the resolution because an increased column demagnification (producing a smaller electron probe) reduces the beam current and thereby reduces the secondary flux. For efficient collection systems, high-brightness electron guns, and surfaces of high secondary yield (e.g., gold), the probe size can be reduced to the limitation imposed by spherical aberration of the final lens. Thus, it is more difficult to obtain high resolution on low-Z materials with low secondary yields. Because laser fusion targets generally fall in this category, it is desirable to use a higher-brightness electron source (e.g., LaB₆). This increases the beam current and secondary flux without reducing the column demagnification.

For maximum resolution on laser fusion targets, the best electron source would be a cold-field emitter with a brightness up to 100 times that of tungsten and a much smaller initial size requiring much less demagnification. Unfortunately, the present field emitters are more difficult to operate and cannot produce a beam current much over 10 nA. Thus, it is almost impossible to perform an x-ray analysis on elements below fluorine. Obviously, this severely limits the application of these electron sources. However, field-emitter technology is rapidly improving and perhaps the shortcomings of field emitters can be overcome in the near future. For the present, maximum resolution on low-secondary-yield target materials is best obtained by overcoating the specimens with gold. (See Refs. 202 and 203 for further treatments of scanning electron microscopy.)

Scanning Transmission

Electron Microscope (STEM)

The next instrument generation beyond the SEM is the STEM. This instrument offers significant possibilities for the high resolution of > 1-μm-thick specimens.²⁰⁴ The sample is immersed in the final lens for very low spherical aberration and there are no lenses after the specimen and thus, chromatic aberration is not a problem. With field-emission electron guns and electron-energy analyzers for detectors, the STEM focuses a very small raster

probe on the sample, detecting the transmitted electrons. This permits bulk elemental analysis as well as the imaging of inelastically scattered electrons. In addition, STEM can be performed with a SEM; however, the high-resolution advantages are not as great because a large spherical aberration of the final lens occurs as a result of the long working distances.

Sample Preparation

To take the fullest possible advantage of the techniques offered by electron microscopy, some special procedures must be followed for the preparation of laser fusion target materials.

Glass Shells. To attach loose target spheres to a mount, a portion of a stub is thinly coated with conductive silver paint. When the paint is almost dry, (looks slightly damp), a few spheres are dropped from a small spatula or needle onto the damp areas. With a little practice, the paint will cover only about 5 to 10% of the sphere after contact. Large concentrations of spheres should be avoided because they tend to charge; it becomes difficult then to obtain a good overall view of an individual sphere. An alternate cement is isopropyl alcohol made "dirty" by storage in a plastic squeeze bottle. Manipulative devices that avoid the "cement" problem for mounting spheres in the SEM are being constructed; these devices will provide a 4π scanning of the spheres without damaging target surface.

Particles. A solution of 1% collodion in amyl acetate provides a simple mounting cement for particles. In most cases, it is only necessary to place a small drop over the particle (viewed through a microscope), fixing the particle in one location. The coated sample is air-dried in a dust-free area for about 1 hour. If the collodion film is too thick, a drop of amyl acetate is placed on the particle to thin the cement and the sample again is allowed to dry. This is repeated until adequate thinning is achieved; however, care must always be taken when dropping liquid onto a particle so that the particle is not carried away by the thinning flow.

Targets Mounted on Stalks. Whenever possible, samples should be metalized before examination with an electron microscope. A uniform coverage over the entire surface and a good electrical contact to ground are essential. In cases where it is not possible to overcoat, the sample is placed under a microscope and silver paint is applied with a very

fine artists' brush up the stalk, as close to the target as possible. Some charging is impossible to prevent (see Fig. 4-134), but as long as the electrical path to ground is a few hundred microns, suitable images generally can be obtained.

Metal Parts and Mandrels. Usually no special preparation is necessary for these components. However, if contamination is a potential problem in later processing of the part, the sample must be cleaned before examination with the electron microscope.

Elemental Analysis. When an elemental analysis of insulating materials at high-beam currents is anticipated, a 500-Å carbon or aluminum overcoating is necessary. Both evaporated and sputtered aluminum films work well. However, the coating operation must be carefully controlled because too thick an aluminum or carbon coating will interfere with low-Z x-ray fluorescence analysis.

Conclusions

The SEM is a highly versatile tool for examining laser fusion materials. It has potential, not only as a research tool but also as a means of characterizing the targets that no other analytical technique can handle. With its image processing and additional staging, the value of the SEM to laser fusion will continue to increase and, in particular, SEM analysis will probably become a routine step in the target-fabrication sequence.

References

202. O. C. Wells, *Scanning Electron Microscopy*, (McGraw-Hill, New York, 1974).
203. J. I. Goldstein, H. Yackowitz, D. E. Newbury, E. Lifshin, J. W. Colby, and J. R. Coleman, *Practical Scanning Electron Microscopy*, (Plenum Press, New York, 1975).
204. T. Groves, "Thick Specimens in the CEM, STEM Resolution and Image Formation," *Ultramicroscopy* 1, 15 (1975).

Author
C. M. Ward

Major Contributors
C. D. Hendricks
B. W. Weinstein
K. L. Montgomery

4-9.7 Techniques, Tools, and Methods of Target Part Handling

Target fabrication requires the handling of tiny, fragile parts without damage or loss. For example, 100 or more typical 50- μm target spheres can fit on the head of an ordinary straight pin. The wall thickness of these spheres may be as thin as 500 nm with a required surface finish of 10 to 100 nm. Clearly, delicate handling techniques are required to minimize damage and loss. In addition, with such small parts, electrostatic forces dominate gravitational forces, which can lead to unexpected behavior. Vibration is a major cause of target damage with glue-joint failure the most common form. Even experienced personnel must contend with a target mortality rate of approximately 15%.

The fundamental, pervasive nature of target parts handling is illustrated in Fig. 4-96 where the steps necessary to produce a complex, noncryogenic target are diagrammed. Some parts can be processed in a batch mode with relatively simple and noncritical handling methods. However, most

parts must be handled repeatedly and individually, requiring much effort, care, and time. The basic tools for handling and processing the target parts are presented in Table 4-14, along with their typical applications and constraints to their use.

Vacuum Chuck

Vacuum chucks, the microscopic equivalent of tweezers, are used for the precision handling and positioning of target parts. These chucks are made by pulling 1.5-mm glass capillary tubing in a pipette puller, breaking the tip, and grinding the end to a smooth finish. The vertical gravity pipette puller (Model 700C, David Kopf Industries) uses a heater wire to soften the capillary in the middle (see Fig. 4-136). By varying the heater current, the tapered capillary tube can be made 6 to 10 mm long and flexible or short and rigid.

For a vacuum chuck, the capillary tip is broken at the desired diameter, usually in the 25- to 50- μm range. The end is then lapped to a smooth finish by the same methods used to grind and lap glass target spheres. However, vacuum chucks take only about 1 min to grind to a suitable finish. After grinding,

Table 4-14. Important tools used in the handling of laser target parts

Tool	Applications	Constraints
Vacuum chuck	Picking up and positioning of target parts.	May puncture sphere or scratch smooth surface.
Micromanipulator	Precise positioning of vacuum chuck or "glue stem."	Bulky; only two will fit under one microscope.
Microscope	Visual aid; size and dimension are measured with either a calibrated reticle, or split-image microscope.	Depth of field is small; some microscopes reverse directions.
Camera	Documenting parts and finished targets.	Can only be used through a microscope; lighting is critical.
Drill	Drilling holes in diagnostic parts not easily accomplished by laser drilling.	Smallest available drill is 5 μm ; holes can be drilled only to a depth 7 times the drill diameter or less.
Lathe	Shaping and cutting of surfaces by diamond knife.	Stock components must be cylindrically symmetrical. Cut depth of only 10 to 20 μm and a surface finish of about 1 μm .
"Cookie cutter"	Stamping out disk and "lollipop" target.	Only plastic thicker than 1 μm can be used.

Fig. 4-136. Gravity pipette puller used to pull 1.5-mm diameter glass capillary tubing for vacuum chucks.

the chuck is cleaned in chloroform and blown dry. Finished chucks are sorted and bent in the pipette puller to any desired angle. The chuck tip must be smooth because jagged points may scratch smooth surfaces or puncture a fuel sphere. Next, the vacuum chuck is mounted in an aluminum holder with a quick connect fitting at one end and a tubing nipple at the other. Vacuum is brought in with flexible tubing through a metering valve that regulates pressure. Too great a pressure differential distorts or crushes target parts.

An easier, alternate means for handling simple metal parts is available. Any soft instrument such as a wooden spatula is simply pressed against the part, allowing the metal piece to be picked up. A light tap on the spatula is all that is necessary to release the piece. However, this technique is only suitable for inexpensive, flat, noncrushable parts.

Cement Application

A variation of the vacuum chuck is used for permanent mounting of parts or cement application is

the "glue stem." After the pipette is pulled, the tip is broken, usually at a 5- μ m diameter. In contrast to the vacuum chucks of larger diameters, no grinding is necessary. With the small opening, it is possible to form the smallest possible drops of epoxy. The epoxy (Double Bubble 5-min epoxy, Hardman Inc.) is mixed on a Teflon slab, scooped into a hypodermic syringe, and squirted into the "glue stem." The "glue stem" is then mounted in a vacuum chuck holder and connected to a rubber pressure bulb. The slightest pressure on the bulb causes a bead of epoxy to form at the tip of the "glue stem." This bead is then carefully touched to a target part. At this point, the "glue stem" can either be left to harden onto the part as a stalk or it may be withdrawn, leaving the drop of epoxy behind. Other parts can then be brought in on vacuum chucks and attached to the first piece with the drop of epoxy. When attaching a stalk, a constant air pressure on the "glue stem" must be maintained during curing because the epoxy has a tendency to contract back into the capillary tube.

Micromanipulators

Once the vacuum chucks and "glue stems" are mounted in holders, they are positioned with micromanipulators. The best manipulators (Leitz) available (Fig. 4-137) are not suitable for our needs

Fig. 4-137. Basic handling equipment including micromanipulator (lower right), light (upper right), microscope, and tool scope (left).

because they drift 20 to 30 $\mu\text{m}/\text{h}$ or more and have a tendency to backlash when the direction of motion is reversed. However, we were able to correct these problems by refitting the manipulators with graphite guide rings and by using a grease of the proper viscosity (Rocol Kilopoise 0001G) so that the cam followers ride on a film of grease on the joystick ball. The reappearance of backlash indicates that the joystick ball needs to be cleaned and regreased. With this upgrading, the manipulators now perform with drifts of only 1 to 2 $\mu\text{m}/\text{h}$ with an instrument occasionally showing no drift when left for overnight intervals. Continuous, smooth motion is possible with submicrometer increments.

Optical Equipment

The minimum necessary optical equipment includes microscopes, cameras, and lights. Stereo zoom microscopes provide a rapid three-dimensional view whereas binocular microscopes can be equipped with camera mounts and are needed for detailed work and for photography. Unfortunately, binocular microscopes reverse the field of view and direction. This can cause some confusion when an operator switches between stereo zoom and binocular microscopes.

Adequate lighting is achieved with stage lights and multiple spotlights of adjustable intensities. Lighting for viewing and photography is necessary to give the image three-dimensional character and to separate the foreground and background surfaces. For photography, harsh lighting must be avoided; otherwise, bright highlights appear as defects and severely distort the image. Accurate, good quality scientific photographs are essential to document the finished parts and targets; thus, several documentation photographs are taken of each finished target.

Part dimensions can be measured with a calibrated reticle or with a direct-readout, split-image microscope. Reticles are usually calibrated against a stage micrometer with 10- and 100- μm intervals. The split-image microscope (model M41, Vickers Instruments; see Fig. 4-138) is used to measure objects with dimensions from 3 to 500 μm , using several internal scales with an accuracy of 0.5%. Additional eyepieces can extend the range of this microscope to about 3 mm.

Fig. 4-138. Split-image microscope. This instrument model is able to measure from 1 μm to greater than 3 mm with an accuracy of 0.5%.

Storage and Transport

The storage and transport techniques are designed to minimize the effects of vibration, electrostatic charging, and diffusion of hydrogen out of the fuel spheres. Characterized fuel spheres are stored on aluminum planchets inside a square of closely spaced dots that aid in relocating the sphere after storage. Because the beta decay of tritium leaves a positive charge on the fuel spheres, the spheres are covered with aluminum foil and stored in foil-lined glass boxes to minimize losses by electrostatic forces. Storage of these boxes at -20°C retards fuel-gas diffusion through the glass shells and extends the useful life to a few months.

Spheres within the dot pattern may be easily transported in covered planchets while a covered microscope slide suffices for larger, more visible gold parts. Finished targets are stored at low temperature with the stalk wrapped in a foam pad, inserted in a cork base, and the entire assembly covered with a plastic cap. The cork base and plastic cap minimizes vibrational damage and provide a convenient handle for transport. Cases of these targets may be packed in glass boxes and stored in foam pads for several weeks.

Fabrication Techniques

Drilling. Parts made from plastics and glass may be processed to obtain a finished target. Targets and diagnostic parts often arrive for processing as a 10- μm gold coating on a silicon or copper mandrel.

Gold disks and disks with holes are made on silicon mandrels in sizes from 50 μm in diameter and larger; up to 100 disks can be made on a single mandrel. The smallest hole in a disk (disk and hole made in the same step on the mandrel) is at the present limited to 50 μm ; smaller holes must be drilled in a separate step in solid disks. Laser drilling is the most flexible method. However, our present laser is not conveniently used to drill 10- μm -thick gold, so a mechanical drill press (Najet precision drilling machine, model 1M) is used instead (Fig. 4-139). With this press, holes as small as 5 μm in diameter can be routinely drilled in a variety of materials from gold to tantalum and through parts as thick as seven times the drill diameter. For soft materials like gold, one drill may last for 10 holes whereas when drilling hard materials such as tantalum more than one drill per hole must be used.

A micrometer mount is used as the drill base, complete with a stud holding the tapped aluminum substrate. The gold disk to be drilled is held to the substrate by means of a small drop of melted wax (see Figs. 4-140 and 4-141). When larger holes of approximately 50 μm in diam are drilled, lucite cement

Fig. 4-139. Drill press which is able to drill holes 5 μm and larger in diameter.

Fig. 4-140. Micrometer mount with drill and lights in position. The microscope normally used for viewing was removed for this photograph.

is used to secure the disk to the substrate because the heat generated by the drilling would melt the wax. After drilling, the wax is melted in hot water or the lucite is dissolved in carbon tetrachloride and the gold disk is recovered. Lastly, the disk is cleaned with chloroform in a modified Soxhlet extractor. Ultrasonic cleaning is not used because the parts tend to fracture in the sound field.

Handling Parylene Film. Parts are routinely fabricated from parylene films that range in thickness from 50 nm to 20 μm . Lasers are used to cut parts of all thicknesses and shapes; in addition, some disks are stamped from the thicker films with a "cookie cutter." "Cookie cutters" are made from tool rods that have been drilled to the desired diameter and then relief drilled for all but the cutting end. The cutting end is ground by conventional means to a sharp edge. A stock of these cutters in 50- μm increments covers the usual range of disk or "lollipop" targets (Fig. 4-142). To punch targets, a parylene sheet is laid on lint-free paper on a rubber pad and punched by hand with a "cookie cutter." The punched targets are easily pushed from the cutter with a wire and picked up with a soft spatula.

The handling of 50-nm films is more difficult because they tend to curl up into small, unusable wads. The films (Union Carbide Corp.) come on large glass slides from which a small piece can be

Fig. 4-141. View through the microscope of a gold disk and a 5- μ m drill.

Fig. 4-142. "Cookie cutter" and parylene film from which a parylene disk will be punched.

scribed. The slide is then angled slowly into water and the scribed piece floats off the slide. A washer with a handle or a wire loop is then used to lift the piece of parylene film from the water. The film adheres to the washer or loop during the subsequent bonding to additional parts.

As an example, we describe the steps required to place a film on a 200- μ m washer. At an assembly station, cement is applied to the washer which is held by a vacuum chuck. Next, the washer is pressed onto the film, inside the encircling wire loop which is holding the film. After the cement sets, the vacuum chuck is withdrawn and the washer/film/wireloop assembly is transported to the laser cutting station. The gold washer is neatly cut out of the film and caught on a surface with a contrasting background to facilitate finding the washer. The finished washer with its film covering is then inspected for defects. Films thicker than 1 μ m

are strong enough to support themselves and do not require the wire support loop.

Conclusions

The techniques and methods for handling small and fragile parts have evolved in response to the increased demand for complex multilayer targets and advanced diagnostics. In the future, more refinement of the present techniques will be required and additional capabilities for handling new types of targets will have to be developed. Automation of some of the repetitions steps may reduce the work load and speed up the process.

Author
S. F. Meyer

4-9.8 Cryogenics

Some target designs to achieve significant thermonuclear burn include a frozen DT layer on the inside of a multilayered fuel pellet. Construction of cryogenic facilities in the Shiva building for fabrication of such targets has begun. Initially a uniform layer of DT will be frozen on the inside of a hollow glass sphere. This work will then be extended to more complex designs.

In preliminary experiments, we have frozen DT on the inside of a sphere suspended between two sheets of Parylene that are attached to two thin copper washers. We are now optimizing system parameters such as freezing rate and cell temperature to obtain the required symmetry. The results of these experiments will be used to finalize the design of the target chamber support system for a cryogenic target.

Not only must the cryogenic layer be formed but it must be characterized. The cryostats are compatible with interference microscopes and wedge interferometers so that the thickness of the cryogenic layers can be measured accurately. We are using a high-resolution closed circuit TV system coupled to a video tape recorder to make a quick determination of the quality of the cryogenic layer.

In addition, we are constructing an apparatus to test the complex target parts at low temperatures. Problems such as parts distortions and adhesive failures due to thermal contraction will be studied. A test chamber attached to a liquid-nitrogen-cooled cold tip has already been assembled. Since most problems will occur below liquid nitrogen temperature (80 K) and this chamber has a rapid turnaround time, it will be used for preliminary trials. A liquid-helium-cooled cryostat for final testing is nearly complete.

Future laser targets may also consist of layered cryogenic materials such as a hollow deuterium-tritium shell coated with a layer of neon or xenon. We have continued to experiment with systems for generating, controlling, and coating hydrogen pellets.²⁰⁵ The pellet generator forms uniform drops by acoustic disintegration of a liquid jet.^{206,207} Spheres of hydrogen can be generated over a wide frequency range, but in practice the midrange from 75 to 120 kHz is most useful. We have increased the maximum diameter of the solid hydrogen pellets from 70 μm to 210 μm .

For laser fusion applications the drops must be injected into vacuum with a low-viscosity gas such as hydrogen at 20 K. However, a shock will be developed across an aperture that is both large enough to allow the pellets to pass and that has a significant pressure drop across it. Since liquid hydrogen drops have a very low surface tension, we had to partially freeze the drops before vacuum injection. The vacuum injection system also accelerates the drops by gas dynamic drag. Typically, at the exhaust of the injection tube, intact solid pellets measuring $70 \pm 5 \mu\text{m}$ in diameter have a velocity of 90 m/s with a velocity dispersion of $\pm 5\%$ and with an angular dispersion of $\pm 3\%$. Similar ranges of performance are achieved by the 200- μm system.

To fabricate hollow microspheres of hydrogen, bubbles larger than the critical size for growth were nucleated in the solid pellet. Bubbles can be nucleated by increasing the transducer amplitude and tuning the frequency so that cavitation occurs near the nozzle exit where the jet is superheated. Injection of charge into the cryogenic fluid also enhanced bubble production and provided a way to control the drops.

In experiments to date, the bubbles have been more or less uniform. However, the shells seem to be growing too rapidly to produce perfect symmetry. Careful control of the nucleation site and the growth rate may enable us to produce symmetric shells. Further experiments are currently under way to determine the range of sizes for which hollow pellets can be produced as well as the range of bubble sizes.

References

205. Part of this work was done under subcontract at the University of Illinois.
206. J. M. Schneider and C. D. Hendricks, *Rev. Sci. Instr.* 35, 1349 (1964); J. M. Schneider, N. R. Lindblad, C. D. Hendricks, and J. M. Crowley, *J. Appl. Phys.* 38, 2599 (1967).
207. C. A. Foster, C. D. Hendricks, and R. J. Turnbull, *Appl. Phys. Lett.* 26, 580 (1975).

Authors

R. L. Woerner
C. D. Hendricks
J. W. Bell

4-9.9 Target Characterization

Characterizing laser fusion targets to ensure acceptable quality is almost as difficult as fabricating the targets. Detecting the subtle defects that can cause target failure requires several different measurement techniques, each developed to state-of-the-art capabilities. Defects must be measured not only on final targets but at all stages of target development and fabrication.

This discussion of target characterization is divided into two main parts. The first describes recent improvements in the techniques now used for routine characterization. The second reviews the capabilities of several measurement methods suitable for advanced targets. The latter not only describes the capabilities of some specific techniques but also shows how we analyze them to determine their appropriate role in target characterization.

Present Characterization Techniques

Several reports²⁰⁸⁻²¹⁴ have discussed the techniques used in routine characterization of laser fusion targets. We will summarize the current capabilities and elaborate only on recent advances.

The linear dimensions of target parts are measured with an image splitting microscope to an absolute accuracy of $1\text{ }\mu\text{m}$. The wall thickness and

uniformity of microspheres are measured interferometrically to within $0.05\text{ }\mu\text{m}$. The thickness and uniformity of plastic and metal layers are also measured interferometrically to an accuracy of $0.03\text{--}0.05\text{ }\mu\text{m}$. We determine the DT fill density of each ball to an accuracy of 7% from measurements of the x-ray flux from tritium radioactivity. Mass measurements are made with a quartz torsion microbalance to a precision of 2 ng.

Recently we have made advances in our techniques for measuring nonuniformities in glass microspheres and in analysis of the interference measurement process. We have also improved the accuracy of the x-ray counting technique used to measure the fill, and acquired the quartz torsion microbalance for sensitive mass measurements.

Wall Thickness and Uniformity Measurements. Previous reports^{210,212-214} have discussed in detail the interferometric technique we use for measuring the wall thickness and uniformity of hollow glass microspheres. Recently we have improved our methods of quantifying the magnitude of non-uniformities in the walls and have investigated ways in which the specific optics used in the interferometer affect the wall-thickness measurements.²¹⁴

Wall Thickness Measurement Method. For all interferometric measurements, we now use a double-pass, two-arm, Twyman-Green interferometer (see Fig. 4-143). With minor modifications, all of our

Fig. 4-143. Double-pass Twyman-Green interferometer used for wall thickness and uniformity measurements.

techniques can be used equally well with a single-pass interferometer.

With the double-pass instrument, the microsphere to be measured is placed on the surface of the reflecting mirror in one arm of the interferometer. With the white-light interference pattern as a reference, one measures the optical path through the center of the microsphere in terms of the fringe shift caused by its presence. The average of the top and bottom wall thicknesses is given by

$$t = x\lambda/4(n - 1) \quad (152)$$

where x is the number of fringes, λ is the illumination wavelength, and n is the index of refraction of the glass. If the microsphere contains a gas, then the wall-thickness formula becomes

$$t = \frac{1}{(n - 1)} \left[\frac{x\lambda}{4} - r_i (n' - 1) \right] \quad (153)$$

where n' is the index of refraction of the gas and r_i is the internal radius of the microsphere. One iteration to determine r_i and t is usually adequate for a thin wall. (With a single-pass interferometer, one must include an additional factor of 2 in both of these expressions for t .)

By eye, one can estimate the phase shift caused by the microsphere to within one-tenth of a fringe. If $n = 1.5$ and the illumination wavelength is $0.54 \mu\text{m}$ (our typical values), then the measurement of the average of the top and bottom wall is accurate to about $0.03 \mu\text{m}$ ($0.05 \mu\text{m}$ for single-pass interferometry).

The above derivation assumes parallel illumination of the microsphere and ignores the effects of the illuminating and viewing optics. The errors introduced by this assumption are small (of the order of a few percent) so long as (a) the microsphere wall is thin relative to its diameter and (b) the ball is illuminated and viewed with an objective of moderate magnification (10 to $25\times$). When these conditions are not met, appreciable errors can occur. We shall discuss these errors and the means of correcting for them.

Measurement of Wall Nonuniformities. A perfect microsphere placed on a mirror in one arm of the

interferometer will appear as a symmetric pattern of circular fringes when the reference mirror and object mirror are parallel to each other. Any defects in the ball will cause deviations from the symmetrical interference pattern. It is imperative that one be able to measure, reposition, and remeasure in order to develop an accurate picture of defects that may not be visible in specific orientation or require more than one view for unambiguously definition.²¹⁵

Figure 4-144 shows the measurement of several types of defects and the need for repositioning. Figure 4-144(a) shows an interferometric picture of a microsphere that has many small filaments on its surface but otherwise appears symmetrical. The measurement of defects of small spatial extent, such as these filaments, is quite simple: one rotates the ball until the defect is near the center of the microballoon image and then measures the change in optical path caused by the defect. The change in wall thickness, Δt , is given by

$$\Delta t = \frac{\lambda \Delta x}{2(n - 1)}$$

where Δx is the fringe shift caused by the defect.

Figure 4-144(b) shows the same sphere rolled 90° to the right. It is now apparent that the ball has a serious defect in concentricity — both its outer and inner surfaces are approximately spherical, but the centers of these surfaces are offset from one another. In Fig. 4-144(a) the thicker end is oriented directly upward, so the defect is totally invisible. For defects of this type, the average thickness through the sphere's center is independent of orientation, so one cannot determine the magnitude of the defect from measurements made at the center of the image.

There is, however, a simple way to measure the nonconcentricity by, in effect, "tilting" one of the mirrors in the interferometer. The pattern seen on a nonconcentric ball is exactly the same as that seen on a perfect ball lying on a tilted mirror.²¹⁴ Conversely, a ball with a concentricity defect can be made to appear perfect by tilting the mirror on which it is lying or by introducing a linear phase gradient across the field of view and aligned with the defect axis. The magnitude of the gradient needed to "correct" the pattern on the ball is a measure of the

Fig. 4-144. Interferometric picture of a hollow glass microsphere illustrating several types of defects. (a) In this orientation, small-scale surface irregularities are seen but no large-scale defects. (b) The same sphere rolled 90° to the right shows a very severe defect in concentricity. (c) In the same orientation as (b) but with a linear phase gradient across the field of view to compensate for the nonconcentricity, an additional subtle defect with an approximate threefold symmetry is now visible.

magnitude of the defect. (Introducing a linear phase gradient across the field of view at an arbitrary orientation can be done simply by means of optical elements in the interference microscope. Such an adjustment is usually provided on the instrument.)

We define the nonconcentricity as the ratio of the offset between the inner and outer surfaces, Δt_1 , and the average wall thickness, t_0 . If the ball is oriented such that the line along which the inner and outer surfaces are displaced is parallel to the mirror surface (this is the orientation in which the defect appears worst), then the nonuniformity is given by

$$\frac{\Delta t_1}{t_0} = \frac{r_i \tan \theta_i}{2(n-1)t_0} \quad (154)$$

where r_i is the inner radius of the ball and θ_i is the

angle of tilt of the mirror needed to compensate for the defect in concentricity.

The denominator of Eq. (154) is the optical path difference at the sphere's center caused by the presence of the two glass walls. This is precisely the quantity we measure to determine the average wall thickness. The numerator is the optical path difference across the ball's inner radius when the phase gradient exactly compensates for the nonconcentricity. Both of these phase differences are measured in fringe spacings, and they can be ratioed directly to give $\Delta t_1/t_0$ with no intermediate calculations.

The measurement can be made rapidly with excellent accuracy. In practice, we level the mirror on which the microsphere rests, roll the sphere until the fringe pattern appears maximally asymmetric, "correct" the pattern with a linear phase gradient, and then measure the number of fringe spacings

subtended by a distance equal to the inner radius of the ball. The entire procedure takes only a few minutes. Figure 4-144(c) shows the sphere from Fig. 4-144(b) with a phase gradient compensating for the concentricity defect. (The fact that the compensation does not make the ball look exactly perfect implies the existence of a higher-order defect we will discuss shortly.) For measuring the nonconcentricity, the number of fringe spacings subtended by the ball radius can easily be determined within $1/5$ of a fringe spacing. That accuracy determines Δt_1 to within 30 nm (300 Å) for a ball with an index of refraction of 1.5 and illumination at a wavelength of 0.6 μm .

We note that the ball orientation is not too critical. The defect axis must be misaligned with the mirror by more than 25° to cause a 10% fractional error in the measurement of Δt_1 . Thus, unless the defect is extremely severe (in which case we are usually not interested in the ball, anyway), the resolution of the measurement is not limited by the positioning accuracy.

As observed, the pattern on the ball in Fig. 4-144(c) is not perfectly symmetric. This indicates that the large-scale defect in the ball is not purely a defect in concentricity. The pattern on the sphere in Fig. 4-144(c) shows a much less severe defect with an approximate threefold symmetry. In a decomposition in terms of Legendre polynomials (P_ℓ 's), this defect would contribute a large $\ell = 3$ component. The magnitude of the defect can be determined by measuring the difference in the optical paths through different points on a circle concentric with the outside of the ball. (A defect in concentricity can also be measured in this manner, but the "tilted mirror" method is considerably faster and more accurate.)

It is interesting to note how the "tilted mirror" method helps in identifying higher-order defects. In Fig. 4-144(b) the severe defect in concentricity totally obscures the subtler nonuniformity. In Fig. 4-144(c), with the effect of the nonconcentricity removed, the higher-order defect is very obvious.

In measuring actual target spheres, the situation is seldom as complex as that shown in Fig. 4-144. Characterization of an almost perfect sphere is quite simple, and a ball with more than a few minor defects is usually rejected immediately. However, our examination of the ball in Fig. 4-144 does show how, by viewing the ball in several orientations, one can build a composite picture of the defects.

Effect of Microscope Optics on Interferometric Measurements. There are limitations on the interference technique imposed by the optical system itself. The simple model used in the foregoing analysis is entirely adequate so long as the illumination is apertured to a cone with a half-angle less than about 20° . For thick-walled spheres, the restrictions on the illumination are more severe.

To analyze the effect of the optical system, one must trace rays from various parts of the system through the microsphere. One calculates the path of any given ray and also its phase relative to the rays in the other arm of the interferometer with which it eventually interferes. For a uniform, hollow sphere, this is straightforward.²¹⁴ In fact, the calculations can be programmed on a hand-held calculator.

Earlier analyses have treated aspects of the interference pattern by assuming parallel incident illumination.^{210,212} With our simple ray-tracing procedure, we are able to study the situation without making this assumption; and we find that, under conditions of high magnification, the results are altered significantly.

If the microsphere is illuminated by parallel light, then the rays that seem to come from a given point in the focal plane can have traversed only one specific path through the ball. However, with the Twyman-Green system, the illumination comes from light that is parallel in the interior of the interferometer and is focused by the final objectives. Each point in the field of view is illuminated by a cone of light with a half angle determined by the numerical aperture of the objective lens and by the details of the illumination system. Also, all light propagating back from the sample along a path lying in the acceptance cone of the objective is captured and focused in the imaged plane. Thus, the light that appears at any particular point in the image plane is the sum of many rays that have taken different paths through the microsphere.

There are two undesirable effects of the multiple paths. First, at the center of the microsphere image, the information is not exclusively about the projection of the center of the microsphere onto the mirror. Second, two rays appearing at the same point in the image plane have not necessarily traversed the same optical distance and so may no longer be in phase.

We will first address the problem of overlapping information from different points on the ball.

Fig. 4-145. "Blurring" of lower wall caused by nonparallel illumination. The amount of overlap or blurring is plotted as a function of illumination half-angle for three values of the ratio of wall thickness to radius.

Clearly, the pattern in the image plane contains some sort of "average" over the ball's upper surface, and the spatial extent of this averaging is controlled by the numerical aperture of the objective. (This is really nothing more than a statement of fact that we look through an upper wall that is out of focus.) A more subtle problem is that the information at the center of the image is not even exclusively from the center of the bottom wall of the microsphere.

The fact that the measurement is an average over a portion of the upper surface is not usually a problem and may often be an advantage. For example, a (spatially) small defect on the upper surface sets "averaged out" and thus has only a very minor effect on the measurement of defects on the lower surface.

Figure 4-145 shows the extent of the information overlap from points on the ball's lower surface. The amount of overlap (expressed in terms of an angular fraction of the ball) is plotted as a function of the objective aperture angle or the illumination angle, whichever is smaller. Curves are shown for three values of t/r_0 (the ratio of the wall thickness to the outer radius). If the objective acceptance angle is large enough to allow more overlap than the desired resolution, one must aperture the illumination system to give a small enough illumination angle to assure adequate resolution.

Regarding the variation in length of the different optical paths taken by rays that appear at the same point in the image, our ray trace results show that, at each point of the image, the ray with the longest

optical path to the image plane is the one that was incident on the ball parallel to the optic axis. All other rays appearing at that point in the image followed shorter paths. The variation in ray path through the microsphere is shown in Fig. 4-146 as a function of the angle between the optic axis and the final path of the ray after it exits the microsphere. The normalization is to the ray with the longest optical path appearing at the point of interest in the image plane. This normalization length is thus just the optical path that one would calculate assuming parallel illumination.^{210,212} For the center of the microsphere image and an illumination and acceptance angle of $\pm 10^\circ$ (typical for about a $10\times$ objective), the spread in optical path lengths is only about 1%. With an acceptance and illumination angle of $\pm 40^\circ$ (typical for a $60\times$ objective), the total variation is about 10%. For the range of concern, these values are more or less independent of t/r_0 .

It is easy to have a situation where the total phase spread of the light is large enough to reduce the coherence such that interference measurements are not possible. This will occur when the total phase spread is on the order of π . For a $\pm 10^\circ$ acceptance angle, this would occur for a ball wall about $10\text{ }\mu\text{m}$ thick. For a $\pm 20^\circ$ angle (about $25\times$), it would occur for a wall thickness of only $2.5\text{ }\mu\text{m}$. A fully illuminated objective with a $\pm 40^\circ$ acceptance angle would lose coherence at a wall thickness of only $1\text{ }\mu\text{m}$. Noticeable degradation in the coherence of the light will take place for even thinner walls. It is obvious that proper aperturing of the illumination is necessary except for thin balls or for objective lenses of small numerical aperture.

A related problem is that what one actually measures is an average optical path. For most measurements, aperturing to ensure good coherence will also ensure a sufficiently accurate absolute measurement value. If very high absolute accuracy is desired, one can use an integral of the calculated path length differences to correct for the effect of multiple-path illumination.

The above analysis shows the precautions that must be observed when making interferometric measurements to ensure the desired levels of accuracy and spatial resolution.

Deuterium-Tritium Fill Measurement. Once a candidate microsphere has been selected and characterized optically, the next step is to determine the DT fill.^{208-211,216,217} For this measurement we use the natural radioactivity of the tritium.

Fig. 4-146. Variations in the optical path of rays as a function of exit angle for several ratios of thickness to radius. The solid line is for rays appearing at the center of the ball image (assuming the microscope optics are focused on the background mirror). The dashed line is for points one-quarter of the radius from the center. The dotted line is for points halfway between the center and outer edge of the sphere.

Fig. 4-147. Energy spectrum of electrons emitted in beta decay of tritium.

Tritium decays with a half life of 12.3 y by the following reaction:

The electrons are emitted with the spectrum of energies shown in Fig. 4-147. These electrons impinge on the glass shell and on the substrate on which the microsphere rests, producing characteristic x rays and bremsstrahlung. These secondary x rays can be counted and used as a measure of the tritium content of the sphere.

Measurement Procedure. Figure 4-148 shows the counting geometry schematically. The microsphere is placed on an aluminum planchet in a standard gas flow proportional counter. The 1-mil-thick beryllium window excludes electrons from the counter. A significant number of electrons from the tritium decay have high enough energies to escape the microsphere completely (see Fig. 4-147). The

Fig. 4-148. X-ray proportional counting arrangement.

number of escaping electrons is a strong function of the wall thickness. If these electrons are not blocked from reaching the counter, they will be detected along with the x rays, causing the count rate to have a very strong dependence on the wall thickness.

The actual spectrum of x rays penetrating the proportional counter window was measured using a high-resolution Si(Li) detector with a multichannel analyzer. This spectrum is shown in Fig. 4-149; its components are listed in Table 4-15. About half the spectrum is characteristic x radiation, primarily from silicon and aluminum. The other half is the result of bremsstrahlung.

For each individual fuel-containing ball, the total x ray count is measured with the gas flow proportional counter. The counting can be done rapidly and accurately, and it provides a convenient measure of the tritium fill. Then, using the D/T ratio for the original fill gas, we can calculate the total DT fill for each individual ball.

Calibration of Proportional Counter Measurement. The gas flow proportional counter measurement is calibrated using the ionization chamber described in § 4-9.10. Individual balls of target quality are selected on the interferometer, measured, counted in the proportional counter, and then individually crushed in the ionization chamber.

Table 4-15. Components of x-ray spectrum penetrating 1-mil beryllium window of a standard gas flow proportional counter

Component	Percent
Na K_{α}	—
Al K_{α}	6.25
Si K_{α}	36.1
S K_{α} (?) Mo L_{α}	0.70
K K_{α}	0.72
Ca K_{α}	6.40
Ca K_{β}	0.72
Bremsstrahlung	49.0

Fig. 4-149. X-ray spectrum reaching proportional counter active volume through 1-mil beryllium window.

Fig. 4-150. Effect of microsphere wall thickness on x-ray count rate (proportional counter rate/ion chamber measurement). The overall normalization has been eliminated.

This provides a direct measurement of the total amount of tritium in the ball. From this information we can generate a calibration that relates the x-ray production to the tritium present with no need for modeling the x-ray production process.

The cross-calibration technique was carried out for more than 50 samples. We found that the calibration exhibited a random error of about 7% standard deviation. Our results show that, even with the electrons blocked from the proportional counter, there is some wall-thickness dependence in the x-ray production (which is not surprising since the wall is the production site for most of the x rays). Figure 4-150 shows the observed wall-thickness effect. The x-ray count exhibits a moderate, linear decrease with wall thickness for walls from 0.4 to 2.0 μm . The data points were generated with targets having fills of 0.5 to 8.0 mg/cm^3 total DT and diameters of 60 to 140 μm . No significant differences were seen for different sizes or fill densities.

Because of the wall-thickness effect on total x-ray production, the calculation of the wall thickness and the calculation of DT fill are inextricably linked. The microsphere wall-thickness measurement must take into account the gas fill [see Eq. (153)], and the gas fill calculation contains a term that depends on the wall thickness. Calculations of the thickness and fill must therefore be done together and iteratively. First, we calculate the wall thickness from Eq. (153) assuming the DT fill to be zero. Using this approximation for wall thickness, we then calculate an approximate fill that put back into Eq. (153) to calculate the wall more accurately.

This process is continued until both the wall and fill calculations have converged to within 1%. These operations are performed on a small programmable calculator and require only a few seconds per ball.

Once the calibration is complete and the computational procedure streamlined, the proportional counter gives us a rapid, convenient method of determining the fill of an individual microsphere to an accuracy of about 7%.

Quartz Torsion Microbalance Mass Measurements. For measuring the mass of laser fusion targets, we have recently acquired a Rodder equal-arm quartz torsion microbalance. This instrument is shown in Fig. 4-151.

The microbalance consists of a beam assembly (of fine fused silica rods) suspended from a single silica fiber 10 μm in diam and approximately 8 in. long. A sample pan is hung from each side of the beam assembly.

Coarse adjustment of the balance is accomplished as with any equal-arm balance by adding weights to one side. Fine zeroing and measurements are made by turning a dial attached to one end of the suspension fiber. Twisting the suspension fiber raises the heavier side of the beam. Beam position is determined by a microscope system with two objectives, one viewing each arm of the beam. The images are combined in the eyepiece to facilitate accurate realignment of the beam.

Because of the very linear elastic modulus of the fine suspension fiber, a precise measurement of the amount it has to be twisted to balance the beam provides an extremely accurate method of measuring mass. The sensitivity of the balance is less than 2 ng. To put this in perspective, 2 ng is the weight of the DT fill gas inside a 100- μm -diam microsphere pressurized to 20 atm. The ball itself weighs 70 ng if its wall thickness is 1 μm . Considering the sensitivity, the balance is also very strong. A total load of up to 20 mg is permitted.

Advanced Target Characterization

Target designs for high-gain implosions call for pellets with concentric layers of various materials that are compressed to extremely high densities (10^3 to 10^4 times liquid density). Nonuniformities in any layer or perturbations of the surface of a sphere are potential limiting factors with respect to the densities that can be attained. The amplitude of any perturbations grows exponentially with time as the sphere is compressed, possibly causing breakup of

Fig. 4-151. Internal structure of quartz torsion microbalance.

the pellet before the desired compression is achieved.

Developing techniques for the measurement of small, subtle defects is a challenging problem. In this portion we outline the difficulties involved and explain how we have evaluated possible methods for making the required measurements.

Relevant Range of Defects. In choosing characterization techniques for laser fusion targets, it is important to define accurately the type of defects that must be detected. The parameters of interest are as follows:

w — the spatial extent of the defect being examined. The lateral size of the smallest detail that can be resolved with the technique is designated as $w_{\min}$. If the wall nonuniformities are characterized by a decomposition in terms of Legendre polynomials (P_l 's), then the highest-order component detectable by the method is $\ell_{\max} = 2\pi r/w_{\min}$, where r is the radius of the ball.

d — The integral of the density, ρ , through the shell — $\int \rho dr$. One should keep in mind that what is actually measured is an average over an area of size $w_{\min}^2$. We denote the resolution of the method for detecting changes in d as $\Delta d_{\min}$.

h — The height of an imperfection in the sphere's surface. We denote $\Delta h_{\min}$ as the resolution of the method for detecting imperfections on the surface, as opposed to integrated density differences.

The expected growth rate for a given perturbation is calculated with LASNEX, the computer program used to model laser fusion experiments. These results are discussed in detail elsewhere.^{218,219}

The important features of these LASNEX calculations are fairly simple and easily understood. The effect of a defect on the compression depends on both the spatial extent of the defect and the initial amplitude. As the sphere is compressed, defects with small spatial extent (small w) are predicted to grow in amplitude more rapidly than those of large spatial extent (large w). However, the exponential growth of a defect is not expected to continue once the height of the defect is comparable with its width.

These predictions about growth rates imply that defects of intermediate size are the ones that must be measured and controlled most accurately. Broader defects that grow more slowly can have larger initial amplitudes, whereas those of smaller spatial extent will reach the "saturation" level with amplitudes too small to break through the pellet wall.

Figure 4-152 shows the projected maximum allowable initial defect amplitude as a function of defect spatial extent for two different targets. Figure 4-152(a) is for a target designed to achieve a compression of 100 times liquid density. Figure 4-152(b) is for a typical high-gain target such as might be tested with the Shiva laser system. Requirements for

Fig. 4-152. Spectrum of unacceptable defects as predicted by fluid instability calculations: (a) for a target with 35- μm radius and 8- μm wall designed to achieve 100 $\times$ liquid density; (b) for a high-gain target with 300- μm radius and 40- μm wall.

the targets needed to achieve scientific breakeven are expected to resemble the latter.

On a graph such as those shown in Fig. 4-152, one can plot the limits of resolution — for both spatial extent and amplitude — that any given characterization method can achieve. This gives a clear picture of the portion of the “defect space” that a given technique can cover. One then attempts to find a combination of techniques that will permit characterization to the required accuracy of all defects in the size ranges of interest.

Fig. 4-153. Resolution limits of optical interferometry for a typical high-gain target: (a) for a transmission system; (b) for a reflection system. Vertical lines indicate an integrated density measurement. Horizontal lines indicate a surface measurement. Solid lines show present capabilities whereas dashed lines show limits of a system with a high-precision phase measurement.

Capabilities of Available Techniques. We have investigated the capabilities of several characterization methods for measuring the defects of importance to the performance of fusion targets.²²⁰ Three of the most promising are optical interferometry, electron microscopy, and radiography.

Optical Interferometry. An optical interferometer can be used in either a reflection or a transmission mode. In reflection, one measures the phase of light that is reflected from the surface of a layer. Non-uniformities in the surface appear as phase differences in the light reflected from different parts of the sample.

For a transparent layer or pellet, one can make a transmission interferometry measurement. In this case, one measures the phase shift caused by the light passing through the material. Transmission interferometry is the technique now used to measure defects in glass targets.

Both interference techniques provide excellent resolution for the height of defects, and do so more or less independent of defect spatial extent. A reflection interferometer measures only features on the surface, but even a simple, manual instrument has resolution of 20 to 30 nm for measuring Δh . By automating the phase measurement, the resolution for Δh can be improved to better than 5 nm.

Transmission interferometry measures Δd rather than Δh and is able to sense nonuniformities in the

Fig. 4-154. Resolution limits for the scanning electron microscope. Solid line assumes detection of defects with a height-to-width ratio of 1/20. Dashed line is for a detection limit of 1/50.

bulk of the material. The sensitivity of the method depends on the index of refraction of the material being measured. For glasses or polymers, the resolution for Δd is typically 30 to 60 nm for a standard system and 6 to 12 nm for a system with automated phase measurement.

The chief limitation on both interference techniques is that the spatial resolution is limited to that obtainable with an optical microscope: that is, about $1\mu\text{m}$. All measurements of Δd or Δh are therefore averages over an area approximately $1\mu\text{m}$ in diam. Fortunately, this value of $w_{\min}$ is smaller than the worst defect size for high-gain targets.

Figure 4-153 shows the resolution limits of transmission and reflection interferometry superimposed on the "unacceptable defect space" curves of Fig. 4-152. With automated phase measurement, these techniques quite effectively cover the worst defect size range. The primary deficiencies are lack of resolution at very small w and the fact that, for opaque targets, only the surface can be inspected.

Scanning Electron Microscopy (SEM). Applications of the SEM to target characterization are described in detail in § 4-9.6. However, a few general observations are in order here.

Scanning electron microscopy provides a very useful complement to interferometry. The SEM has excellent spatial resolution — less than 10 nm on many materials. There are two main limitations on the SEM. The first is that, as with reflection interferometry, it measures only surface defects. The second is that it measures contour directly and thus cannot detect defects with a small aspect ratio: that is, defects that are much wider than they are high. Ordinarily one cannot detect bumps or valleys with

aspect ratios less than about 1/20, so a defect with a spatial extent (w) of $2\mu\text{m}$ must have an amplitude of $0.1\mu\text{m}$ to be detectable; and a defect $10\mu\text{m}$ wide must be $0.5\mu\text{m}$ or more high. By careful use of the SEM, resolution may be improved to detect defects with aspect ratios as low as 1/50, but this is still the limiting consideration.

The portion of the defect space covered by the SEM is indicated in Figure 4-154. It is worth noting that many coating techniques result in defects with w values on the order of 0.1 to $2\mu\text{m}$ and aspect ratios of about 1/10. Such defects are precisely in the region of best resolution for the SEM.

Radiography. Radiography uses soft x rays as a probe for the measurement of fusion targets. Its primary appeal is that it is capable of measuring Δd for opaque pellets.

There are two basic ways of applying the technique. The first is to use the x rays to project the contour of the ball onto film and then measure the contour directly. This method has the same problems with low-aspect-ratio defects as the SEM but with more complications. For this technique to be at all effective, the spatial resolution must be high. To get high spatial resolution requires that the source be very small or else very far from the sample, either of which severely limits the available flux. Also, the detector (usually film) must have high spatial resolution. Unfortunately the mean free path of an x ray in an emulsion is long enough to cause significant blurring. This seriously degrades the film's spatial resolution. Other methods of high resolution x-ray detection are complicated, time-consuming, and generally unsatisfactory.

A second, and more productive, way of applying radiography is to measure the absorption of x rays by the pellet walls. This method can be made very sensitive to variations in wall thickness, but is limited by the amount of available x-ray flux.

From statistical considerations, one can calculate the optimum x-ray energy and minimum flux needed to attain a given resolution in a given length of time.²²⁰ One finds that the optimum energy for the incident photons is that which results in an absorption length, x_0 , equal to $0.90 t$, where t is the wall thickness. (The absorption length is the distance over which the x-ray flux decreases by a factor of e .)

In specifying F_s , the minimum flux necessary from the x-ray source, the relevant parameters are w_{min} , the spatial resolution defined previously; $\Delta d/d$, the fractional accuracy for measuring d ; θ_s , the maximum angle that the source can subtend as seen from the pellet; r_b , the radius of the pellet; and T , the total time allowed for measuring the entire surface.

To assure that the desired $\Delta d/d$ is three standard deviations above statistical fluctuations (about 0.3% spurious measurements), the minimum source flux in photons per unit area per unit time is given by

$$F_s \approx \frac{6 \times 10^3 r_b^2}{w_{min}^4 T \left(\frac{\Delta d}{d}\right)^2 \sin \theta_s} \quad (155)$$

Fig. 4-155. Resolution limits for precision microradiography assuming an absorption measurement and the parameters discussed in the text.

A reasonable physical arrangement should result in $\sin \theta_s$ of about 0.1. For a given pellet size, r_b , one must then trade off the desired spatial and thickness resolution against the available source strength and the time allowed for the measurement.

The best continuous x-ray sources now in use²²¹ achieve flux levels on the order of 10^{19} photons/m²-s. At the present stage of laser fusion research, the maximum time allowable per fuel pellet for final inspection is of the order of a few hours.

In Fig. 4-155 we plot the defect space of a typical high-gain target that could be covered by a system with $\sin \theta_s = 0.1$, $F_s = 10^{19}$ photons/m²-s, and $T = 1$ h. Illustrated here is the importance of carefully matching the measurement technique to the requirements of target design. The radiography system could be operated so as to obtain very good spatial resolution but only at the expense of thickness resolution. The optimum use of a radiographic technique is to push the system as far down the "allowable defects" line as possible. It is this consideration that determines the proper trade-off between spatial resolution and thickness resolution.

One can, of course, inspect a smaller portion of the ball with better thickness and/or spatial resolution, or take more time for the measurement. But from Eq. (155) it is clear that no major gains will be

Fig. 4-156. Composite capabilities of scanning electron microscopy, high-precision interferometry, and precision radiography for characterizing a typical high-gain target. Capabilities are shown for both a transparent pellet (a) and for an opaque pellet (b). Vertical lines indicate a capability for measuring integrated density; horizontal lines denote surface measurement. Cross hatching shows a region where both measurements can be made.

possible, since the spatial resolution only increases as the fourth root of either the total time for the measurement or the reciprocal of the area size to be scanned.

Although the range of defects detectable by the x-ray inspection technique is somewhat limited, the technique is still very useful. For opaque pellets it provides the capability of measuring integrated density, ρ , rather than only the surface, for at least part of the defect size range of interest.

Composite Capabilities. Figure 4-156 shows the composite capability of high-precision interferometry, electron microscopy, and precision radiography for measuring Δh and Δd over the relevant range of w for high-gain targets. Most of the defect space of interest is covered, but some gaps remain. The primary deficiency is that, for opaque pellets, the measurement of Δd is limited to large values of w . Some possible methods for supplementing the measurement of small- w defects in opaque materials are scanning transmission electron microscopy, acoustic microscopy, and destructive "process testing" of representative samples.

Conclusions

Because of the wide range of defects that must be characterized for successful laser fusion experiments, we must develop all three of the techniques discussed above and also investigate possible supplements. Each technique must be developed to state-of-the-art capabilities and carefully designed to meet the needs of target characterization.

The combination of precision radiography, electron microscopy, and high-precision interferometry will provide most of the needed capability for characterizing high-compression and high-gain laser fusion targets. We are confident that supplementary techniques will be found to supply the remainder.

References

208. P. C. Souers, R. T. Tsugawa, and R. R. Stone, *Fabrication of the Glass Microballoon Laser Target*, Lawrence Livermore Laboratory, Rept. UCRL-51069 (1974).
209. P. C. Souers, R. T. Tsugawa, and R. R. Stone, *Rev. Sci. Instrum.* **46**, 682 (1975).
210. R. R. Stone, D. W. Gregg, and P. C. Souers, *J. Appl. Phys.* **46**, 2693 (1975).
211. C. D. Hendricks, R. D. Behymer, J. A. Brown, G. W. Heaton, E. R. McCann, and B. W. Weinstein, *Fabrication and Characterization of Laser Fusion Targets*, Lawrence Livermore Laboratory, Rept. UCRL-76679 (1975).
212. R. R. Stone, P. C. Souers, G. C. Abell, and J. W. Reed, *Light Interference in Hollow Glass Microsphere Laser Targets*, Lawrence Livermore Laboratory, Rept. UCRL-77487 (1975).
213. Berthold W. Weinstein, *J. Appl. Phys.* **46**, 5305 (1975).
214. B. W. Weinstein and C. D. Hendricks, *Interferometric Measurements of Laser Fusion Targets*, Lawrence Livermore Laboratory, Rept. UCRL-78477 (1975).
215. We have found that a glass fiber pulled to a very fine tip ($\sim 1 \mu\text{m}$) works well for rolling a glass microsphere on a mirror surface. The fine tip keeps the ball from sticking to the fiber. More recently we have developed a manipulator that provides positive control of the sphere orientation during inspection. See B. W. Weinstein, C. D. Hendricks, C. M. Ward, and D. W. Willenborg, *A Simple Manipulator for Rotating Small Spheres* (to be published).
216. R. Jay Fries and Eugene H. Farnum, *Nuc. Instrum. and Meth.* **126**, 285 (1975).
217. I. M. Moen, C. D. Hendricks, and B. W. Weinstein, *Bull. Am. Phys. Soc.* **21**, 1137 (1976).
218. W. C. Mead and J. D. Lindl, *Behavior of Fluid Instabilities in Laser Fusion Pellets: Results of 2-D Calculations*, Lawrence Livermore Laboratory, Rept. UCRL-77057 (1975).
219. R. E. Kidder, *Nucl. Fusion* **16**, 3 (1976).
220. B. W. Weinstein, C. D. Hendricks, R. M. Singleton, C. M. Ward, and D. W. Willenborg, *Physical Characterization of Advanced Laser Fusion Targets* (to be published).
221. J. L. Gaines, *Nuc. Instrum. and Meth.* **102**, 7 (1972).

Author

B. W. Weinstein

Major Contributors

I. M. Moen

R. M. Singleton

C. M. Ward

D. L. Willenborg

4-9.10 DT Loading

We are improving our procedures for selecting microspheres and loading them with deuterium/tritium (DT) gas.

Precrush

Many microspheres are imperfect and have to be eliminated. Our selection process for most purposes is precrush. The sieved shells are grouped by size, placed in a pressure vessel, and then pressurized with argon until half the shells are crushed. (For 3M batch No. 0097, the argon pressure is 68 MPa.)

The weak and imperfect shells are crushed, leaving the strongest — those with slightly thicker walls — intact. The spheres are then washed with alcohol into a separatory funnel, where the broken pieces sink and are drawn off. Since precrush eliminates thin-shell spheres, it is not performed when thin shells are wanted.

DT Loading System

After drying, the spheres are placed in a beryllium tube, which is attached to a pressure manifold (Fig. 4-157) that accommodates up to six such tubes. For pressuring the spheres with DT gas, a special apparatus has been designed and built to strict safety standards: i.e., material testing, x-rayed welds, double containment, gas traps, hood operation, quality-assured materials.

The loading system²²² (Figs. 4-158 and 4-159) operates up to 773 K and 68 MPa, although limited to 27 MPa when beryllium tubes are used. Stainless steel tubes containing two 100-W heaters are placed over the beryllium tubes. A secondary containment vessel encloses the entire manifold system. A DT vessel previously pressurized with 1:1 DT gas is attached to the system. A controller monitors the sample temperatures; valve V2, cooled by a welded water jacket, controls the DT pressure in the pressure chamber, and a transducer monitors the pressure. The high-pressure lines have a maximum working pressure after weld of 136 MPa. The input pressure transducer pressure vessel heater-transducer system are both secondarily contained to prevent leakage. Argon gas is admitted to the pressure vessel secondary container to expedite heat transfer to the sample.

The gas recovery system consists of a DT recovery tank, a D₂ flush recovery tank, and an abort tank for the pressure transducer. The system incorporates an activated uranium trap to getter the DT gas remaining in the lines after a D₂ flush. A pressure gage measures the gas pressure in all tanks.

The samples are heated to 693 K, pressurized to 1 MPa, and held for 24 h to allow the DT to permeate into the spheres. The samples are allowed to cool to room temperature, then stored in a freezer at 243 K to reduce outgassing. The spheres contain nominally 2 mg/cm³ of DT when filled under the above conditions. (The system capability is 22

Fig. 4-157. Detailed view of the pressure vessel, transducer, heater, and secondary container.

mg/cm³, limited by the beryllium tube strengths.) The DT loading is verified by crushing microsphere samples and measuring the tritium in an ionization chamber. This process is described later as part of the checks done on microspheres just before target assembly.

Analysis of Loading Conditions

Precipitation of the proper gas mix for diffusion-loading of the microspheres is not a simple process, especially where there is demand for more components in the gas mix as well as a match to preselected mole ratios. The DT gas is a two-component (actually D₂-DT-T₂) gas at a nominal DT ratio of 1:1.

To provide a source vessel of the correct gases, tritium gas (previously analyzed by a mass spectrometer) is compressed into the vessel and then topped with deuterium (also previously analyzed by a mass spectrometer). The pressures used in the filling are calculated from the perfect gas law using a compressibility correction.²²³ The actual mass of gas added to the source is determined by a precise gravimetric method. This allows the DT ratio to be held to ± 1 mole % of the requested value. Final assay of the gas mixture is accomplished by an integrated analytical system using a high-resolution mass spectrometer to determine the isotopic ratios, a calorimeter to check the tritium content, and the mass measurement. The overall assay accuracy is better than ± 1 mole %. Targets requiring equimolar DT in addition to 10 mole % of neon have also been

prepared within ± 5 mole % of the requested values (accuracy ± 1 mole %). (Permeation time must be increased to 48 h to ensure complete filling with neon.)

Once the source vessel has been prepared, we must determine the fill conditions for the microspheres. The previously referenced perfect gas calculations with a compressibility correction must again be made to set the pressure conditions for filling the microspheres. These calculations must also account for the ^3He generated from the tritium decay.

Extensive permeation studies have been conducted to investigate the outgassing rates of DT, helium, and neon from the microspheres.^{223,224} The studies show that outgassing does not follow the expected exponential pressure-vs-time relationship.

Fig. 4-158. DT pressurizing system.

Fig. 4-159. DT fill system.

The deviation is related to varying time constants for the individual microspheres. Thus while the permeation behavior for a batch of microspheres can be generally described within the experimental conditions, it is not possible to predict the results for an individual microsphere. Therefore, the permeation studies have been applied to batch filling to determine the loading temperature (693 K), pressure (1 MPa at 300 K for 2 mg/cm³), and permeation time at temperature (24 h). We have also developed

techniques for determining the actual amount of fuel in an individual microsphere selected after storage for mounting as a target. These techniques are described in § 4-9.9.

References

222. P. Souers, R. Tsugawa, and R. Stone, *Fabrication of the Glass Microballoon Laser Target*, Lawrence Livermore Laboratory, Rept. UCRL-51609 (1974).

223. P. Souers, I. Moen, R. Lindahl, and R. Tsugawa, *Permeation of He, Ne, and D-T from Soda-Lime Glass Microbubble Laser Targets*, Lawrence Livermore Laboratory, Rept. UCRL-78635 (1976). (Accepted by *J. Am. Ceram. Soc.*)
224. P. Souers, I. Moen, and R. Tsugawa, *Distribution of Ne Gas Permeabilities in Glass Laser Targets*, Lawrence Livermore Laboratory, Rept. UCRL-78636 (1976). (Accepted by *J. Appl. Phys.*)

Author
J. G. Rittmann

Major Contributor
J. F. Shaw

4-9.11 Target Assembly

The extremely small size of the targets now being constructed — 10 to 500 μm — requires that all the typical assembly processes, such as adhesive bonding or manipulation, be done under the objectives of a high-power microscope. Because movements of a few tenths of a micrometer cause separation of an assembled part (for example, a hollow glass sphere held in a vacuum chuck while being bonded to a stem), the entire assembly station must remain mechanically stable during all construction processes.

To make targets of small size, we have assembled

the following equipment. First, a granite table supported on air bladders is installed to reduce the vibrational coupling to the surrounding building. A drilled metal plate, to which the other equipment can be easily attached, is bolted to the table. A high-quality, movable optics trinocular microscope equipped with a four-place turret for different objectives is attached to the baseplate. Preferably, the microscope is equipped with both incident and transmitted light sources.

On either side of the microscope are mounted micromanipulators to provide x, y, z movement. These micromanipulators, described in the previous article on target parts handling, are normally mounted opposite each other on a line perpendicular to the center line of the microscope objectives.

Both pressure and vacuum lines are attached to the manipulator body to help prevent movement of the vacuum chucks used for holding the target parts or target mounting stems. Movement of the chucks would result if a loose pressure or vacuum line was supported by the micromanipulator extension alone.

For viewing the vertical axis position of the target, a microscope tube with a 45° bend to facilitate viewing along a horizontal plane is mounted on an x, y, z positioner. Either high-intensity lamps or light pipes provide additional lighting of the target under construction. Figure 4-160 shows a

Fig. 4-160. Target assembly and characterization area.

section of our assembly area, including three assembly stations.

Construction of a typical ball-on-stalk target proceeds as follows. A planchet containing a previously characterized ball is removed from storage and placed on the stage of a microscope. A vacuum chuck of proper size is placed in one of the holders of the micromanipulator and connected to a vacuum line. The ball is then picked up with the vacuum chuck and positioned for assembly; the microscopes are focused on the ball. A two-part epoxy resin is mixed thoroughly on a clean Teflon block and taken up in a plastic hypodermic syringe fitted with a 20-gage needle. After selection of a support stem for the target, the epoxy is injected into the stem by slipping the stem over the tip of the hypodermic needle. The support stem containing the epoxy mixture is then placed in a pressurizable holder in a second manipulator and moved until the tip is in contact with the ball. Pressure is applied to the material in the stem until the epoxy resin extrudes making a very small fillet between the glue stem and the ball. The support stem is maintained in this position for approximately 30 min while the adhesive cures. The vacuum chuck is then carefully removed from the assembled target. After photographic documentation of the target, the support stem is assembled to a base that mounts in the insertion mechanism of the target chamber. At this state, we recheck and document the DT fill of the ball; the target is either delivered to the target chamber or placed in storage.

We routinely produce targets such as balls-on-stalk, lollipops, flat circular plates, pinholes, and disks. Our production figures are, by the above techniques, impressive (see Table 4-16). We also recognize, however, that growth in the numbers of

complex targets to be fabricated requires continuing development of new and improved techniques for microscopic assembly.

Author
C. W. Hatcher

Major Contributors
R. D. Behymer
C. S. Demo
G. W. Heaton
E. R. McCann
J. R. Mazuch
J. T. Weir
L. A. Witt
P. G. Young

4-9.12 Automation of Microsphere Characterization

As design requirements for laser fusion targets grow more severe, the need for automation in characterization of glass microspheres becomes greater. Analysis of experimental results for surface finish effects will soon require a detailed map of fully characterized targets. The volume of data required to generate such a map for short spatial wavelengths is tremendous. For example, a 600- μm -diam microsphere has a surface area of $1.1 \times 10^6 \mu\text{m}^2$. Characterization of a 600- μm -diam sphere with a spatial resolution of $2 \mu\text{m}$ results in 2.8×10^5 data points. The actual sampled areas will more likely be circular (as opposed to rectangular) with about 22% overlap required to cover the surface, thus increasing the number of sample data points to about 3.4×10^5 . As requirements for spatial resolution become more severe, the number of data points will increase as the square of the reciprocal of the spatial resolution.

Surface-finish-ripple requirements are currently of the order of 300 to 500 $\text{\AA}$, with requirements changing to the 100 $\text{\AA}$ range as target designs change. Optical interference systems are capable of measuring surfaces within $\lambda/100$ accuracies thus requiring resolution of at least one part in 100. Digital representation of a 1% resolution will require 7 bits for a complete description of the data. A

Table 4-16. Target production

Target type	Number constructed
Ball-on-stalk	525
Disc	215
Complex	264
Miscellaneous	48
Total	1052

scanning electron microscope (SEM) system will require at most 6 bits, owing to the signal-to-noise ratio attainable at high magnification. An x-ray radiography system will be designed to measure density variations of about 0.1% and will require at least 10 bits. Minicomputers are expected to control the characterization systems and will have 16-bit word lengths. To reduce data processing time, perhaps at the expense of increased data storage, the optical and SEM systems will use 8 bits (1 byte) per data point and the radiography system will use 2 bytes per data point.

Estimates of data handling requirements vary with the measurement system used. To resolve spatial wavelengths of $1000 \text{ \AA}$, a SEM system must analyze about 140 million bytes of data to characterize a $600\text{-}\mu\text{m}$ -diam ball. A radiography system, however, will only resolve spatial wavelengths of $50 \text{ }\mu\text{m}$ and will analyze slightly more than 1000 bytes of data. An optical system will resolve spatial

wavelengths of $2 \text{ }\mu\text{m}$ and will analyze about 0.4 million bytes of data.

The quantity of data per target sphere is large enough for data accumulation rates to become a major consideration. For reasonable statistical accuracy, a radiography system will require about 1000 ms per data point, a SEM will operate at about 1 ms per data point, and an optical system will provide data at a rate of about 0.5 ms per data point. Another data rate limitation may be the speed of the manipulation system used to position the spheres through 4π radians for total surface characterization. A SEM will not require a fast manipulation system, as the electron beam of the SEM will electronically scan about 3% of the sphere surface before the sphere has to be repositioned for the next scan. The scan time for a single section will be on the order of 1 h for $1000 \text{ \AA}$ resolution; thus the SEM manipulator speed is of little consequence. The manipulator does not have to be fast. It does,

Fig. 4-161. Automated optical interference measurement system.

however, have to be compact to fit inside the SEM vacuum chamber, and it must also be stable within 100 Å.

A radiography manipulator system must be faster than a SEM system even though the data rate will only be 1 s per data point. Greater speed is required, because the manipulator will have to reposition the sphere about 600 times to cover the total surface, and rapid slew rates will be needed to minimize manipulator positioning time. Manipulators currently in use require about 1 s for a 50- μm increment. This would result in a 100% increase in characterization time. Mechanical assembly size is not a problem and neither is the vibrational stability requirement of 10 μm .

The optical system combines transmission interferometry for transparent microspheres and reflective interferometry for opaque, coated microspheres. The reflective system will lend itself to scanning 1% of the surface area during each scan with scans of about 2-s duration. Distances between scan areas along the surface will be about 30 μm , and with present manipulators it will take 0.6 s to reach a new scan area. Thus the overhead due to manipulator movement will be about 30% of the data recording time.

The optical reflective system manipulator will require reasonable speed but, more importantly, will require vibrational stability of a few hundred angstroms. The mechanical assembly size will not be a major concern. The optical transmission system cannot be used in a scan mode, however, but requires μm increments for each data point. Scanning is not possible because, for greater accuracy, the light is focused to a 1- μm spot only at the top center of the microsphere surface. The step rate of present manipulator systems is such that about 20 ms of manipulator-positioning time are needed for every data point which can be measured in less than 1 ms. The manipulator motion requires movement times that are 20 times greater than the system measurement rate. Thus, the system is clearly manipulator limited. The mechanical assembly and the vibrational stability are not critical because a 1- μm vibration is tolerable, but the slew rate of the manipulation system should be increased by an order of magnitude to take advantage of the data measurement rate.

Each characterization system will automatically record data, control manipulation of the microsphere, and analyze data for display and long-

term storage. The system shown in Fig. 4-161 is under construction. The system at present is semi-automatic but with manual control of the step-motor drivers of the manipulator and with manual data recording. When the computer subsystem is fully integrated with the manipulator and with the measurement systems being developed, the system shown in Fig. 4-161 will allow exploration of manipulator designs and data analysis schemes.

Author

D. L. Willenborg

4-9.13 Levitation

Targets designed to reach future milestones (significant thermonuclear burn, 1000 times liquid density, etc.) require smooth surfaces on the fuel balls. Production of coated spheres without blemishes cannot be accomplished if sphere-to-sphere contact occurs during processing. To obtain uniform coating or total observation, complete 4 π -steradian access to the fuel ball must be provided. These requirements immediately direct attention to some form of levitation. Numerous coating and characterization operations, in addition to new techniques, can be performed during levitation. The current list of techniques being developed utilizing levitation include: (a) coating without mechanical damage to the surfaces, thus providing optimum conditions for the currently required surface finishes, (b) automated characterization, and (c) generation of spheres, perhaps layered, in which droplets of one fluid are levitated inside another levitated fluid of differing dielectric constant.

Electric fields provide an excellent means of levitating a particle as they are passive to most operations of ball production, coating, and manipulation. Work at LLL has led to an operational quadrupole levitator being utilized for further developmental target efforts (see Fig. 4-162). The Q-pole levitator used was that developed by Wuerker, Shelton, and Langmuir²²⁵ following other work by Paul,²²⁶ Fischer,²²⁷ and others. The levitator consists of a hyperbolic electrical configuration similar to those used in a Q-pole mass spectrometer. To provide the third dimension of

Fig. 4-162. LLL levitation system.

particle orbit stability, the hyperbolic electrodes are made cylindrical in symmetry as shown in Fig. 4-163. The end caps are driven with a high-voltage ac signal, 180° out of phase with respect to the ring electrode. The driving frequency (about 200 Hz) and amplitude (about 2000 V) are adjusted to obtain stable particle orbits as predicted by solutions to Mathieu's equation of motion for a wide range of

Fig. 4-163. Cylindrically-symmetric hyperbolic electrodes used to provide three-dimensionally stable levitation of charged particles.

charge-to-mass ratios (q/m) of the particle. This differs from the narrow range adjustment usually used with this electrode configuration for precise selection of q/m ratios. A dc field at 100 V/cm is superimposed on the end caps to cancel the effects of gravity, allowing the size of the orbit traversed by the levitated particle to be reduced.

The particle (i.e., glass shell) introduced into the levitation cavity must have low kinetic energy and a charge-to-mass ratio sufficient to insure that its motion, asynchronous with the ac electric field, does not allow its orbit to be larger than the device. The injector consists essentially of a parallel-plate capacitor as shown in Fig. 4-164. The particle produces a nonuniformity in the electric field, resulting in charge buildup on the particle to an ideal value of $q = 4\pi\epsilon R_0 E \cdot (1.65)$ as described by Cho.²²⁸ Sometime during the charging process, the particle is lifted off the lower plate and is accelerated toward the upper plate and into the levitator where it is decelerated as it approaches the center of the levitator. If the lower plate is at ground potential at lift off and the ac voltage is symmetrical, the particle arrives at the center of the Q-pole with little kinetic energy.

Biasing both injector plates at a positive voltage about 10 kV and clamping the lower plate to ground provides the electric field needed to charge and inject glass microspheres.

Successful injection results in capture in a wide orbit, as shown in Fig. 4-165(a), where the kinetic energy is converted to angular energy about the center of force of the Q-pole. With time, the particle loses the kinetic energy to the background gas pressure of 10^{-4} Torr as shown progressively in Fig.

Fig. 4-164. Injector for charging and propelling particles into the levitator.

Fig. 4-165. Typical orbit of a captured particle as its kinetic energy is dissipated in the 10^{-4} Torr background pressure: (a) particle trajectory just after capture; (b) and (c) progressive damping, and (d) after application of the gravity-cancelling dc field.

4-165(a) and (b). The final picture [Fig. 4-165(d)] illustrates the reduction in oscillation amplitude with the addition of the gravity-cancelling dc field.

The first use slated for the levitator is in coating hollow glass spheres; therefore, techniques must be developed to reliably inject and extract prefilled spheres one at a time to reduce further losses of spheres surviving the previous low-yield characterization processes. A facility may also be required for keeping the sphere cool during the coating process to avoid fuel loss or rupture of high-pressure-filled spheres.

Work at Colorado State University²²⁹ in Dr. Tom Jones' laboratory is aimed at exploring techniques for the levitation of uncharged particles in an electric field by dielectrophoretic processes. Figure 4-166 shows a simple electrode configuration which induces a dipole moment on the particle and produces a force on the dipole in an electric field gradient.

A simple theory shows that the force on a bubble is

$$F_e = 2\pi R^3 \epsilon_1 \left(\frac{\epsilon_2 - \epsilon_1}{\epsilon_2 + 2\epsilon_1} \right) \nabla E^2, \quad (156)$$

where ϵ_1 is the permittivity of a sphere of radius R , and ϵ_2 is that of the surrounding fluid. If $\epsilon_2 < \epsilon_1$, the sphere is attracted to a field maxima. If $\epsilon_1 < \epsilon_2$, field minima are sought by the particle. This force must counteract gravity if the sphere is denser than the surrounding fluid, or buoyancy must be counteracted if the sphere is less dense.

Figure 4-167 displays a bubble levitated in corn oil, the electrodes providing a cylindrical electric field gradient. As field minima away from electrodes are physically realizable, electrode geometries are required that optimize high field

Fig. 4-166. Electrode configuration used to levitate a bubble by production of a force on the individual dipole.

Fig. 4-167. Bubble levitated in corn oil (scale is in cm).

gradients at a potential minimum. These requirements are met by the hexapole geometry shown in Fig. 4-168. The adjacent ring electrodes provide the ac field gradients, and the end electrodes provide the dc field that produces the dipole moment in the levitated particle or bubble. Obviously, the smaller the dipole moment, the larger must be the ac-supporting gradient fields. As with almost all

dynamic levitator schemes, the tradeoff between frequency, levitating field (ac gradient), and the methods by which the force is transferred to the particle (here, the dipole interaction) are related by Mathieu's equation. The region of stability as determined by Mathieu's equations and the obvious constraint that the oscillation amplitude must be less than the device dimension is shown in Fig. 4-169. This latter constraint is only valid when fluids of very low viscosity are considered.

The fundamental drawback of this scheme is the elongation of the bubble under the influence of the dc polarizing field. To make targets as spherical as possible, low dc fields must be used; and, therefore, high ac levitation fields are required. Figure 4-170 shows the deformation of prolate spheroidal-shaped bubbles of various radii vs the polarizing field. Since surface tension is the force that restores sphericity of the bubble, these curves for liquid hydrogen, a fluid with low surface tension, represent the worst case.

To accomplish operations on liquid droplets, levitation of these droplets in a three-phase Q-pole device²³⁰ is also being considered. Complications, in addition to those previously discussed in solid sphere levitation, include liquid droplet breakup due to elongation and Rayleigh limit of droplet breakup with large droplet charge. Since no dipole is formed in the three-phase device, surface tension does not have to fight an elongating force; thus, sphericity can be more easily maintained.

The levitation methods under development will enable us to perform operations on spherical, solid

Fig. 4-168. Structure of three-dimensional hexapole electrode (shown on left in cross section) and its high voltage circuit: V_{dc} supplies and polarizing field, and V_{ac} supplies the dynamic stabilizing field.

Fig. 4-169. Determination of stable levitation conditions for cryogenic hydrogen.

Fig. 4-170. Deformation of an incompressible droplet of liquid hydrogen at the triple point.

mandrels without mechanical damage. The techniques using liquid or gaseous mandrels will provide the capability of carrying out various reactions in either the liquid or gaseous phase.

References

225. R. F. Wuerker, H. Shelton, and R. V. Langmuir, *J. Appl. Phys.* 30, 342 (1959).
226. W. Paul, and M. Raether, *Z. Physik* 140, 262 (1955).
227. E. Fischer, *Z. Physik* 156, 1 (1959).
228. A. Y. H. Cho, *J. Appl. Phys.* 35, 2561 (1964).
229. Sub-contract #8962605 to Target Research and Fabrication Group.
230. R. F. Wuerker, H. M. Goldenberg, and R. V. Langmuir, *J. Appl. Phys.* 30, 441 (1959).

Author

W. L. Johnson

4-9.14 Sieving Commercial Hollow Glass Microspheres

The commercial hollow glass microspheres we use are supplied as a mixture of many diameters. To obtain spheres of the diameter selected for a particular experiment, sieving procedures have been developed. Because of their extremely low mass and dielectric character, the electrostatic forces acting on the spheres are usually greater than the gravitational forces. Thus, ordinary downward sieving by gravity is not satisfactory. Instead, we have taken advantage of the buoyancy of the spheres and have developed an upward-sieving procedure.

Basically, upward sieving requires a stack of sieves, differing in mesh size by about 10 μm , in a cylindrical tank filled with a flotation medium. The unsorted glass spheres are placed on a sieve lid at the bottom of the stack, underneath the largest mesh sieve. When the tank is filled with liquid, the spheres attempt to float to the top. Depending on the number of sieves used and the mesh sizes selected, specific diameters of spheres can be separated.

Ethyl alcohol is usually selected as the flotation medium for its wetting ability, solvent properties, and electrical conductivity which minimizes the effects of static charges on the spheres. This combination of properties facilitates the sieving operation by

breaking up agglomerates of spheres, dissolving some surface hydrocarbon contaminants, and removing much of the inorganic debris (mostly glass fragments) that clings to the surfaces.

Two upward-sieving facilities are currently in operation, both using 8-in.-diameter Buckbee-Mears screens rated to $\pm 2 \mu\text{m}$. The first sieving facility was built at LLL and employs the following basic operating procedure. First, the unsorted spheres are placed in a sieve lid. The selected sieves are stacked inverted on this lid with the largest mesh sieve on the bottom and the smallest mesh sieve on the top. This assembly is placed in an ultrasonic-cleaner tank that is then filled with ethyl alcohol. As the bouyant spheres rise, they are sorted into those that are too large (trapped underneath the first sieve), those of the desired size range (trapped by the second small sieve), and that are too small and have passed through the smallest mesh sieve. Both ultrasonic and impact (tapping with a rubber mallet) agitation are used to break agglomerations of spheres and to prevent the meshes from clogging.

The spheres of the proper diameter (trapped on the second sieve) are then transferred to a separatory funnel where they are washed with trichloroethylene and alcohol. Heavy debris that was also collected sinks to the bottom of the funnel

and is drained out, leaving behind only the cleaned spheres.

These cleaned spheres are then dried and inspected with a light microscope to detect any inclusion of debris, twin balls, or nonuniformity of diameters. Unsatisfactory quality at this stage indicates a break in a sieve mesh, a very high percentage of unacceptable microspheres in the original batch, or poor control over the sieving process.

The spheres that were either too large to pass through the first sieve or too small and passed through both sieves are then collected and dried. Both size ranges are saved separately for later sieving when a diameter other than the one already removed is needed.

The second sieving facility (see Fig. 4-171) operates at the Rocky Flats Plant of the Rockwell International Corporation under contract to ERDA. This facility was put into operation in 1976 and is essentially an expanded and refined version of the first with a substantially increased efficiency of operation.

For this setup, two cylindrical sieving tanks are connected to each other by an overflow tube. A total of seven sieves are used, three in the first tank and four in the second tank. Mesh sizes run from the largest at the bottom of the first tank to the

Fig. 4-171. Apparatus to sieve hollow glass microspheres.

smallest at the top of the second tank, decreasing typically by about 10 μm .

In the first tank, the three large-mesh sieves are stacked and inverted over a sieve lid containing the unsorted spheres. When the tanks are filled with alcohol, the spheres rise and are separated in 10- μm -diameter ranges. Those shells that pass through all three sieves in the first tank are carried through the overflow tube and into the bottom of the second tank.

Four more sieves are stacked in this second tank. The last (smallest) sieve in the series is sized so that almost all remaining spheres are trapped but most of the debris is passed. Usually a 20- or 30- μm mesh is chosen for this sieve, depending on the amount and size of the debris observed in the original batch of spheres.

To operate this sieving system, the first tank is set inside an ultrasonic cleaner and the space between the sieve tank and the cleaner is filled with water. The second sieve tank is placed next to the ultrasonic cleaner. The heights of the two tanks are adjusted so that when they are filled with the ethyl alcohol, neither tank overflows, the liquid level in the first cylinder is above the overflow, and the alcohol levels in both tanks are the same.

Once again, both ultrasonic and impact agitation are used. In addition, a small pump circulates the flotation medium, pumping alcohol from the top of the second tank, through a tube, and into the bottom of the first tank. Holes in the sieve lid in the first cylinder and spacers at the bottom of the second tank permit the alcohol to circulate freely through the sieves.

After the sieving is complete, the spheres from the largest mesh sieve in the first tank are dried and saved for later sieving when larger shells are needed. Spheres from all the other sieves except the final (20- to 30- μm) sieve are transferred to individual separatory funnels. These are washed in trichloroethylene and alcohol and the debris is drained off. The spheres collected on the 20- to 30- μm sieve are transferred to a sieve lid and the entire sieving process is repeated with appropriately finer mesh sizes.

4-9.15 Special Target Parts Handling and Production

The targets for all LLL laser systems obviously must be fabricated with the greatest possible accuracy and precision. Because many different types of targets and target materials are needed, we have developed some very specialized procedures and handling techniques.

Fabricating Hollow Microspheres

Hollow microspheres for laser targets can be fabricated from a variety of organic and inorganic materials. Microhemispheres of the exact required diameter must first be formed over convex mandrels. These hemispheres are then joined to form a complete microsphere.

Obviously, to obtain a spherical target with a high-quality surface finish, extremely accurate and smooth mandrels are essential. The finished microhemispheres have an inside diameter equal to the outermost diameter of the mandrel and their inside surfaces mimic the mandrel surface. In addition, the outside diameter and surface finish of the microspheres are in part determined by the mandrel characteristics.

To manufacture the mandrels needed to form our targets, we use specially designed or adapted equipment. The machine that turns the mandrels is structurally extremely rigid, isolated from vibrations, and maintained at constant temperature to minimize thermally and mechanically induced deflections that could decrease the accuracy of the mandrels. Also, gas bearings are used to minimize spindle runout. Diamond cutting tools are selected for their edge retention and because they can be shaped to the profiles required for our targets.

The depth of cut, rate of tool feed, spindle speed, and cutting-tool path of the mandrel-turning machine are numerically controlled for accurate repeatability and exact control of the machining process. With the selection of the proper diamond cutting tool and numerically controlled variables, mandrel surface finishes can be produced that are accurate to within a few hundred angstroms. Figure 4-172 is a photograph of a turned 300- μm -diameter copper mandrel.

Author
E. J. Hodges

Major Contributors
R. O. Lindahl
W. L. Ramer
R. T. Tsugawa

Fig. 4-172. Copper mandrel, 300 μm in diam, on which microspheres are formed.

To form the hollow microspheres, a layer of the particular target material is deposited on the mandrel to the desired thickness by any one of several possible coating methods. After coating, the excess material is machined away and the mandrel is removed from the finished hemisphere by chemical etching. Obviously, the mandrel material and etchant must be carefully chosen so that the mandrel is removed without damage to the finished hemisphere. We have found that high purity copper and ferric chloride are quite suitable for these respective functions. Gas bubbles usually produced by acid-etch systems must be painstakingly avoided lest they break up the thin layers coating the mandrel that form the hemisphere. Once the hemisphere is removed from the mandrel, it can be characterized and matched hemispheres can be cemented or microwelded together to form completed hollow microspheres.

Large Spherical Targets

Large hollow and solid spheres, ranging in diameter from one to several centimeters, are also

needed as laser target diagnostic components. These are mounted on hollow stems through which targets can be inserted.

Fabrication of the hollow spheres begins by forming two hemispheres, each with a concentric hemispherical cavity. These hemispheres can be formed by any method appropriate to the particular target material (e.g., turning, grinding, molding, or sintering). Next, the edges of the internal cavities of two hemispheres are lapped. Following internal lapping to the finish required, the two halves are joined by welding, edge-diffusion bonding, or cementing to form a completed sphere.

The targets must be mounted on a stem which, for hollow targets, also serves as an inlet port to fill the internal cavity. The fill-tube (stem) hole is formed and the external edges are lapped on the exterior surface. Finally, a hollow stem is inserted into the hole and sealed in place with cement, solder, or weld.

The solid spherical targets are much less complicated to fabricate. They require only a piece of the desired material which has been cast, machined, ground, or otherwise shaped into a sphere which is

then lapped. The stem is then attached; as with the hollow spheres, the stem-mounting hole may be formed before the external surface is lapped.

The exterior surfaces of both the hollow and solid spheres are lapped on a three-axis lapping machine located at the Rocky Flats Plant of Rockwell International Corporation (see Fig. 4-173). The spindles of this machine ride on gas bearings for accuracy and are mounted 120° apart when viewed from above and at an angle of about 10° from horizontal when viewed from the side. The spindle ends closest to each other are elevated. When the cupshaped laps are in place, they form a cradle for the sphere being lapped. The three circular areas of contacts formed by these laps prevent surface irregularities caused by the presence of the stem-mounting hole. A completed sphere is shown in Fig. 4-174.

Multiple-Mandrel Forming of Disk Targets

Photolithographic techniques developed for integrated-circuit-semiconductor processing have

Fig. 4-173. Three-point lapping machine.

been used to produce disk mandrels. These methods permit the simultaneous production of several hundred disk targets on a single substrate. The photolithographic mask used in this process contained a discrete pattern for each disk mandrel and

Fig. 4-174. Large bronze solid sphere 5-cm in diameter.

Fig. 4-175. Gold disk formed on a multiple mandrel.

thus, a variety of disk sizes can be incorporated into the same mask. We have been able to produce disks of various thicknesses, with or without apertures and ranging in diameter from 50 to 750 μm .

Fig. 4-176. Mandrel used to form gold disk targets.

When the substrate is etched to form the mandrels, the etching is continued long enough to produce a considerable undercutting just below the mandrel's flat disk-shaped surface (see Fig. 4-175). As a result of this undercutting, the mandrel sides lie in the "shadow" of the disk-shaped surface when sputtering is used to deposit the disk material. Therefore, the layer of material deposited on each mandrel stops at the disk edge and is not deposited down the sides. Thus, the disks do not have to be trimmed and can be mounted on stalks as soon as they are removed from the mandrels. Figure 4-176 is a photograph of a gold disk which has been removed from the mandrel.

The ease with which the disks can be removed from the mandrels minimizes the chances of damaging either the disks or the mandrels during separation. Thus, if most of the mandrels remain undamaged, each group of mandrels can be reused several times. Disk-mandrel separations are greatly facilitated by selecting a substrate material that forms a mandrel surface to which the disk material

will not adhere. For the gold disks, we use a silicon substrate that forms a silicon dioxide mandrel surface.

Author

E. J. Hodges

Major Contributors

C. W. Hatcher

G. W. Heaton

C. D. Hendricks

E. R. McCann

W. L. Ramer

W. E. Tindall

J. F. Wengert

FUSION TARGETS

John Nuckolls - Program Leader

Billie Stachle - Secretary

Target Design Group

John Nuckolls - Group Leader

Barbara Hazelhofer - Secretary

Roger Bangerter

Glen Dahlbacka

Jon Larsen

John Lindl

Bill Mead

Don Meeker

Heiner Mudner

Yu-Li Pan

LASNEX/MHD/Fusion Code Group

George Zimmerman - Group Leader

Barbara Hazelhofer - Secretary

Dave Kerst

Dave Bailey

Dick von Holdt

Plasma Theory/Simulation Group

Bill Kruer - Group Leader

Marilyn Strong - Secretary

Kent Estabrook

Bruce Langdon

Barbara Lasinski

Claire Max

Jeff Thomson

Ernie Valeo

Target Fabrication Group

Charles Hendricks - Group Leader

Marilyn Gadd - Secretary

Rick Behymer - Target assembly

Jim Bell - Mechanical systems

Judy Brown - Target assembly

Cherry Demo - Records and clerical

John Dressler - Liquid jets

E. L. Goldman - Electronics

Bill Hatcher - Polymer coatings

Gary Heaton - Target assembly

Wayne Johnson - Levitation and coatings

George Korbel - Mechanical assembly
Ralph Loop - Electrical assembly
Joe Mazuch - Target assembly
Earl McCann - Micromachining and target assembly
Steve Meyer - Material physics
Bill Miller - Mechanical and cryogenics
Iven Moen - Characterization
Kerm Montgomery - Electron microscopy
Ed Pyle - Photography
H. G. Redmond - Coatings
Russ Singleton - Microradiography
Mike Ward - Electron microscopy
Bert Weinstein - Characterization physics
John Weir - Opto-mechanical techniques
Jack Wenger - Technical coordination
Dave Willenborg - Electronic systems
Larry Witt - Target assembly
Bob Woerner - Cryogenics
Pat Young - Target assembly

Section 5

PROGRESS TOWARD LASER FUSION

Contents

Section 5 — PROGRESS TOWARD

LASER FUSION	5-5
5-1 Exploding Pusher Targets: Janus-Clamshell System	5-6
5-1.1 Target Design and Simulation	5-6
Calculations of Implosion Symmetry	5-6
Estimated Fusion Yields	5-8
Laser Absorption Regulation by Target Placement	5-8
Dependence of Implosion Velocity on Thermal Inhibition	5-9
Temporal and Spatial X-Ray Emission ..	5-9
5-1.2 Experimental Results	5-10
Absorption and Transport Measurements	5-16
Conclusions	5-24
5-1.3 Time-Resolved X-Ray Emission from Exploding Pusher Targets	5-25
5-1.4 Janus Postshot Calculations and Analysis	5-31
5-2 Exploding Pusher Targets: Cyclops System	5-37
5-2.1 Target Design and Simulation	5-37
5-2.2 Experimental Results	5-38
5-2.3 Cyclops Postshot Calculations and Analysis	5-46
5-3 Exploding Pusher Targets: Argus System	5-51
5-3.1 Target Design and Simulation	5-51
5-3.2 Experimental Results	5-52
5-3.3 Spatial Resolution of Thermonuclear Burn in Laser Fusion Targets	5-65
5-3.4 Spatial Resolution of Plasma Energy ..	5-69
5-3.5 Argus Postshot Calculations and Analysis	5-75
5-4 Exploding Pusher Targets: D ³ He Fuel, Argus System	5-77
5-4.1 Design and Simulation Experiments ..	5-77
5-4.2 Experimental Results	5-79
5-4.3 Comments on D ³ He Experiments	5-82
5-5 Exploding Pusher Targets: Summary	5-83
5-5.1 Experimental Data	5-83
Absorption	5-90
Pusher Dynamics	5-98
Neutron Yield	5-103
Thermonuclear Burn and Compression	5-105
5-5.2 Comparing LASNEX with Experimental Data	5-109
5-5.3 Exploding Pusher Scaling Model	5-113
Scaling Laws for Exploding Pushers ...	5-114
Comparison of Scaling Law with Experimental Data and LASNEX Simulations	5-116
Validity of Scaling Law	5-117
Conclusions	5-126
5-6 Super Liquid Density Targets: Janus-Clamshell System	5-126
5-6.1 Target Design	5-126
5-6.2 Neon Line-Width Calculations	5-131
5-6.3 Neon Line Measurement Experiment ..	5-135
5-6.4 Interpretation of Neon Line Measurement	5-144
5-7 Absorption and Transport Studies	5-146
5-7.1 Interaction of 1.06- μ m Laser Radiation with Tungsten Glass and Parylene Disks	5-146
5-7.2 Scattered Light Evidence for Short Density Scale Heights Near Critical Density in Laser-Irradiated Plasmas	5-150
Polarimetry Measurements on Scattered Light	5-152
Spatial Distribution of Scattered Light	5-156
Analytic Solution of Wave Equations for Density Profile	5-159

Section 5

PROGRESS TOWARD LASER FUSION

In 1976 we achieved record-breaking thermonuclear conditions in many target experiments. We increased the neutron yield by two full orders of magnitude over our 1975 best. DT ion temperatures of 8 keV and densities of about 1 g/cm^3 were achieved. Especially noteworthy were DT gains of 10^{-2} , never before attained in laboratory experiments. These results are summarized in Table 5-1, which compares our 1976 accomplishments with those of 1975.

The Hyperion targets imploded in these experiments were all of the exploding pusher type used in 1974 and 1975. Those of highest yield were driven by 3-TW, 30- to 100-ps pulses from our new Argus laser. Those of higher density were imploded with the 0.5-TW Janus laser and the confocal ellipse illumination system. Advanced diagnostic instruments, including the newly developed x-ray streak pinhole camera and the alpha-particle imaging system, were used to resolve these implosions to un-

precedented accuracies in space and time. In general, as shown in Table 5-2, the experimental data were accurately predicted by the LASNEX magnetohydrodynamic-fusion computer code.

Table 5-1. Progress toward laser fusion

Fusion parameter	1975	1976
Neutron yield	10^7	10^9
DT ion temperature, keV	2	8
Peak fusion power, MW	2	200
DT density, g/cm^3	0.1	~ 1
Target gain	10^{-6}	4×10^{-5}
DT gain	10^{-4}	10^{-2}

Table 5-2. Measured and calculated laser fusion parameters (1976)

Fusion parameter	Instrument	Accuracy (resolution)	Measured	Calculated (LASNEX)
Neutron yield	Copper activation scintillator photomultiplier tube	15% 20%	$1 - 2 \times 10^9$	2×10^9
Alpha energy, MeV	Alpha TOF	1%	3.3	3.3
DT ion temperature, keV	Alpha TOF Neutron TOF	20%	6 - 10	8
Implosion velocity, cm/s	Streaked x-ray pinhole camera	$6 \mu\text{m}$ 15 ps	3×10^7	3×10^7
Density, g/cm^3	X-ray microscope X-ray spectrometer	$4 \mu\text{m}$ 1 eV	0.1 0.5 - 1	0.1 - 0.2 0.5 - 1.5
Absorbed energy	Calorimeter	10%	up to 50%	up to 50%

By using LASNEX in advance to simulate many possible target designs and associated experiments, we were able to choose an optimum set for experimental tests. Post-shot LASNEX calculations provided a basis for understanding in depth the meaning of the experimental results. Within the laser program we successfully solved the problem of closely coupling the efforts of the Target Group, which runs LASNEX, with those of the Experiments Group.

In addition to the experiments with DT fuel intended to improve the thermonuclear performance and explore various aspects of target design, we also ran experiments with D³He fuel that were capable of detecting even small components of nonthermonuclear burn. None were detected. These experiments also corroborate the temperatures measured by neutron and alpha-particle time-of-flight (TOF) spectrometers.

Absorption and transport experiments were made with disk targets to determine the effects of target atomic number (Z) on the suprathreshold electron spectra, electron conduction, and laser light absorption. The most important finding was a significant increase in the hardness of the suprathreshold spectrum with increasing target Z.

In December 1976, we performed the first superliquid-density experiments. The density was determined by measuring the pressure broadening of the

neon x-ray line. Although exploding pusher targets were used, the DT fuel adiabat was significantly closer to the ideal Fermi adiabat. These experiments were precursors to the major thrust of the 1977 program reaching toward very high densities—ultimately 1000 g/cm³. These super-high-density experiments will involve more isentropic targets in which the pusher does not explode, more powerful lasers with special pulse shapes, and new types of diagnostics including radiochemistry.

This section emphasizes the full cycle of our laser fusion experiments from initial design through actual experimental data to post-shot analysis and interpretation of results. Experimental design is of course an iterative process; progress is made most rapidly when the results of each experiment are fed back into subsequent calculations. Our program emphasis—directed and applied research—is strongly reflected in the articles that follow, which describe not only our 1976 experiments but also some important advances in specific techniques that made them possible.

Authors

J. Nuckolls

H. Ahlstrom

5-1 EXPLODING PUSHER TARGETS: JANUS-CLAMSHELL SYSTEM

5-1.1 Target Design and Simulation

Experiments in 1975 with Hyperion (glass microsphere) exploding pusher targets and the Janus laser system with f/1-lens illumination demonstrated the implosion of DT fuel to thermonuclear conditions.¹ The experimental results are in good agreement with LASNEX calculations. In 1976, we implemented a confocal, ellipsoidal mirror (clamsell) illumination system and an x-ray

pinhole streak camera on the Janus laser system. These permitted a number of experiments to enhance our confidence in our predictions of the performance of laser fusion targets.

Calculations of Implosion Symmetry

LASNEX simulation of the implosion experiments with the f/1 lens reveals a marked asymmetry of the compressed state, especially for targets with

diameters greater than $60\text{ }\mu\text{m}$. Our calculations indicate that, with the available power, the clamshell illumination system can provide greater implosion symmetry and improve the neutron yield by a factor of 2 to 3 for an optimized microsphere.

This is illustrated in Fig. 5-1(a), where the ion temperature isotherms are plotted for two implosions of identical microspheres, one using the $f/1$ -

focusing system and the other using the clamshell illumination system. Figure 5-1(b) shows the numerical simulation of an x-ray microscope picture of the two implosions. As seen, these pictures are considerably more symmetric than the ion isotherms indicate.

The x-ray pictures are time-integrated over a period considerably longer than that for which the DT ion temperature remains high. Additionally, the

Fig. 5-1. Differences in illumination systems result in marked effects on the implosion. The numerical simulation of the ion isotherms within the fuel at the time of peak reaction rate is plotted in (a) and (b). In (a), the $f/1$ -illumination system is used (the laser is incident from the right). In (b), the confocal mirror system is used. A comparison of these implosion shapes shows that the isotherms are more spherical in shape for the mirror systems and more oblate in shape for the $f/1$ illumination. In (c) and (d), the computer-simulated x-ray micrographs for the two illumination systems are plotted. The confocal mirrors (d) heat the shell more uniformly than does the $f/1$ -lens system (c); the compressed core also shows a more spherical shape for the mirror system of illumination.

x rays are emitted by the interaction of electrons with other electrons and the higher-Z ions of the glass shell; consequently the x-ray image comes from that portion of the glass with the highest density.

There is still a noticeable improvement in symmetry for the clamshell illumination but the comparison shows that these time-integrated pictures are not a reliable measure of burn symmetry or compression. The clamshell-illuminated implosion is still far from spherical. Because of this, the yield degradation relative to a perfectly spherical implosion may be as great as ten, even for the clamshells with an 80- μm diameter target at 0.4 TW.

Estimated Fusion Yields

For the Janus 0.4-TW laser pulse, LASNEX predicts maximum neutron yields for spherical targets with a nominal diameter of about 40 μm , a wall thickness of 0.4 μm , a DT fill of about 2 mg/cm^3 gas, and a 30-ps pulse length (see Section 4). The yield is proportional to the product of M and $\rho r(\bar{\sigma}v/V_s)$, where M is the fuel mass, ρ and r are the fuel density and radius, V_s is the ion sound speed, and $\bar{\sigma}v$ is the Maxwell-velocity-averaged reaction rate, all in the imploded configuration. For these exploding pusher targets, the maximum fuel density is approximately constant. As a result, the neutron yield depends only on the fuel mass and temperature.

In the ion temperature range of a few kiloelectron volts achieved in these experiments, $\bar{\sigma}v$ varies with roughly the fourth power of temperature. Consequently, the yield is maximized by imploding relatively small targets to high temperatures. However, in an attempt to relax the laser-clamshell-focusing requirements, we used somewhat larger than optimum targets in these experiments.

Experiments with an $f/1$ lens at optimal focus indicate that the absorbed energy is 20 to 25% of the incident energy, just as predicted by our plasma theorists. This experimental value is based on a nonlinear, angle-dependent absorption curve derived from plasma simulations.² The distribution of incident angle varies as the focal position of the illumination system is altered, relative to the target center. Such a variation changes the total absorption; in addition, there is an optimal focal shift that maximizes resonance absorption.³

Laser Absorption Regulation by Target Placement

The solid line in Fig. 5-2 illustrates the results of applying a ray-trace calculation, including beam aberrations, to the Janus clamshell system for microspheres ranging from 70 to 140 μm at an intensity of about $10^{15} \text{ W}/\text{cm}^2$. The absorption is plotted as a function of focal shift relative to the ball diameter. At intensities of $10^{15} \text{ W}/\text{cm}^2$, we expect significant plasma steepening so the nonlinear absorption curve is used.

The principal absorption mechanism is resonance absorption; however, near normal incidence, parametric decay absorption dominates. Inverse bremsstrahlung accounts for 20% or less of the absorption. The analytic theory depends on the diameter of the critical surface and is not time-dependent. Calculations presented in Fig. 5-2 apply to the critical surface diameter at peak laser power.

Another important input is the laser beam shape. This parameter's effects are moderately well known for the Janus clamshell system. The calculations are done with a 2-to-1 super-Gaussian ring beam. For the conditions assumed here, resonance absorption is seen to peak at incidence angles of 20 to 25° from

Fig. 5-2. The fraction of laser light absorbed by nonclassical processes depends on the position of the spherical target relative to the mirror's focus (positive offset means placing the target center closer to the mirror's surface). The dependence of absorption on target diameter is shown for a 70- μm sphere (solid line) and a 140- μm sphere (dashed line).

normal. The peaks in absorption at a relative overlap of 0.35 occur because, for the beam profile, lens f-number, and target-sphere diameter characteristics of Janus, this overlap concentrates an optimal amount of energy near the proper angles for efficient resonance absorption.

Because resonance absorption is only effective for the polarization component with the electric vector in the plane of incidence, the scattered light should show a polarization dependence near the peak of the absorption curve. Near zero-focal overlap, the incident rays are all nearly normal. Here, resonance absorption is ineffective and the principal absorption mechanism is parametric decay, a polarization-independent parameter. Thus, both scattered light distribution and absorption vary with the focal overlap.

Dependence of Implosion Velocity on Thermal Inhibition

Laser light is absorbed at critical or lower density and thus, to generate the high pressures required of an efficient implosion, electron transport must carry the energy into regions of high density. Both the efficiency and symmetry of the implosion depend on this transport process. Calculations of previous experiments required some form of inhibited thermal-electron conduction to explain such features as neutron yields, x-ray spectra, and x-ray microscope pictures. This inhibition may arise from the existence of magnetic fields and plasma instabilities.

The LASNEX code includes models for the generation of thermoelectric magnetic fields and for the inhibition due to the ion-acoustic, two-stream instability. One measure of the degree of inhibition is the implosion velocity achieved with a given laser pulse.

Figure 5-3 plots the calculated pusher velocity with and without the electron-ion, two-stream inhibition model for a 70- μm sphere imploded with a 30-J, 65-ps laser pulse. There is almost a twofold difference in the peak velocity. This will be converted into a fourfold difference in the ion temperature of the compressed fuel and a difference of about 200 in the neutron yield. However, the measured neutron yield agrees with the calculation including inhibited conduction.

Fig. 5-3. Calculated pusher velocity is sensitive to the thermal-energy transport model. The velocity of the glass-DT interface is plotted for the duration of the implosion process; times are relative to the peak of the laser pulse. The dashed curve represents classical transport by thermal conduction and the solid curve denotes transport modified (reduced) by the electron-ion, two-stream instability.

Temporal and Spatial X-Ray Emission

The x-ray streak camera provides additional information about the implosion. LASNEX simulations of the x-ray streak record for a relatively large-diameter microsphere imploded with a Janus-like pulse reveals two distinct peaks of x-ray emission in the region of 2.5 to 3.0 keV (see Fig. 5-4).

The LASNEX calculation indicates that the first x-ray peak is approximately coincident with the peak of the laser pulse. This emission comes from the dense glass shell in its approximately initial position. The second peak appears at the time of shell stagnation and peak gas compression. Again, the emission comes from the part of the glass that is now the hottest and most dense. In addition, Fig. 5-4 depicts the emission in the 3.5- to 4.0-keV range. The higher-energy window shows a similar x-ray flux at both peaks, in contrast to the 2.5- to 3.0-keV window.

The ratio of the two signals at corresponding times is related to the shell temperature. The ratio of the intensity in the upper window to that in the lower window at stagnation time indicates a higher temperature than at peak laser time. The relative amplitudes of the peaks depend on the mass of the

Fig. 5-4. Relative x-ray intensity vs time (relative to the laser pulse) exhibits a behavior that varies as a function of x-ray energy. The solid curve is for the x-ray energy from 2.5 to 3.0 keV and the broken line is energy from 3.5 to 4.0 keV. The peak near $T = 0$ results from laser heating of the glass shell; the peak at $T = +65$ ps is the stagnation of the glass shell, resulting in the conversion of kinetic energy to thermal energy. The ratios of the windows indicate that the temperature is hotter at stagnation than at the peak of the laser pulse.

Fig. 5-5. Expected velocity history of an imploding Hyperion target (glass microsphere) as simulated by LASNEX is represented by the solid line. The target is 60 μm in diameter with a 0.7- μm shell thickness and filled with 0.002 g/cm^3 DT. Laser peak power was 0.5 TW in a 65-ps FWHM Gaussian pulse. Times are relative to the peak of the pulse. The position of the maximum x-ray intensity ($2.0 < h\nu < 3.0$ keV) is represented by the dashed line. Although the two positions are separated by several micrometers at any instant, their rates of change (velocity) are similar. The average velocity of the x-ray path is 3.9×10^7 cm/s whereas the pusher-DT interface velocity is 3.0×10^7 cm/s.

target and laser power. The temporal separation of the two peaks is an indication of the implosion time, provided that the rise time of the laser pulse is not longer than the implosion time.

We will employ the x-ray streak pinhole camera to obtain a more direct measure of the implosion velocity. With a measure of the peak x-ray emission position as a function of time, we will be able to determine the velocity and acceleration of the implosion so long as the emission arises near the pusher-DT interface. Figure 5-5 is a calculation of the positions of the pusher-DT interface and the peak emission regions vs time. Throughout the implosion, the positions of these two features are within a few microns of each other.

References

1. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), pp. 467.
2. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975).
3. J. J. Thomson, C. E. Max, J. Erkkila, and J. E. Tull, *Phys. Rev. Lett.* **37**, 1052 (1976).

Author
J. Larsen

Major Contributor
J. Lindl

5-1.2 Experimental Results

Efficient heating and spherical compression of microscopic laser fusion targets require highly uniform compression of the pusher and fuel. Previous experiments at LLL used two $f/1$ lenses to focus the 1.06- μm laser light onto the 40- to 100- μm -diam targets at about 0.4 TW.^{4,5} As expected, the resulting compression is definitely nonspherical.

Figure 5-6 shows x-ray micrographs⁶ of a series of laser-fusion experiments with the Janus laser operating at about 0.4 TW with two $f/1$ focusing lenses. The reduced heating at the equatorial region for the 80- and 100- μm diam targets is consistent with inhibited thermal conduction by electrons.⁷⁻⁹ For the 60- μm ball we observe that the laser radiation is beginning to heat the equatorial region, making the implosion more spherical. It is not until we get to the 40- μm -diam target that the incident intensity (W/cm^2) and specific absorbed energy are high

enough to make the scale length for the thermal conduction sufficiently long to allow thermal conduction to transport the energy all the way around the glass shell.

To ensure more uniform irradiation of spherical targets, we implemented a spherical illumination

system for use with the Janus laser.¹⁰⁻¹² As shown in Fig. 5-7, it consists of $f/0.47$ doublet lenses and eccentricity $1/3$ ellipsoidal mirrors; it is essentially a modified version of the system designed by Thomas¹³ and used by KMS Fusion for laser fusion experiments.¹⁴ With the system in "best focus," i.e.,

75100306-4, 2.5 keV, 40- μ m ball,
 3.8×10^{16} W/cm²

75080711-4, 2.5 keV, 60- μ m ball,
 1.5×10^{16} W/cm²

75062405, 2.5 keV, 80- μ m ball,
 7.8×10^{15} W/cm²

75080803, 2.5 keV, 100- μ m ball,
 3.8×10^{15} W/cm²

Fig. 5-6. Implosion symmetry is dependent on the incident laser intensity.

with the two foci from the ellipsoidal mirrors coincident with the center of the target, the marginal rays have a theoretical half-angle of 81.5° (Fig. 5-7). In this configuration, the rays are all at normal incidence on the target for an unaberrated beam and ideal optics, which produces a total illumination coverage of about $0.85 \times 4\pi$. To cover the equatorial region of the target, the two foci must be shifted. This configuration is shown in Fig. 5-8, together with the measured intensity distribution on the target surface.¹² Maximum illumination uniformity is thus achieved at the expense of deviation from the ray normality condition. However, as absorption due to electron plasma wave resonance effects^{8,15-18} requires non-normal incidence, this tradeoff is actually advantageous for target performance. This effect is discussed in more detail below.

This spherical illumination system was first used for a series of exploding-pusher^{19,20} target experiments on the Janus laser system. These pilot experiments were intended to study the increase in neutron yield over the implosion experiments using $f/1$ lenses^{4,5} and to study the effects of absorption and target performance as a function of illumination overlap of the SIS. For the neutron yield experiments, the targets used were SiO_2 microspheres $67 \pm 3 \mu\text{m}$ in diameter with a nominal wall thickness of $0.5 \mu\text{m}$. These were filled with an equimolar mixture of deuterium and tritium at 2 mg/cm^3 . The absorption studies were performed with microsphere targets between 60 and $120 \mu\text{m}$ in diam.

Aligning the SIS with the numerous and to some extent "coupled" degrees of freedom between the

Fig. 5-7. Ellipsoidal mirror illumination system is shown in cross-sectional view. Target diagnostics are located in the annular ring between the mirrors and behind eight small holes in the mirrors.

Fig. 5-8. Intensity distribution at the target surface was reconstructed from the interferometrically measured distortion of the mirrors together with the measured input beam profile. For a 60- μm target, the most uniform illumination conditions occur when each foci is shifted 10- μm past the target center.

four optical elements is a time-consuming and delicate operation. Since a detailed description of the operation of the 4π illumination system is given in Ref. 12, we include only a brief summary. Aligning the system using interferometric techniques was essential. A 30- μm -diam gold-coated microsphere was placed in the target holder, and a 1.06- μm cw YAG laser, collinear with the pulsed beam, was used to make one lens/mirror combination of SIS and the gold ball into a Twyman-Green interferometer²¹ as shown in Fig. 5-9. The lens and gold-coated ball were then manipulated to obtain the desired interference pattern on the ir vidicon (fewer than 4-5 fringes). With one lens/mirror pair aligned and the common focal point determined by the center of the ball, the opposite lens/mirror pair was made into a Twyman-Green interferometer and aligned on the ball. The gold-coated ball was then removed, and the actual target inserted in its place

with the aid of a telemicroscope. Final alignment of the target ball was made using the reflection from the glass surface. This left the target in the best focus condition with the marginal rays converging at an 81.5° half-angle. The target was overfilled by first aligning the target to best focus and then using stepping motors to move the appropriate lens/mirror combination. Linear variable differential transformer (LVDT) sensors were used to indicate the positions of the optical elements with a resolution of 1 μm .

Figure 5-10 shows a typical example of a target experiment using SIS. For this experiment the lens/mirror pairs had been moved to provide a 10- μm focal shift, as indicated in Fig. 5-10(a). The relevant target and laser parameters and thermonuclear yield are given in the accompanying table. Figure 5-10(b) shows the time- and space-integrated x-ray spectrum from this target together with an x-ray

spectrum from a similar target illuminated with two f/1 lenses.^{4,5} As expected, the f/1 lens illumination produces a hotter suprathermal x-ray spectrum due to the higher intensities on the target. Figure 5-11 shows the x-ray microscope image (in the 2.5-keV region) together with a density scan in the vertical and horizontal direction showing the nearly spherical nature of the implosion. (Compare this with the implosion of the 80- μ m target shown in Fig. 5-6.) Figure 5-12 shows a comparison between the charge collector data²² from this experiment and a typical experiment using f/1 lenses for illumination. The shift of the distribution function to

higher energies for SIS experiments is particularly evident in Fig. 5-1(c). As of yet, there is no definite, satisfactory explanation for this shift to higher energies. However, since the charge collector probes for the SIS are located in the gap between the two mirrors, essentially they look down the incident beam and are therefore in a better position to detect "fast" or non-thermal ions. For the f/1 lens experiments, physical constraints limited the placement of the Faraday cups to angles more than about 20° away from the marginal rays; thus the Faraday cups were not monitoring the plasma energy directed back towards the focusing lens.

Fig. 5-9. Spherical illumination system was aligned interferometrically.

Fig. 6-10. (a) Typical symmetrical irradiation experiment performed at conditions giving maximum absorption and uniformity of x-ray emission. (b) Continuous x-ray spectrum appears to be little affected by changes in illumination.

Fig. 5-11. Very symmetric implosion is possible with the spherical illumination system.

The experiment cited in Fig. 5-12(a) produced the largest neutron yield, 1.4×10^7 , for this series of experiments; the average yield was 6×10^6 . Thus both the maximum and the average yield are a factor of about 2.5 greater than those observed in the experiments using f/1 lenses and similar targets.^{4,5} The simple scaling rules developed in Ref. 5 show that to first order, the neutron yield is determined by the useful fraction of the absorbed energy. This simplistic concept is particularly true for targets of the same diameter, wall thickness, and DT fill. Therefore, since the experiments using the SIS were done at laser and target conditions virtually identical to those of Ref. 5, we must expect the final DT ion temperatures to be comparable. This is confirmed by the α -particle time-of-flight energy spectrum.²³ The increase in target performance will thus be due to the improved symmetry of the implosion, i.e., because more DT fuel is being heated to the peak ion temperature.

Absorption and Transport Measurements

When it was discovered that spherical targets illuminated as in Fig. 5-13 by f/1 lenses consistently absorbed more laser energy than those illuminated by f/2.5 lenses (see 1975 Annual Report, p. 467, and § 5-2.2), it became apparent that both the energy tribution at the target and the angles of incidence of the rays impinging on the target affect the absorption fraction. With one beam purposely blocked, forward-scatter calorimetry showed that the energy had not simply missed the target in the f/2.5 case. Still a third absorption fraction appeared to be characteristic of irradiations using the SIS. Table 5-3 summarizes these findings and compares them to the theoretical estimates of Thompson et al.¹⁵ Further data relating angle of ray incidence to absorption were accumulated by a focusing study using the SIS.

Ion probe data for 60- μm balls

Marginal rays of
focused laser beams
from f/1 lenses

Target diam = $85.7 \mu\text{m}$
Wall thickness = $0.64 \mu\text{m}$
DT fill = 2 mg/cm^3

Fig. 5-13. Microshell target is positioned with respect to the foci of the converging beams of the aspherized lenses such that the marginal rays from both lenses are tangential to the target surface. The target is centered by viewing along the beam axis in the plane of the target as shown on the right.

Table 5-3. Fractional laser light absorption for spherical microshell targets

Focusing system	Intensity range (W/cm^2)	Calculated absorption	Measured absorption		
			Plasma calorimetry	Box calorimetry	Pin diodes
f/2.5 lenses	10^{15} to 3.5×10^{15}	0.10	0.13 ± 0.04	0.13 ± 0.09 - 0.05	0.15
f/1 lenses	10^{15} to 1.5×10^{16}	0.27	0.22 ± 0.04	0.27 ± 0.03	0.21 ± 0.04
Ellipsoidal mirrors	10^{15} to $4 \times 5 \times 10^{15}$	0.18	0.20 ± 0.03	-	-

Figure 5-14 shows x-ray micrographs of microshell targets about $100\text{ }\mu\text{m}$ in diam irradiated with varying focal overlaps. Since the angles of incidence of the rays are being changed, angle-dependent absorption processes such as resonance absorption should vary in their effect. Ideally, if the beam foci and the center of the microshell target coincide, all rays enter normal to the surface; and if it were not for density-gradient modification by ponderomotive forces, resonance absorption would not be operative at all. Even with an imperfect beam

profile, the data displayed in Fig. 5-15 show approximately the expected absorption with focal overlap.¹⁵ The calculated fractional absorption is made up of contributions from parametric decay instabilities and electron plasma wave resonance effects. The absorption due to inverse bremsstrahlung is included in the calculated curve, but accounts for less than $1/5$ of the overall absorbed energy. The shape of the curve can qualitatively be described as follows. At "best focus," the absorption is largely due to parametric decay instabilities, as resonance

(a) 100- μm non-overlap
15.2 J/15.3 J/102 ps
PDS: 76081902-4-3

(b) Best focus
15.2 J/14.5 J/62 ps
PDS: 76022006-4-4

(c) 21- μm overlap
12.9 J/13.2 J/110 ps
PDS: 76082603-4-3

(d) 100- μm overlap
18.4 J/18.2 J/112 ps
PDS: 76081202-4-1

Fig. 5-14. Janus 4x Illumination system x-ray micrographs showing the effect of different focusing positions on absorption and implosion symmetry.

76072302-4-3

64 μm^D 2.5 keV (a)

75062506-2

88 μm^D 0.8 keV (b)

76080503-4-1

101 μm^D 1.5 keV (c)

76082903-4-1

126 μm^D 1.5 keV (d)

Fig. 5-16. (a-d) Single-sided illumination of microspheres provides energy transport data. (e) Ratio of the energy transported to the rear side of microspheres illuminated from one side to that absorbed on the front side increases with specific absorbed energy.

diameter of about 0.35, which, for a 60- μm -diam ball, corresponds to a 21- μm separation—a number in excellent agreement with the calculations performed with the measured intensity distributions as shown in Fig. 5-8.

The fact that the heated regions are confined approximately to the illuminated areas is more evidence for inhibited thermal conductivity. For example, classical conductivity at $\theta_e \approx 1.5$ keV would diffuse the energy over approximately 150 μm in the 70-ps laser pulse duration; however, the presence of a several megagauss magnetic field drops this distance to approximately 15 μm in agreement with these observations.²⁴ The questions of thermal transport inhibition and fluid dynamic behavior in these targets were further addressed by irradiating microspheres of several diameters on only one side. The x-ray micrographs shown in Fig. 5-16(a) through (d) indicate that the thin spherical shell was heated, exploded, fluid-dynamically focused near the center of the sphere, and finally stagnated against the slowly imploding rear wall. The location

of this final stagnation provides a measure for the relative velocities of the front and rear walls of the imploding microshell and, therefore, data on energy partition and transport.

Ten of these one-sided irradiations were carried out using both lenses and the SIS. In all cases, the hemisphere exposed to the laser was heated into the keV range; however, the rear of the target did not emit strongly enough to be visible on our micrographs. The energy partition between the imploding portions of the front and rear of the target was estimated by squaring the ratio of the distance that the rear wall moved to the distance that the front wall moved before stagnation. Figure 5-16(b) shows that the fraction of the implosion energy transported to the rear of the target increases with specific energy absorbed.

As was pointed out by Storm, all of the energy absorbed is not useful in the implosion since the imploding target wall appears to be decoupled from the heated target atmosphere after it has moved a short distance.⁵ This tends to put a premium on

Fig. 5-17. Implosion symmetry is significantly affected by the incident laser intensity and the specific absorbed energy.

Fig. 5-18. Space-time x-ray emission characteristics for laser-imploded glass microspheres.

high intensity at the target surface. As Fig. 5-17 demonstrates, increasing the intensity on target has the affect of symmetrizing the x-ray emission (as observed in the x-ray microscope images) even though the energy deposition and absorption due to the f/l lens illumination is still asymmetric. Although the sequence of events listed above in the description of the one-sided implosion is a plausible one, it must be confirmed by simultaneously resolving both the temporal and spatial x-ray emission from an imploding microsphere.²⁵ These experiments are dis-

cussed below in detail. Figure 5-18 shows one example of the space-time implosion diagrams obtained from these experiments. In this figure, a "ridge-finding" computer program was used to determine of the $r-t$ trajectories. All three targets have diameters in the 67- to 69- μm range, similar wall thickness, and similar DT fills. The upper two images were obtained from targets irradiated from two sides with almost identical focusing conditions and similar pulse powers. With the "ridge-finding" technique, we were able to unambiguously locate

the trajectories of the brightest x-ray emitting portions of the target as they approached and as they exited the convergence region.

The r-t diagrams are alike, one being more symmetric, but both show final implosion velocities of about 3.1×10^7 cm/s. Neutron yields of about 10^6 were recorded for both of these shots. The third target was the same as the first two, but purposely irradiated from only one side. A convergence region due to fluid focusing is clearly evident except that conservation of momentum causes it to coast across the target for some distance. Impact with the imploding rear wall is not detectable. Unlike the implosion phase, target disassembly is clearly two sided. These data were obtained with a 125- μ m-thick beryllium filter giving a spectral window in the 2- to 3-keV range. These images unambiguously show that the rear of the target is not heated to temperatures high enough to make it visible at early times. Although several attempts were made to observe the stagnation of the front and rear target walls in a one-sided irradiation with the x-ray streak camera, the emission from this region in large targets was too weak to record even when the beryllium filter was removed.

Numerical simulation of selected one-sided irradiations by the LASNEX computer code demonstrate general agreement with experiment. Self-generated thermoelectric magnetic fields seem to play the significant role in inhibiting the thermal transport laterally along the glass shell. The electron-ion two-stream instability or resonantly generated magnetic fields may also contribute to the radial conduction inhibition. This is discussed in detail in § 5-1.1 and 5-1.4.

Conclusions

Experiments have been performed on the Janus laser with a spherical illumination system producing nearly uniform energy deposition on microscopic laser fusion targets. The target performance as measured by the thermonuclear reaction yield was increased by a factor of 2.5 over experiments performed with f/1 lenses. Simple considerations of useful absorbed energy together with α -particle time-of-flight measurements indicate that the DT ion temperatures were not increased over those of earlier experiments. The increased neutron yield is thus caused by the greater uniformity of compression

achieved. Measurements of absorption as a function of focal shift of the ellipsoidal mirrors support the hypothesis that resonance absorption plays an important role in these laser fusion experiments.

Preliminary measurements of absorption and thermal transport in 1.06- μ m laser-illuminated microshell targets show that energy deposition depends on both the profile and angle of incidence of the laser beam. Large thermoelectrically generated magnetic fields may be the cause of the reduced flow of energy in the target plasma atmosphere; however, their effects can apparently be mitigated by raising the specific energy absorbed and/or by increasing the incident laser intensity above about 10^{16} W/cm².

Improvement in compression symmetry has been observed by increasing the incident laser intensity on the target. This improvement may be due to increased electron thermal flux that causes an increase of the effective conduction scale length, reducing the effect of the thermoelectrically generated magnetic fields mentioned above.

References

1. E. K. Storm et al., *Bull. Am. Phys. Soc.* **20**, 1266 (1975) and *The Effects of Fill Pressure and Pulse Simultaneity on the Laser Driver Implosion of DT-Filled Glass Microspheres*, Lawrence Livermore Laboratory, Rept. UCRL-77083 (1975).
2. E. K. Storm, J. T. Larsen, and H. G. Ahlstrom, *Exploding Pusher Target Experiments and Simple Scaling Rules*, Lawrence Livermore Laboratory, Rept. UCRL-78729 (1976), submitted to *Phys. of Fluids*.
3. T. D. Seward et al., *Rev. Sci. Instr.* **47**, 464 (1976).
4. J. T. Larsen, J. J. Thomson, and C. E. Max, *Electron Transport Inhibition in Spherical Microshell Target Irradiation*, Lawrence Livermore Laboratory, Rept. UCRL-78467 (1976).
5. J. T. Larsen, C. E. Max, E. K. Storm, and J. J. Thomson, *Absorption and Conduction in Spherical Laser Targets*, Lawrence Livermore Laboratory, Rept. UCRL-77901 (1976).
6. R. C. Malone, R. L. McCrory, and R. L. Morse, *Phys. Rev. Lett.* **34**, 721 (1975).
7. S. S. Glaros and A. J. Glass, *Compound Ellipsoidal Focusing System for Fusion Lasers*, Lawrence Livermore Laboratory, Rept. UCRL-77249 (1975).
8. J. A. Monjes, *Laser Program Annual Report — 1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75.
9. J. E. Swain et al., *Realities of the Janus 4 π Illumination*, Lawrence Livermore Laboratory, Rept. UCRL-78445 (1976), submitted to *Appl. Opt.*
10. C. E. Thomas, *Appl. Opt.* **14**, 1257 (1975).
11. G. Charatis et al., *Plasma Phys. Controlled Nucl. Fusion Res.* **11**, 317 (1974).

15. J. J. Thomson, C. E. Max, J. Erkill, and J. E. Tull, *Phys. Rev. Lett.* **37**, 1052 (1976).
16. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975).
17. W. L. Kruer et al., *Collection Behavior in Recent Laser-Plasma Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-77730 (1976).
18. J. P. Freiberg, R. W. Mitchell, R. L. Morse, and L. I. Rudinski, *Phys. Rev. Lett.* **28**, 795 (1972).
19. G. H. Dahlbacka and J. H. Nuckolls, *Laser-Driven Isothermal Implosions*, Lawrence Livermore Laboratory, Rept. UCRL-75885 (1974).
20. J. H. Nuckolls, *2nd Orbis Scientiae Conference*, Univ. of Miami, Jan. 1975, and *Outlook for Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-76395 (1975).
21. M. Born and E. Wolf, *Principles of Optics* (Pergamon Press, 1970), p. 303.
22. V. C. Rupert et al., *Particle and X-Ray Energy Measurement in Laser-Plasma Interaction Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-78439 (1976).
23. V. W. Slivinsky et al., *Phys. Rev. Lett.* **35**, 1083 (1975).
24. L. Spitzer, *Physics of Fully Ionized Gases* (Interscience, J. Wiley & Sons, 1962).
25. D. T. Attwood, L. W. Coleman, M. J. Boyle, J. T. Larsen, D. W. Phillion, and K. R. Manes, *Phys. Rev. Lett.* **38**, No. 6 282 (1977).

Fig. 5-19. X-ray temporal signatures (2.6 keV) for targets with and without a significant prepulse. The solid line is for target 503 (76082002), with no prepulse, 0.28 TW, 100 ps, and 3×10^5 neutrons. The broken line is for target 430 (76081802), with a 1-mJ prepulse, 0.41 TW, 71 ps, and no neutrons.

Authors

K. R. Manes

E. K. Storm

Major Contributors

J. T. Larsen

J. E. Swain

M. J. Boyle

V. C. Rupert

D. T. Attwood

D. W. Phillion

H. G. Ahlstrom

5-1.3 Time-Resolved X-Ray Emission from Exploding Pusher Targets

We have previously described the LLL 15-ps resolution x-ray streak camera used to record significant spectral and temporal structure in the unimaged kilovolt x-ray emission from laser-compressed fusion targets.^{26,27} In addition to providing time-dependent temperatures on a picosecond time scale, two temporal peaks are generally observed; the first is identified with early-time laser heating and the second burst is associated with the conversion of kinetic energy of the pusher to thermal energy as the implosion stagnates near the

target center. In this section, we describe the results of recent experiments of a similar nature²⁸ and correlate the observed peak-to-peak "implosion time" with laser and target performance. In addition, we describe the results of single-spectral-channel experiments in which x-ray imaging was combined with the streak camera to observe space-time resolved x-ray emission records, R,t diagrams, from which we obtain detailed implosion-velocity histories as well as acceleration values.²⁹

First, we consider the time-resolved spectral measurements in which the temporal x-ray signature is correlated with laser and target performance. Two experiments involved the irradiation of glass microshell targets (typically 105 μm in diam and 1 μm thick) by 100-ps laser pulses. Although the target details and the high-power laser pulses were similar, differences in the laser prepulses resulted in differences in target performance and, concomitantly, in the observed x-ray temporal signatures. Although these particular targets were designed to produce moderate fuel densities rather than large neutron yields, the relative yields provide a convenient measure of target performance. In addition, these heavy-wall target experiments are particularly interesting because their implosion time is sufficiently long compared to the laser-heating time and because x-ray emission from the two distinct

Fig. 6-20. X-ray temporal signature laser power for three cases of no detectable prepulse. The lower curve shows that a low-power-laser firing produces a slower implosion, less x-ray emission at peak compression, and fewer neutron-producing reactions. Within a small variance, all three targets are characterized by an 82- μm diameter, a 1.7- μm wall thickness, and a DT-Ne fill of 1.2 mg/cm^3 . The solid line is for target 515 (76082602), 0.36 TW, 93 ps, and 9×10^5 neutrons. The dotted line is for target 520 (76082604), 0.35 TW, 92 ps, and 7×10^5 neutrons. The broken line is for target 517 (76082603), 0.24 TW, 110 ps, and 10^5 neutrons.

Fig. 5-21. One-dimensional LASNEX computation of the x-ray temporal signature of target 515 in the 2- to 2.4-keV band. (Note the linear ordinate.)

periods is temporally well separated. Such a temporal separation is not always observed. For instance, the two emissions are temporally overlapping for experiments with longer laser pulses and smaller target radii. Figure 5-19 shows the time-resolved 4-keV x-ray signatures measured in target experiments with and without significant prepulse.

For target 76082002, no prepulse was detected (16 μJ detection threshold) and the x-ray signature in Fig. 5-19 exhibits the familiar two-peaked behavior; as mentioned previously, we correlate that with laser heating and core stagnation, respectively. Target 76081802, on the other hand, was subjected to a 1-mJ prepulse, a value above the threshold for damage on these targets.³⁰ Here, the x-ray temporal structure does not show any emission produced by the prepulse directly (because the intensity is too low), but does indicate the influence of the prepulse on target performance. In this case, we observe only the early-time peak due to laser heating; the peak corresponding to core stagnation is not observed in this shot. This indicates that the target had disassembled before the arrival of the main laser pulse and that no material was effectively accelerated inwardly to act as a pusher. In addition, this target produced no detectable neutrons, whereas target 76082002 produced 3×10^5 neutrons, providing additional evidence in support of our interpretation of the x-ray temporal signatures. We interpret these correlated observations as further confirmation of our previous work²⁷ regarding the two-peak x-ray temporal profiles of laser-compressed targets. These conclusions are also supported by data in the remaining x-ray channels recorded on these shots.

We now investigate the dependence of implosion time (peak-to-peak temporal delay) on delivered laser power and its correlation with target performance. In Fig. 5-20, we show the 4-keV x-ray temporal signatures obtained from irradiation of three similar glass microshell targets (82 μm in diameter and 1.7 μm in wall thickness). In each case, there was no detectable prepulse and, as a result, each of these shots displayed the now-familiar two-peak temporal signature. On two of these shots, the laser performance was nearly identical, producing 0.36 and 0.35 TW. As seen in Fig. 5-20, the x-ray signals and the measured neutron fluences were nearly identical. The peak-to-peak implosion time for these targets was measured to be 92 ps; the stagnation peak was somewhat larger in amplitude. On the third shot in these series, laser power dropped by

Fig. 5-22. Space-time record of three implosions recorded by the pinhole/streak camera combination. The colored lines are contours of equal x-ray intensity. The dashed lines follow peak x-ray emission from the imploding glass shell. Final-implosion velocities of approximately 3×10^7 cm/s are indicated for each experiment. Curvature of these trajectories indicate accelerations of 3 to 4×10^{17} cm/s². The upper two implosion diagrams are the results of two-sided irradiation experiments. The lower left diagram shows the implosion dynamics of a single-sided irradiation experiment in which the laser beam from the left was purposely blocked. In this case, the imploding shell converged near the target center and then disassembled in a two-sided but asymmetric fashion.

33%, resulting in a longer (133-ps) implosion time and a significantly reduced second peak. The less-intense second peak generally indicates that less kinetic energy has been converted to thermal energy at the target center. This is consistent with the observed reduction in neutron yield. The results of a one-dimensional LASNEX modeling of target experiment 76082602 are shown in Fig. 5-21. The computed x-ray emission is given as a function of time in the 2- to 2.4-keV range and should be com-

pared with the top curve of Fig. 5-20, which shows the measured emission in a nearby energy band. The two-peaked behavior is evident in both the computed and measured profiles, both of which display a 92-ps peak-to-peak temporal separation. Similar agreement is found in other spectral channels. In summary, we have recorded time-resolved x-ray spectral data that is consistent with both calculations and other measures of laser/target performance.

The technique for obtaining space-time records of x-ray emission from laser irradiated targets is described in detail in a separate section. Basically, the technique employs an x-ray pinhole that images target self-emission onto the slit-shaped photocathode of our x-ray streak camera. Typical results are shown in Fig. 5-22. Resolution boxes in the lower right side of each streak record show the approximate resolutions of $6\text{ }\mu\text{m}$ and 15 ps . The streak records have been color coded in each case to show increasing x-ray intensity from blue to red (most intense). The R,t diagrams on the upper left and upper right were obtained from two-sided irradiation experiments which, according to other diagnostics, were essentially identical. The dashed white lines following the peak x-ray emission indicate final-implosion velocities of $3.1 \times 10^7\text{ cm/s}$. Fitting these contours to a constant acceleration, parabolic-trajectory model, we obtain typical acceleration values of $3\text{ to }4 \times 10^{17}\text{ cm/s}^2$. The result shown in the lower left of Fig. 5-22 shows the space-time record of a target irradiated from only the right side. From this we observe that the target converged near the original target center, despite the asymmetric irradiation, and later disassembled in a two-sided asymmetric fashion. Implosion times were typically 100 ps for these $70\text{-}\mu\text{m}$ -diam targets.

Figure 5-23 shows a comparison of two-dimensional (time-integrated) x-ray microscope images with the temporally resolved, single-space-dimension streak records. The complementary features from the two diagnostics are obvious. The comparisons are made for two classes of exploding pusher targets which represent the extremes we have studied to date. On the left, we show results for a massive (105 ng) target of large radius that absorbs light for a significant length of time before "exploding." Upon explosion, the density drops dramatically for this large-radius target, decreasing x-ray emission intensity below our detection threshold. At about 160-ps later, the oppositely directed shell masses meet near the target center, stagnating, and converting kinetic energy to thermal energy, again at high density and higher temperature. The resultant peak of x-ray emission is seen in both the space-space and space-time diagrams. Note that both images reveal that stagnation occurred at a position slightly off center and that the split central core (where the weakly emitting, high-pressure, low- Z fuel is located) is resolved in both cases.

The space-space and space-time records to the right in Fig. 5-23 show the results obtained with a smaller mass (18 ng), smaller radius target. In this case, the target explodes much earlier in the irradiation pulse (because of its small mass) and converges on the target center at a much earlier time, using less of the absorbed energy in an effective manner. In addition, because of the small radius, density does not decay nearly as much; thus, x-ray emission never drops below the detection threshold (i.e., the familiar "ring" pattern is absent). The upper right microscope image shows that the higher electron temperature attained in this smaller-mass case enhanced the electron conduction of energy to areas at the top and bottom of the target. The comparable final-implosion velocities for the two cases in Fig. 5-23 show that the useful absorbed energies per unit mass were, in fact, rather similar (see § 5-5.3).

Further details of the spatially and temporally resolved data are shown in Fig. 5-24. This data was previously presented in the upper right section of Fig. 5-22. Figure 5-24(a) shows an isometric view of the data in which x-ray emission from the imploding target is presented as a function of space and time. The heavy lines follow the spatial-emission profiles at two selected times, peak-emission time and 80 ps earlier. The two-sided nature of the data at earliest time is identified with laser heating of the shell at its full, uncompressed diameter. At a later time, peak x-ray emission emanates from the center of the imploded target.

Several of these spatial profiles are shown in Fig. 5-24(b) as a function of time. Again, we observe that early-time emission ($\sim 106\text{ ps}$) emanates from the uncompressed shell. The fact that emission peaks are separated by less than the $69\text{-}\mu\text{m}$ initial diameter results from the ringlike intensity pattern of the converging laser light, heating a distributed area of the target surface. X-ray emissions are detected from these curved, emitting polar regions which extend inward from a projection of the outer target diameter. At later times (e.g., $\sim 78\text{ ps}$) x-ray emission increases in intensity and coalesces as the target implodes and stagnates at the target center. Figure 5-24(c) shows temporal profiles for two spatial positions. The $25\text{-}\mu\text{m}$ offcenter trace shows that, as a function of time, peak emission passes twice, once during implosion and once during postcompression target disassembly. This suggests that, in this particular experiment, target "integrity" was maintained throughout the process. Finally, Fig. 5-24(c)

Fig. 5-23. Complementary x-ray microscope and streaked pinhole images are compared for targets of large and small radius. The large-radius ($63 \mu\text{m}$), massive (105 ng) target on the left shows the familiar ring pattern that is associated with steep-density decay in the post-explosion, prestagnation period. The smaller-diameter, lighter target ($67 \mu\text{m}$, 18 ng) on the right does not experience the decreased x-ray emission because it "explodes" earlier in the laser pulse and, because of its smaller radius, does not experience as sharp a decrease of density in the prestagnation period. Although the absorbed energy per unit mass is significantly different for these two cases, the "useful" energies per unit mass are similar because of the earlier jumpoff in the lighter target case. This fact is evidenced by the similar final-implosion velocities of the two cases.

Fig. 5-24. The data from the upper right of Fig. 5-22 is presented in isometric form in (a). Attention is drawn to spatial profiles at two specific times to aid in reading the data. Further, spatial contours are shown in (b) at a variety of times. Also, temporal profiles at two distinct spatial positions are shown in (c).

also shows that emission from the core region began somewhat late, rose rapidly as the implosion proceeded, and decayed with a 58-ps FWHM.

In summary, time-resolved x-ray emission provides significant information regarding the dynamics of exploding pusher targets. Spectral measurements provide time-dependent signatures that we can correlate with gross features of laser and target performance. Time-resolved x-ray imaging provides details of the time-dependent implosion velocity as well as measures of shell acceleration. Because these velocities and accelerations are sensitive to the creation and transport of thermal and suprathermal electrons, their measurement gives us

an insight into the physical processes which dominate the physics of exploding-pusher experiments.

References

26. *Laser Program Annual Report — 1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976).
27. D. R. Attwood, L. W. Coleman, J. T. Larsen, and E. K. Storm, *Phys. Rev. Lett.* **37**, 499 (1976).
28. D. T. Attwood, L. W. Coleman, J. E. Swain, D. W. Phillion, K. R. Manes, D. S. Bailey, and Y. L. Pan, "The Correlation of X-Ray Temporal Signatures, Neutron Yields, and Laser Performance," presented at the 10th European Conference on Laser Interaction with Matter, Palaiseau, France, October 1976; see also Lawrence Livermore Laboratory, Rept. UCRL-78739 (1976).

29. D. T. Attwood, L. W. Coleman, M. J. Boyle, J. T. Larsen, D. W. Phillion, and K. R. Manes, *Phys. Rev. Lett.* **38**, 282 (1977).
30. J. F. Holzhrichter, R. Speck, and J. Swain, *Bull. Am. Phys. Soc.* **19**, 855 (1974).

Authors

D. Attwood
L. Coleman
J. Swain
D. Phillion
K. Manes
M. Boyle
J. Larsen

5-1.4 Janus Postshot Calculations and Analysis

Using the Janus laser confocal elliptical mirror system, we irradiated ball target, 222 (shot 76020904), with about 32.5 J in a 71-ps FWHM pulse. We chose this shot for detailed analysis because its performance is representative and because we have an especially complete data set for it. The target diameter was 87 μm , the shell

thickness was 0.7 μm , and the initial DT gas density was 0.002 g/cm^3 . The target absorbed about 9 J and produced $7.2 \pm 2.4 \times 10^6$ fusion reactions.

Postshot calculations were performed in a two-dimensional geometry (axisymmetric about the laser beam) using the laser ray-trace capability of LASNEX to simulate the energy profile incident upon the target. Calculations were made assuming the mirror focal points at different positions relative to the target center. These calculations assumed that 25% absorption occurred for every ray whose turning point was at a density greater than 75% of critical, and that electron transport was also inhibited by magnetic fields with Bohm diffusion coefficients.

Table 5-4 lists important parameters from the numerical simulation of this experiment. The maximum interface velocity varies as a function of position and time, depending on the local heating and conduction for different portions of the spherical surface. This maximum occurs about 60 ps after peak intensity. DT density and ion temperature are volume-averaged at the peak reaction rate, which occurs at about 100 ps past the laser pulse peak.

Figures 5-25 and 5-26 are taken from the LASNEX simulation and show the development of the implosion. Figure 5-25 shows the position of the Lagrangian mesh at the peak power point of the

Table 5-4. Comparison of important quantities for target 222

	Calculated	Measured
Energy absorbed, J	9.3	9.0 ± 0.5
Maximum interface velocity ^a , $\mu\text{m}/\text{ps}$	0.26	$\sim 0.3^c$
Maximum DT density ^b , $\text{g} \cdot \text{cm}^{-3}$	0.19	—
Maximum DT ion temperature, keV	1.6	$1 - 2^c$
ηr ($r = 18$ ps), $\text{s} \cdot \text{cm}^{-3}$	8.2×10^{11}	—
DT fusion reactions	$5.7 - 8.1 \times 10^6$ ^d	$7.2 \pm 2.4 \times 10^6$

^aAveraged over surface of glass/DT interface.

^bVolume-averaged at peak reaction rate.

^cData obtained from similar shot. Not measured in this shot.

^dVariation in yield is for several different illumination patterns.

Fig. 5-25. Lagrangian grid from the numerical simulation of target 222 shows the development of an asymmetric implosion. The $r = 0$ axis is an axis of symmetry and the $z = 0$ plane is a plane of symmetry; the laser is incident from the right. This "snapshot" is at the peak of the laser pulse; the glass-fuel interface is shown as a darkened line and the critical surface for light absorption is the dashed line. The scale is $60 \times 60 \mu\text{m}$.

Fig. 5-26. The mesh is severely asymmetric at the time of peak reaction rate, 100 ps after the peak of the laser pulse. Most of the reactions occur near the $Z = 0$ plane of symmetry; this is the region of peak DT ion temperature. The scale is $30 \times 30 \mu\text{m}$.

Fig. 5-27. Fuel ion temperature contours at 100 ps after the laser peak. Indicated values are in kV. The glass-fuel interface is the dashed line. The scale is $6 \times 6 \mu\text{m}$.

Fig. 5-28. Fuel density contours corresponding to the imploded geometry of Figs. 5-27 and 5-27. Values are in g/cm^3 ; the scale is $6 \times 6 \mu\text{m}$.

laser pulse. The glass-fuel interface has moved inward about $10\text{ }\mu\text{m}$ at the farthest point. This "dent" is a result of a non-uniform illumination intensity and has a radial velocity of $0.08\text{ }\mu\text{m/ps}$. Figure 5-26 is the mesh at the time of maximum thermonuclear reaction rate, 100 ps after the peak of the laser pulse. The reaction rate depends strongly on the ion temperature, which reaches a peak value of about 2.3 keV in the region near the $Z = 0$ plane. Figure 5-27 is an expansion of the central portion of Fig. 5-26 showing the contour lines for the various ion temperatures; Fig. 5-28 is a similar plot for the density contours. Figure 5-29 shows the velocities at the time of maximum interface velocity. The central portion of the fuel is being compressed in a convergent but aspherical manner.

The x-ray spectrum presented in Fig. 5-30 shows excellent agreement between calculation and experiment. Figures 5-31(a) and (b) are the experimental and calculated x-ray photomicrographs, respectively.

As explained in § 5-1.1 and 5-1.2, one of the important experiments we conducted with the elliptical mirror system was the measurement of the gas-pusher interface history. Two-dimensional LASNEX simulations have also been done for targets 410 (shot 76070805) and 409 (shot 76070906).

Fig. 5-29. At 60 ps following the peak of the laser pulse, the fuel-glass interface reaches maximum velocity. The magnitude of arrow is proportional to the local velocity. The scale is $30 \times 30\text{ }\mu\text{m}$.

Fig. 5-30. Experimental x-ray spectrum (circles) agrees well with the spectrum from the numerical simulation. The portion of the spectrum below 10 keV is produced by the thermal electron distribution from bremsstrahlung and free-bound processes, while the superthermal portion (above 10 keV) arises from bremsstrahlung interactions. The superthermal parameter (α) is 9 for this calculation.

Target 410, a ball with a $69\text{-}\mu\text{m}$ diameter and a $0.44\text{-}\mu\text{m}$ wall, was irradiated symmetrically with 28.2 J in a 64 ps FWHM Gaussian. The numerical simulation was similar to that discussed above for target 222. The focal point of the beams coincided with the target center. Of the incident energy, 5.3 J was absorbed in the calculation; however, based on diffraction theory and the plasma resonance absorption model, about 19% (5.4 J) should be absorbed. The calculated yield was 3.5×10^6 while the measured value was $9.7 \pm 2.6 \times 10^5$. The simulated x-ray streak camera picture (Fig. 5-32) was generated with the LASNEX post-processor code TDG; the interface near the laser beam axis was observed since LASNEX calculations show that the peak x-ray emission comes from the region of the glass near the glass-fuel interface. The trajectory (r - t plot) is also shown in Fig. 5-33, together with a fit to the parabola $r = r_0 - at^2$, which gives an acceleration of approximately $6.3 \times 10^{16}\text{ cm/s}^2$. The acceleration of the interface is approximately constant over most of the implosion.

Fig. 5-31. Experimental (a) and calculated (b) two-dimensional x-ray photomicrographs show good uniformity of laser heating on the outside of the shell. However, the calculated picture shows an asymmetric compressed region.

Fig. 5-32. Computer-simulated x-ray pinhole streak image for target 410 shows the initial target position of $69 \mu\text{m}$. The compressional phase of the implosion is about 65 ps , the time from the peak of the laser pulse until core stagnation. The interface is near the position of the maximum x-ray emission. The calculated maximum velocity is $2.6 \times 10^7 \text{ cm/s}$.

Fig. 5-33. Pusher interface implosion history is described by a constant acceleration model. LASNEX computed points are shown with times relative to the peak of the laser pulse. The solid line is a parabolic fit over the interval $-40 \leq t \leq +40 \text{ ps}$ and gives an acceleration of about $6.3 \times 10^{16} \text{ cm/s}^2$.

Figures 5-34(a) and (b) are traces drawn through Fig. 5-32 along both dimensions. They show x-ray intensity as a function of space at the indicated times and the intensity as a function of time at three spatial positions. (These figures should be compared to the experimental ones in § 5-1.3.) The traces in Fig. 5-34(a) are for times (relative to the laser pulse) of -10, +20, and +65 ps. At $t = -10$ ps the humps at $\pm 34 \mu\text{m}$ show the limb (nose) of the ball being heated by the laser; the rise at $\pm 14 \mu\text{m}$ shows the points of highest emission coming from the "ring" portion of the beam. The trace at +20 ps shows that the denser portion of the nose of the ball has imploded about $11 \mu\text{m}$ to $\pm 23 \mu\text{m}$. At peak reaction time, +65 ps, the wall has moved to a radius of about $13 \mu\text{m}$; the most intense emission at $\pm 5 \mu\text{m}$ comes from that part of the shell driven the hardest by the ring part of the beam, which is not on the limb of the ball as viewed by the streak camera. The three curves of Fig. 5-34(b) are at spatial positions of ± 4 , ± 24 , and $\pm 34 \mu\text{m}$ relative to the target center. The trace through the $34\text{-}\mu\text{m}$ position corresponds to the initial position of the nose of the

target. The most intense emission comes 10 ps after peak laser irradiation. Next, at $24 \mu\text{m}$, the peak emission comes at about +40 ps; and finally at the $4\text{-}\mu\text{m}$ position, the emission is most intense at +70 to 75 ps, corresponding to the stagnation of the shell. The x-ray emission has the highest rate at stagnation time because kinetic energy is being converted into thermal energy, and the hot plasma is relatively motionless for several tens of picoseconds.

Target 409 was similar to 410 except it was irradiated with only one-half the confocal mirror system. The experiment put 15.3 J on the target from the east beam in a 65-ps FWHM pulse. Alignment of the target in the beam was identical to that used for the B-410; hence 19% absorption would give 2.9 J absorbed. The calculated absorbed energy was 3.1 J. Experimental target yields were $1.1 \pm 0.3 \times 10^5$ neutrons; calculated yields were 1.8×10^5 .

The simulated x-ray streak camera picture is shown in Fig. 5-35. The laser was incident only from the right side in this experiment; hence the motion is toward the left. Again the interface is overlaid, verifying that emission comes from the glass near

Fig. 5-34. Intensity traces for target 410, drawn for constant times (a) from Fig. 5-32. In (a), the target's initial position is at $\pm 34 \mu\text{m}$; the indicated traces are taken along the laser/target axis at the times specified relative to the laser pulse. In (b) the traces are in time for the indicated positions along the laser/target axis relative to the target center.

Fig. 5-35. Simulated x-ray pinhole streak picture for target 409 shows the initial illumination from the right and the acceleration of the shell towards the left. The calculated stagnation time is 80 ps after the peak of the laser pulse. The interface motion is parabolic as it was for target 410.

the interface. Peak axial implosion velocity is about 2.8×10^7 cm/s, so the implosion velocity is similar to that of 410. Note the lack of x-ray emission (above 1 keV) outside the illumination region before the peak of the pulse. Since the mean free path of a keV electron in normal density glass is tens of angstroms, and the ratio of the electron speed to the ion speed is about 100, the thermal conduction wave traversing the normal density glass shell will be cooled in less than $10 \mu\text{m}$ by hydrodynamic blowoff to temperatures much less than 1 keV. A much lower temperature thermal wave should traverse the DT, but the x-ray emission will be greatly reduced by the lower Z , temperature, and density. A thermal wave should also propagate around the sphere in a layer of low density blowoff (where the electron mean free path is much longer), but this region will also be cooled by hydrodynamic expansion into the vacuum and by electron conduction into the dense glass shell. Consequently, the x-ray emission above 1 keV will be greatly reduced because of the lower temperature and density. Superthermal electrons

Fig. 5-36. Both the calculated x-ray microscope picture (a) and a similar experimental picture (b) show that the portion of the initial shell not directly illuminated is relatively cold because of the thermal conduction blockage by intense magnetic fields generated near the edge of the laser beam. Each dashed circle has a diameter of $68 \mu\text{m}$. The laser is incident from the right.

with energies of 10 keV or more have much longer mean free paths but will heat matter to much less than 1 keV at distances of tens of micrometres in times of tens of picoseconds (the thermal temperature where the superthermals are generated is only 1 keV). Because of these complex effects, analyzing this experiment requires detailed two-dimensional LASNEX calculations. These calculations have been done with and without conduction inhibition by means of self-generated magnetic fields. Those with inhibition agree fairly well with the x-ray pinhole streak camera data, whereas those without inhibition show too rapid heating of the cold side of the capsule.

Conduction inhibition by magnetic fields can also be tested with the time-integrating, two-dimensional, x-ray microscope image. Figures 5-36(a) and (b) are the calculated image for this one-sided irradiation together with the experimental image from a similar shot (target 420, shot 76072302). The portion of the shell directly illuminated by the laser is clearly visible, while the corresponding portion on the opposite side of the target has not been

heated sufficiently by conduction to radiate any x-ray energy.

In conclusion, the 4π illumination system improves the symmetry of the implosion significantly compared to an f/1 lens system. Direct observation of implosion velocities to an accuracy of better than 20% confirms the existence of a thermal instability impeding the flow of heat into the pusher; one possible mechanism for this inhibition is the electron-ion two-stream instability in the underdense plasma near the critical surface. An alternative explanation is that magnetic fields within the illuminated region of the sphere are generated by resonance absorption. Single-sided experiments have demonstrated the inhibition of lateral heat conduction, possibly due to magnetic fields. Some of these fields can be minimized by a more uniform illumination, which would reduce the thermal conduction inhibition.

Author
J. Larsen

5-2 EXPLODING PUSHER TARGETS: CYCLOPS SYSTEM

5-2.1 Target Design and Simulation

Hyperion exploding-pusher targets were designed to be irradiated by one or two laser beams at the Cyclops laser/target irradiation facility, described in last year's Annual Report.³¹ In designing these targets, 0.7-TW peak power in a 150-ps pulse through two opposing f/2.5 lenses was taken as nominal laser performance.

Preliminary LASNEX calculations indicated the optimal simple target to have approximately the same dimensions as that used on the 1/2-TW Janus facility, namely, 80- μm to 100- μm -diam with 0.4- μm to 0.7- μm wall thickness and 2 mg/cm³ DT gas fill. The study also showed a pulse width of about 30 to 50 ps would be more efficient than one of 100 ps.

Cyclops has more power than Janus, but Janus has faster illumination optics.

The slower illumination optics degrade the target performance for two reasons. First, the absorption fraction is reduced. In these targets the laser light is absorbed mainly by the plasma resonance mechanism; consequently, absorption falls off with angle of incidence for angles greater than about 30-40°. ³²⁻³⁴ The f/2.5 lens produces a more "parallel" beam than the f/1 lens (half-angles of 11.3° vs 24.5°) so that efficient absorption takes place over a smaller fraction of the spherical surface. A preliminary two-dimensional LASNEX calculation was performed to investigate this possibility. An actual target simulation from the f/1 irradiation system was altered only to change the angle of illumination corresponding to the f/2.5 lens; all other target parameters, laser power and width, and

illumination pattern were the same. The calculated results showed that about 15% of the incident light would be absorbed compared to about 25% for the f/1 system. The target was 82 μm in diameter with a 0.6- μm shell, and the laser pulse was 28 J in a 75-ps Gaussian. The Janus f/1 calculation gave about 2×10^6 DT fusion events, in agreement with experiment, while the Cyclops f/2.5 calculation predicted about 2×10^5 events. However, since Cyclops can put much higher power on target (about 0.7 TW), the predicted neutron yield is approximately the same as on Janus.

Second, because efficient absorption occurs over a smaller fraction of the spherical surface, much poorer heating and implosion symmetry will result. Particularly because of the poor absorption efficiency near the equatorial plane of the target, the waist will be poorly imploded. The overall compressed state will be more oblate than that produced by the Janus system, and this will degrade the target's yield.

LASNEX calculations were also used to investigate the effect on target performance of focal zoom at high peak laser powers.³⁵ The zoom is proportional to the accumulated nonlinear index of refraction and the square of the f-number. We expect a focal shift of approximately 100 μm during the course of the Cyclops laser pulse. Consequently, an initial focal spot the size of the target would shrink to about one-half that size at peak power. However, LASNEX calculations predict that the effect of Cyclops zoom on neutron yield will be very small if the beam is focused so that the focal spot size is equal to the target diameter at maximum power.

Target design calculations for an 85- μm -diam target with a 0.6- μm shell thickness was performed in two dimensions. When we assumed 70 and 100 J in a 100-ps pulse width (using 15% absorption), LASNEX predicted about 2×10^6 and 6×10^6 DT reactions, respectively.

References

31. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), p. 30; *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), pp. 69, 386.
32. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975).
33. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p. 30.
34. J. H. Erkkila, *Laser Light Scattering and Absorption in Dense Spherically Symmetric Plasmas*, Ph.D. thesis, Lawrence Livermore Laboratory, Rept. UCRL-50014 (1975).
35. See Ref. 33, p. 325.

Author
J. Larsen

5-2.2 Experimental Results

The Cyclops laser system was the test bed on which, among other things, the behavior of high-power vacuum spatial filters was first studied.³⁶ As indicated in Section 3, the transmission of the vacuum spatial filter located midway in the Cyclops chain can be approximated by $T \approx [1 - 1/3(B/B_c)^2]$, where B is the instantaneous nonlinear phase retardation accumulated along the path from the input spatial filter to the vacuum spatial filter.³⁷ The value of B for which peak transmitted power is obtained, B_c , was found to be approximately equal to 2.3 rad. The single vacuum spatial filter was located such that half of the nonlinear phase distortion occurred before and half after the filter on a high power shot. For total laser powers greater than 0.35 TW, some beam breakup occurred in the "C" amplifiers after the beam had been spatially filtered; thus not all of the system output energy was focusable on a fusion size target. Since this developmental staging was also used for target studies, Cyclops had a maximum attainable output power of 0.9 TW, of which approximately 0.6 TW was focusable on a small target for single-sided illuminations and only about 0.4 TW was focusable for two-sided illuminations.

To measure the useful focusable fraction directly, three 140- μm pinhole targets, as shown in Fig. 5-37, were irradiated with varying intensities. As in the spatial filter case, small-scale self-focusing structure and hole closure limit the transmission of the pinhole. Figure 5-38 is a plot of the pinhole transmission measured on these shots. Since similar physical effects are involved, it is not surprising that a transmission curve inferred from Fig. 5-38 resembles that shown in § 3-1.2. The pinhole targets in the focus of the Cyclops f/2.5 lenses have $d/f = 280 \mu\text{rad}$. Assuming that the beam quality at the target chamber is similar to that at the vacuum spatial

Fig. 5-37. (a) 140- μm pinhole target; (b) TV display of pinhole 141 μm in diameter; (c) beam at the pinhole plane 500 μm from best focus; (d) beam profile at pinhole.

Fig. 5-38. Pinhole target transmission using 65-ps incident pulses.

filter input, B_c may be estimated from $B_c \approx 132\sqrt{d/f}$, being approximately equal to 2.2 rad. The additional nonlinear phase retardation, ΔB , accumulated between the vacuum spatial filter and the target is about 5 P where P is in terawatts, and this is confirmed by focal plane zoom observations. By assuming a Gaussian temporal and parabolic spatial pulse shape, we can estimate the pinhole transmission at about $(1 - 0.48 P^2)$. The distortion of the pulse shape by the vacuum spatial filter and the location of the pinhole away from the best focus both tend to make this an overestimate of the transmitted fraction. Photodiodes and calorimeters arrayed around these targets permitted us to measure the power scattered forward beyond the pinhole including that refracted out of the 0.12-sr solid angle of the output lens. These data, plotted in Fig. 5-38, show the importance of refraction and pinhole closure on pinhole performance. This curve also represents the net power that could reach a small target. We used 65-ps pulses for these shots, and certainly this curve depends on pulse duration; however, the targets irradiated by Cyclops generally behaved as though they were illuminated by not more than 0.5 to 0.6 TW.

Both one- and two-sided target experiments using spherical shells and ball-on-plate type targets were conducted at the Cyclops laser facility. Both of these were previously used on Janus.³⁹ Target shot 56020501, while not the highest yield spherical microshell target, is a good example of the data accumulated. The super-Gaussian apodizing aperture was installed for this shot so the ring structure in the Cyclops beam was pronounced. The target was placed approximately 400 μm from the plane of best focus on both sides.⁴⁰ The whole beam self-focusing induced focal zoom was about 100 μm . The equivalent plane-beam profile in Fig. 5-39 shows that there was substantial beam breakup on this 0.4-TW shot.

The target itself had a diameter of 85.3 μm with an 0.80- μm wall thickness. It was filled with 2 mg/cm³ of equimolar DT gas. The total energy on target, 32.7 J was divided equally between the two beams. The target absorbed only 4 ± 1 J or about 12% of the incident energy. Because of this relatively low absorption, the target yielded only $6.8 \pm 1.7 \times 10^5$ neutrons. This low absorption efficiency on spherical targets was typical of the Cyclops f/2.5 focusing system as shown in Fig. 5-40. The 1.06- μm light, which was not absorbed by this target, was monitored by an array of filtered photodiodes. Although the intensity distribution on this target shown by the equivalent plane camera reveals no evidence of polarization asymmetry, Fig. 5-41 demonstrates the increase in scattering perpendicular to the plane of polarization. Such measurements are suggestive of resonance absorption, Brillouin sidescatter, or both. The incident beam's intensity distribution is reproduced in Fig. 5-42(a) to the same scale as the x-ray micrographs shown in Figs. 5-42(b) and (c). Figure 5-42(b) was made by an x-ray microscope located above an input beam looking down on the target and suggests that x-ray emission, and thus heating, was increased in the plane of polarization. The hot compressed core, where the glass pusher stagnated and radiated, is noticeably elliptical in this view; however, this can be attributed to the viewing angle. Figure 5-42(c) shows the same event as seen by a second x-ray microscope located at 90° to the input beams. This target was viewed from still another angle by a zone-plate coded aperture described in Section 3. Data were also taken by ion and x-ray spectrometers, and a representative sampling is displayed in Figs. 5-43(a) through (c). These spectra

Fig. 5-39. Densitometered equivalent-plane multiple image and streak camera images provide our best information on the irradiation history of the target. The time-integrated photograph shows that the beam was highly structured, and the streak camera shows that the focal plane moved during the pulse and that small-scale self-focusing removed energy from the beam at the peak of the pulse.

Fig. 5-40. Energy absorbed by the spherical microshell plasma is plotted versus incident energy. While the incident energy is known accurately, there is generally substantial uncertainty in the absorbed energy measurements made with photodiode arrays due to polarization-dependent scattering.

Fig. 5-41. Polarization-dependent scattering is clearly evident in this photodiode array data.³⁸

Fig. 6-42. Although the incident beam had no polarization dependent asymmetry (a), an x-ray microscope positioned 45° above an incident beam saw polarization-dependent heating (b), a second x-ray microscope placed 90° to the beam produced the image displayed in (c).

Fig. 6-43. Experimental data from shot 56020501: (a) X-ray spectrum from the shot, (b) Subkilovolt x-ray spectrum from the shot produced by Koppel's Pb-stearate spectrometer, (c) Ion-distribution function produced by an unfolding of Faraday cup signals obtained from the shot. Two representative angles, $\theta = 90^\circ$ and $\theta = 150^\circ$ from the west beam are shown.

Fig. 5-44. Accumulated one-sided irradiations are compared to LASNEX calculations, assuming 20% and 40% absorption.

Fig. E-45. Accumulated two-sided irradiations are compared to LASNEX calculations, assuming 20% and 40% absorption.

Fig. 5-45. By plotting neutron yield vs peak power into the vacuum spatial filter, the decline of target performance may be related to the decline in beam quality.

may be compared to LASNEX calculation discussed in § 5-1.4.

The accumulated neutron-yield data for one-sided ball-on-plate type targets on both Janus and Cyclops are plotted in Fig. 5-44 with 40% and 20%

Fig. 5-47. Neutron yield increases with increasing x-ray flux from the compressed core region into the 2.5-keV x-ray microscope channel.

absorption curves provided by LASNEX simulations.³⁹ The variation in pulse duration, pulse shape, and focal zoom account for the scatter in the data. One point is included from recent data taken on the Argus laser. This result supports the conclusion that the fall-off in neutron yield results from the increasing degradation of beam quality of high power Cyclops shots. Similarly, Fig. 5-45 shows the accumulated neutron-yield data from two-sided ball-in-plate type irradiations. The measured yield is independent of output laser power above about 0.4 TW. The maximum yield from a similar target irradiation by the Janus facility is shown for comparison. The increased beam breakup observed during two-beam operation of Cyclops probably accounts for the "saturation" of the neutron yield curve.

Figure 5-46 shows the neutron yield for two-sided irradiations as a function of the power input to the Cyclops vacuum spatial filter. The decline in neutron yield above an input power of 130 GW is clear evidence for beam breakup. Finally, Fig. 5-47 shows the correlation between neutron yield from these targets and x-ray intensity in the 2.5-keV x-ray microscope channel. This correlation is evidence that, as might be expected, the neutron yield is sensitive to temperature indicated by x-ray yield. These data, and others accumulated by Argus, convince us that the Cyclops target's insensitivity to laser output power results from poor beam quality and not from target design.

References

36. *Laser Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), pp. 169-174.
37. F. Rainer, Section 3 in this annual report.
38. D. W. Phillion and S. R. Gunn, Section 3 in this annual report.
39. *Laser Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), pp. 462-474.
40. *Ibid*, pp. 486-389.

Author

K. R. Manes

Major Contributors

H. Ahlstrom

E. Bliss

M. Boyle

K. Brooks

L. Koppel

H. Kornblum

D. Phillion

F. Rainer

V. Rupert

5-2.3 Cyclops Postshot Calculations and Analysis

A numerical simulation is presented here of one of the many Hyperion targets successfully tested with the Cyclops laser facility. Target 217 (shot 56020501) was placed between the two beams from opposing $f/2.5$ lenses. This particular experiment is of interest because of the unique diagnostic equipment employed; two x-ray microscopes were viewing the target in addition to an x-ray imaging zone-plate experiment. One microscope (hereafter called "A") was placed orthogonal to the laser beam axis and at 90° to the plane of incident polarization. The second (called "B") was in the plane of polarization at 45° to the beam axis. The zone plate experiment was placed at 45° to the plane of polarization and normal to the laser axis. The combination of orthogonal microscopes permits the viewing of the laser-heated region of the spherical target and may allow the direct observation of the local heating by resonance absorption.

Additionally, as outlined in the target design section, the target's performance (absorption, yield, etc.) was to be measured for the slower illumination optics and the increased peak laser power. As was mentioned in the experimental section above, there

was some limitation to the available peak power that could be focused on the target. This experiment had 32.6 J from the laser chain, and the input streak camera gave a pulse width of 46 ps for a peak power of 0.71 TW. However, the output streak camera showed temporal beam breakup, and thus the peak power delivered to the target was about 0.42 TW corresponding to a 75 ps FWHM. Figure 5-48 shows this temporal behavior of laser power; this pulse behavior was used in the two-dimensional LASNEX calculation reported here.

The target ball parameters were $85.3 \mu\text{m}$ in diam with a $0.8 \mu\text{m}$ shell thickness and 0.002 g/cm^3 DT gas fill. The laser beam radial profile (assumed constant over the duration of the pulse) was a moderate (2:1) ring with the outer half-intensity point of the ring placed at the limb of the target. The choice of beam profile and placement was based on earlier studies of the effect of zoom on the implosion dynamics, and is a compromise of the experimental initial positioning of the incident beams and the effect of zoom. Explicit zoom was not performed in this calculation since there were other uncertainties that played a larger effect on the implosion; these uncertainties were the radial beam profile at the

Fig. 5-48. Temporal behavior of the incident laser pulse is not that of a simple Gaussian. Because of the effects of distortion at high powers, the pulse is effectively clipped to a peak value of about one-half. The target sees a pulse of the same energy but of longer duration and hence lower peak power.

target and the effect of a highly nonaxially symmetric laser beam with large local intensity fluctuations. Examination of the available beam diagnostics, both spatial and temporal, showed these characteristics to be severe.

The calculation was performed in the "ZSYM" mode with the laser pulse of Fig. 5-48; of the 32.7 J incident, 4.64 J were absorbed for 14% absorption. This figure is in agreement with the estimates made in the design calculation section above. Of the 4.64 J absorbed, about 0.13 J was by inverse bremsstrahlung. The experimental total absorption was 4 J for 12%. Figure 5-49 shows the Lagrangian mesh at the middle of the laser pulse, which is reference time 0. Clearly the effects of the f/2.5 lens together with the toroidal-shaped laser beam are seen in the asymmetry of the blowoff and the implosion.

Figure 5-50 shows the mesh at the time of peak reaction rate, $T = +80$ ps. The interface between the fuel and the pusher has been severely distorted by the jet coming from the part of the shell originally illuminated by the ring portion of the beam. Figure 5-51 shows the ion temperature isotherms in the fuel at the same time; these show

Fig. 5-50. At maximum reaction rate, $T = +80$ ps, the compressed fuel has a near toroidal shape resulting from the jet introduced by the ring portion of the laser beam. The pusher-fuel interface is shown. Scale: $30 \times 30 \mu\text{m}$.

Fig. 5-49. Lagrangian mesh shows some distortion at the middle of the laser pulse. The solid line shows the glass pusher-DT fuel interface, and the dashed line shows the critical surface for laser light. The laser is incident from the right. The $Z = 0$ plane is a plane of symmetry, and the $R = 0$ axis is an axis of symmetry. Scale: $60 \times 60 \mu\text{m}$.

Fig. 5-51. DT ion isotherms (in keV) follow the contour of the glass shell. The majority of the reactions take place at the position of maximum intrusion of the jet. Peak reaction time is at $+80$ ps. This figure is an expansion of Fig. 5-50. Scale: $Z = 7.5 \mu\text{m}$, $R = 15.0 \mu\text{m}$.

Fig. 5-52. Calculated scattered-light distribution agrees well with the average of the distribution in the plane of incidence (indicated by $\circ$) and that out of the plane (points with $\square$). The difference in the scattered intensities for the two polarizations are interpreted as a consequence of resonance absorption and possibly the sidescatter instability. The two beams were incident at $\theta = 0^\circ$ and 180° .

that the majority of the reactions take place just ahead of the jet where the temperature is the greatest. Experimental measurement gave a DT reaction number of $6.8 \pm 1.7 \times 10^5$ and the calculated value is 2.1×10^5 . This discrepancy of a factor of 3 can easily be reconciled by slight changes in the initial illumination pattern, either by the radial profile or the temporal behavior (zoom) or the positioning of the focal point relative to the target center.

Figure 5-52 is the experimental and calculated scattered light distribution. The calculation is symmetric about $\cos \theta = 0.0$, and the data is also approximately symmetric indicating both laser beams behaved in a similar fashion. An average value between the data points in the plane and out of the plane of incidence is in good agreement with the calculation ($\approx 1.25 - 1.5$ J/sr). The absorption model for these calculations is that for the rays that approach to within $1/2$ of the critical density, 40% of the power is absorbed through the instabilities.

One of the most important diagnostics is the x-ray spectrum above 2.5 keV. The calculation and experimental points are shown in Fig. 5-53. Agreement is excellent when considering the data has a large uncertainty. Again, the characteristic two-temperature distribution is seen and is related to the

Fig. 5-53. X-ray spectrum above 2.5 keV shows the typical two-component behavior of laser-heated plasmas. The uncertainty in the data points is about 50%. The calculation (solid line) was performed with $\alpha = 9$.

thermal and superthermal electron distributions of the laser-heated plasma. The superthermal parameter (α) used in the calculation was 9. Figure 5-54 shows the x-ray spectrum for the region $0.3 \leq h\nu \leq 1.0$ keV. The divergence between experiment and calculation below 500 eV may be the effect of instrumental attenuation for low energy x-rays. Some of the other calculated quantities are listed in Table 5-5.

We turn now to the comparison of the two x-ray micrographs and the corresponding calculations. As was mentioned, the orthogonal x-ray microscopes might allow one to see the localized heating from the resonance absorption process. Camera A views the target from a position perpendicular to the laser beams and to the plane of polarization. Figure 5-55 is the experimental image for the x-ray region between 1 and 1-1/2 keV from camera A. The two lobes show the initial illumination of the shell by the opposing f/2.5 beams in addition to the stagnation region of the compressed glass. The plane of polarization of the laser is in the page. The image is time integrated and also spatially integrated along the line of sight since the plasma is optically thin in this x-ray region. For camera B, which is in the plane of polarization, the image is somewhat different. Figure 5-56 is the experimental image in the subkeV region; the polarization vector is in the vertical direction and out of the page at about 45°.

Fig. 5-54. SubkeV x-ray spectrum as predicted by LASNEX is in reasonable agreement with experiment to about 1/2 keV. The discrepancy at the lower end of the spectrum may be from an attenuation in the diagnostic instrument.

Table 5-5. A comparison of some calculated and measured quantities for target B217 (shot 56020501)

	Calculated	Measured
Absorbed energy, J	4.6 14%	~4 12%
Fusion reactions	2.1×10^5	$6.8 \pm 1.7 \times 10^5$
Peak average interface velocity, $\mu\text{m/ps}$	0.24	not measured
Ion temperature ^a , keV	0.77	not measured
Fuel density ^a , $\text{g} \cdot \text{cm}^{-3}$	0.02	not measured
$n\tau$, $\text{s} \cdot \text{cm}^{-3}$	3.0×10^{11}	not measured
X-ray emission, J	0.5	not measured

^aAt maximum thermonuclear reaction rate, averaged over the DT volume.

Fig. 5-55. X-ray microscope picture normal to the laser axis shows the heating of the 85- μ m-diam shell in its approximate initial position by the laser and the stagnation region at the time of maximum compression. The two opposing beams are from the right and left with the plane of polarization in the plane of the paper.

Fig. 5-56. The x-ray micrograph taken in the plane of incidence shows the stagnation region superimposed on two uniformly emitting regions of the initial sphere. The polarization vector is vertical and out of the paper at about 45° .

Fig. 5-57. Calculated x-ray spatial emission for camera A shows the initial shell illumination and the emission from the stagnation of the pusher. The polarization plane is that of the paper.

Fig. 5-58. Calculated x-ray emission pattern for the 45° position using the LASNEX uniform heating model has general features in agreement with the experiment of Fig. 5-56. There is no direct x-ray pictorial evidence for polarization dependent absorption.

The numerically simulated x-ray pictures are Figs. 5-57 and 5-58. Figure 5-57 shows the two lobes of emission where the laser heated the shell in its approximately initial position and the central emission from the core stagnation. The results are in qualitative agreement with those of Fig. 5-55; namely, there is nearly uniform heating (top and bottom) in the plane of incidence. Although there is a left and right difference because of the imbalance in the laser beams energies. Figure 5-58 is the simulation for the 45° picture, camera B. There is a superposition of the initial shell heating with that of the core stagnation, as is also observed in Fig. 5-56; hence, the points of interest must be away from this central region. By observing the emission contours near the left and right edges of the figures, one sees a similar pattern corresponding to a uniform heating perpendicular to the plane of incidence. LASNEX does not have the direct capability for polarization dependent absorption; therefore uniform heating within the illuminated area is calculated and this agrees well with the experimental observation.

The lack of a detectable laser polarization-dependent x-ray emission does not preclude resonance absorption as the dominant absorption

mechanism in this experiment. The x-ray emission comes from a region of the shell about 10 to 20 μm inward from the laser absorption critical surface. The effects of electron conduction tend to smooth any spatial variations while transporting the thermal energy from the critical region into the pusher. This fact, together with the line-of-sight integration (because of the optically thin plasma) and the time integration of the film for several nanoseconds over which there is x-ray emission, makes the observation of local heating very difficult.

In summary, the LASNEX calculation agrees well with most aspects of this experiment. The reduced absorption fraction is consistent with the predictions using the angle-dependent resonance-absorption model. The reaction yield is in reasonable agreement, and the difference is easily explainable in slight modifications to the laser source used in the calculations. The several x-ray diagnostics agree well, and the micrographs show uniform heating within the illuminated region, both in the plane of incidence and normal to it.

Author
J. Larsen

5-3 EXPLODING PUSHER TARGETS: ARGUS SYSTEM

5-3.1 Target Design and Simulation

Using the exploding-pusher LASNEX parameter study presented in the target section of this report, we can select the optimal target ball parameters for the 2-TW Argus laser facility. Calculated neutron yields for spherically symmetric implosions with various target diameters/shell thicknesses and pulse widths are summarized in Table 5-6.

The diameter of the target ball is not a sensitive parameter, except for the 1.0- μm -thick shell at long pulse lengths, nor is wall thickness sensitivity as great as at the one-half terawatt level. The 2D simulation, which accounted for laser nonuniformities and implosion asymmetries, suggests

degradation of a factor of 5 to 10 from the 1D calculations for the larger-diameter capsules. Thus, the preferred diameter should be the smaller of the acceptable values to take advantage of conduction smoothing in making the implosion more symmetric.

LASNEX calculations indicate that maximum compressions of about a hundredfold can be expected with peak DT ion temperatures of 6 to 8 keV. The density-radius integral for the imploded glass product will be about the same as for the Janus experiments, about $4 \times 10^{-4} \text{ g/cm}^2$. Consequently, the alpha-particle spectrum will suffer the same energy loss (about 250 keV) as that observed with Janus. (The glass temperature is somewhat higher, but in this temperature range (less than 1 keV) the

Table 5-6. Diameter (in μm) and maximum fusion yield (number of DT reactions) for various wall thicknesses and pulse widths, peak laser power of 2.0 TW

Target shell thickness (μm)	Laser pulse width (ps)		
	30	65	100
0.4	120 μm	170 μm	220 μm
	4×10^9	2×10^9	2×10^9
0.7	100 μm	130 μm	160 μm
	4×10^9	3×10^9	2×10^9
1.0	80 μm	100 μm	120 μm
	2×10^9	2×10^9	8×10^8

effect on the alpha range is small.) The density-confinement time ($\eta\tau$) will be almost 10^{12} .

In summary, exploding-pusher targets used with Argus will behave much as they did with Janus except for the increased fuel-ion temperature and hence increased reaction rate and neutron yield. The increased temperature results from the higher absorbed laser energy (still 20 to 25% of the incident energy) driving the pusher to a higher peak implosion velocity, around 4 to 7×10^7 cm/s.

Author
R. Thiessen

5-3.2 Experimental Results

Argus became operational as a laser fusion experimental facility in June 1976. The first target experiments were performed at the 1-TW level using the north beam only. The south beam became operational in July. Since that time, the laser performance has increased to the point where target experiments have been executed at power levels exceeding 2 TW per beam. In December 1976 we obtained a record 2.8 TW of focusable power from the north beam. The development of the laser and the

methods used to obtain this power level are described in detail in Sections 2 and 3. We performed a total of 91 target experiments on Argus during 1976. This rather small number of target shots was primarily caused by the fact that a significant portion of the Argus operation was devoted to understanding and improving the laser performance. (This is also covered in detail in Section 3.)

Most of the target shots were performed at the 2.0- to 3.5-TW level using both beams. Figure 5-59 shows an example of the laser performance on such a shot in which the north beam produced 1.7 TW of focusable power. The target was a complex Hyperion-type exploding pusher target and produced about 1.5×10^9 neutrons. The term focusable signifies that at the target plane there is no noticeable distortion of the temporal pulse shape and that greater than 90% of the energy lies within the low power focal region. During each experiment, a streak camera, extensive calorimetry, and multiple image cameras record the spatial and temporal laser energy and power distribution in the target plane using an equivalent plane imaging system as described in Section 3.

During the early series of experiments in June, neutron yields in excess of 6×10^7 from Hyperion-type targets were achieved. This was a fivefold increase over similar experiments performed on the Cyclops and Janus lasers at the 0.4- to 0.7-TW level (Ref. 41 and § 5-2.2). Performing two-beam experiments at power levels exceeding 2 TW per beam, DT-filled glass microspheres have been imploded in the exploding pusher target mode to produce thermonuclear neutron yields in excess of 1.5×10^9 per event, implying a DT burn efficiency of 1.6×10^{-5} . Figure 5-60 shows an example of some of the neutron yields obtained, plotted as a function of the incident focusable power. In these experiments, the neutron-yield scaling rule with power is not immediately apparent. This is because a simple scaling rule such as $N \sim P^n$ fails to take into account the complex interaction of the target diameter, wall thickness, and the pulse length. Figure 5-61 shows a different way of displaying the data. Here we plot neutron yield vs total absorbed energy per unit target mass. The neutron yield is also normalized by $(w/w_0)^{2/3}$ and $(r_0/r_*)^{10/3}$ where w_0 and r_* are the nominal wall thickness (0.8 μm) and radius (42.5 μm), respectively. The scaling of neutron yield with $r^{10/3} w^{2/3} (\sigma v) T^{-1/2}$ is discussed in Section 4 and § 5-5.3. Assuming T (the DT ion temperature) to be

Fig. 5-59. Target plane energy distribution for Argus north beam.

proportional to the total specific absorbed energy, produces the solid curve in Fig. 5-61. Although this is clearly a more appropriate way to plot the data, there are still a few points that deviate significantly from the otherwise obvious trend. These data are from target experiments with a total absorbed energy and pulse length that was not optimally matched to the target diameter and thickness. The concept of useful specific energy and a further comparison of experiments at different power and energy levels is discussed in some detail in § 5-5.1 and 5-5.3.

DT ion temperatures of up to 8 keV were measured in the Argus Hyperion experiments. The

final fuel-averaged DT ion temperature was inferred from neutron⁴² and α -particle⁴³ time-of-flight measurements. See Section 3 for a detailed description of the equipment and the diagnostic techniques. Figure 5-62 gives an example of the neutron and α -particle time-of-flight signals and the reduced data from a typical experiment. Table 5-7 lists some of the neutron time-of-flight data for Hyperion type targets, and Table 5-8 lists some of the latest α -particle time-of-flight data, for shots in excess of 3 TW.

In part to explore the symmetry of the compressions, the α -particle flux was monitored in two directions to give an estimate of the uniformity of

Fig. 5-60. Neutron yield vs peak input power for Hyperion targets on the Argus laser.

the compressed DT and SiO_2 pusher. The two detectors were at 45° and 90° from the north focusing lens, in the horizontal plane. Figures 5-63(a) and (b) give an example of the reduced data from an Hyperion target shot. Both the total yield and the α -particle energy loss from the two detectors agree to better than $\pm 11\%$.

Experiments were also performed where the targets were filled with a mixture of D_2 and ^3He . The measured protons from the $\text{D} + \text{D} \rightarrow \text{p} + \text{T}$ and $\text{D} + ^3\text{He} \rightarrow \text{p} + \alpha$ demonstrated the first laboratory

measurement of the thermonuclear burn of D^3He . The measured ratio of the D-D to D^3He protons implied that the Hyperion target was imploded to thermonuclear temperatures of 6 keV. Figure 5-64 summarizes the results from a typical shot. These measurements and the comparisons of experiments with calculations are discussed in detail in § 5-5.1 through 5-5.3.

Using a peak fuel-averaged DT ion temperature of 8 keV and a neutron yield of 1.6×10^9 starting from an initial fill of $2 \text{ mg}/\text{cm}^3$ DT, we can

calculate that a DT burn efficiency of 1.6×10^{-5} , a DT gain of about 10^{-2} , and a density confinement-time product ($n\tau$) of about 10^{12} were achieved.

In addition to monitoring the thermonuclear reaction products, an extensive array of diagnostics routinely monitored the laser target interaction process and the laser performance. Table 5-9 gives a listing of the diagnostics equipment and measurements that are performed routinely on practically every target experiment. Figure 5-65 gives an example of the time and space integrated continuum x-ray spectrum above 2.5 keV and compares it with a typical shot on the Janus facility at about 0.4 TW. Both are for Hyperion-type DT-filled glass microshell targets with a diameter of about 80 μm . We note that the slope of the superthermal tail, $O_{II}(h\nu > 10 \text{ keV})$, scales with the incident power to about 0.40, in reasonable agreement with results quoted in Refs. 44 and 45. We also note an increase in the "temperature" one can assign to the thermal portion of the spectrum, from about 0.75 to about 1 keV. Figure 5-66 shows an example of the space- and time-integrated x-ray spectrum for a typical 4-TW shot, including the subkilovolt region. Figure 5-67 shows the time-integrated x-ray microscope image in the 1.5-keV region for an 80- μm -diam Hyperion target irradiated with 0.4 and 2 TW, respectively. This figure dramatically demonstrates one of the effects of increased power on target performance. The image on the left shows the typical lack of uniform heating associated with the experiments on Janus at about 0.4 TW. On the right we see the same size target from a 2-TW Argus experiment. Both use f/1 focusing lenses. The sixfold increase in intensity at the target surface is thought to be responsible for allowing thermal conduction by electrons to achieve the resulting uniform heating. This result was also noted at the 0.4-TW level on Janus by using 40- μm -diam targets with the f/1 lenses, and during the spherical illumination experiments by varying the incident energy for identical target parameters. These effects are also discussed in detail in § 5-1.2 and 5-5.1 and in Refs. 41, 46, and 47.

Measurements of the scattered 1.06- μm light distribution and the x-ray and asymptotic plasma blow-off has given further evidence for the existence and importance of nonclassical absorption mechanisms. Simultaneous measurements of the polarization dependence of the scattered light and plasma blow-off distributions is highly suggestive of

Fig. 5-61. Neutron yield normalized with radius and wall thickness vs total specific absorbed energy.

resonance absorption. (Measurements performed on the Janus laser in March 1977 demonstrates conclusively that polarization and angle-dependent absorption, consistent with resonance absorption, operates at power levels of 10^{15} W/cm^2). Figure 5-68 shows an example of such a measurement on an 80- μm -diam SiO_2 Hyperion target on Argus. These results are discussed in detail in Section 3, § 5-3.2 and 5-3.4, and Refs. 48 and 49. From the spatial distribution of scattered 1.06- μm light, the x-ray and plasma energy measurements of the absorbed energy can be obtained. Using the plasma calorimeters, we obtain an average absorbed energy of $22 \pm 4\%$ for 80- μm SiO_2 shells illuminated with 1 to 3 TW. Using the scattered 1.06- μm data obtained using Si PIN diodes, the absorption is $21 \pm 4\%$. This is to be compared with an absorption of $27 \pm 3\%$ obtained with f/1 lenses on Janus at the 0.4-TW level using the same size targets.

Table 5-7. Summary of neutron TOF experimental results for Hyperion targets

Shot	Neutron yields ($\times 10^8$)			Detected neutrons	$\langle t \rangle$ (ns)	Δt (ns)	$\langle E \rangle$ (MeV)	ΔE (keV)	T_{ion} (keV)
	Fluor	Copper	TOF						
36100115	10.2 ± 2.1	13.0 ± 1.8	15.3 ± 1.3	650	872.1 ± 3	15.7 ± 1.1	13.94 ± 0.10	497 ± 40	7.9 ± 1.3
36100116	13.7 ± 2.8	17.6 ± 2.0	18.5 ± 1.3	900	873.7 ± 5	15.4 ± 1.3	13.89 ± 0.17	486 ± 45	7.5 ± 1.5
36100712	6.3 ± 1.7	7.1 ± 1.0	6.7 ± 0.8	350	870.5 ± 3	13.3 ± 1.2	14.00 ± 0.10	421 ± 40	5.7 ± 1.2
36100812	5.6 ± 1.1	7.1 ± 1.0	6.9 ± 0.8	350	871.2 ± 3	14.8 ± 1.1	13.97 ± 0.10	463 ± 40	6.8 ± 1.2
36101202	3.0 ± 0.7	3.3 ± 0.5	3.1 ± 0.5	150	870.0 ± 3	11.7 ± 1.2	14.00 ± 0.10	382 ± 40	4.7 ± 1.1
36101203	3.5 ± 0.7	4.4 ± 0.6	3.9 ± 0.6	200	870.0 ± 3	13.8 ± 1.2	14.00 ± 0.10	430 ± 40	5.9 ± 1.2
36101204	4.0 ± 0.9	4.6 ± 0.6	5.1 ± 0.6	200	870.4 ± 3	14.7 ± 1.3	14.00 ± 0.10	472 ± 45	7.1 ± 1.4
36111107	6.2 ± 1.2	5.8 ± 0.8	4.6 ± 0.6	300	872.1 ± 3	12.8 ± 1.3	13.94 ± 0.10	411 ± 45	5.4 ± 1.3
36111110	9.2 ± 1.8	9.3 ± 1.2	7.3 ± 0.8	450	870.3 ± 3	14.4 ± 1.3	14.00 ± 0.10	460 ± 45	6.8 ± 1.4
36120806	3.5 ± 0.6	3.8 ± 0.5	3.8 ± 0.6	200	870.0 ± 3	14.1 ± 1.3	14.02 ± 0.10	451 ± 45	6.5 ± 1.4
36120906	14.0 ± 3.0	16.1 ± 2.0	14.9 ± 1.2	750	869.0 ± 3	14.9 ± 1.2	14.03 ± 0.10	482 ± 40	7.4 ± 1.3
36120910	7.1 ± 1.4	8.9 ± 1.4	9.2 ± 1.0	450	871.0 ± 3	15.7 ± 1.2	13.98 ± 0.10	510 ± 40	8.3 ± 1.4
36120911	9.3 ± 1.8	10.8 ± 1.4	11.0 ± 1.0	550	868.4 ± 3	16.1 ± 1.2	14.06 ± 0.10	518 ± 40	8.6 ± 1.4

Neutrons

$$E_{\text{peak}} = 14.07 \text{ MeV}$$

$$\Delta E = 423 \text{ keV}$$

$$\Rightarrow T_i \leq 5.7 \text{ keV}$$

346 neutrons reacting with detector

α particles

$$E_{\text{peak}} = 3.4 \text{ MeV}$$

$$\Delta E = 460 \text{ keV}$$

$$\Rightarrow T_i \leq 6.7 \text{ keV}$$

405 α 's reacting with detector

Shot: 36092208

Fig. 5-62. Neutron and α time-of-flight measurements determine the fuel temperature.

Time-resolved, ion-plasma blow-off measurements have been made using a wide-band ion spectrometer (Section 3, and Refs. 48 and 50). The data indicated that the fast-ion group (velocity $\lesssim 10^9$ cm/s), seen in earlier Faraday cup measurements on SiO_2 shell targets, were high energy (about 0.5 to 2 MeV) protons, presumably from the hydrocarbons in the glue joint holding the ball to the stalk. Since protons have an A/Z of 1, earlier estimates of the energy carried away by the "fast ions" may have been high by as much as a factor of 2. Figure 5-69(a) shows the oscilloscope output trace from the wide-

band spectrometer on a 80- μm -diam SiO_2 DT-filled Hyperion target. Measurements made with the spectrometer in a narrow-band mode (see Section 3) to identify the species and charge state as a function of time, seem to indicate that the signal for times less than or equal to 175 ns, or to the left of the arrow, are protons. Figure 5-69(b) shows the resulting energy seen by the spectrometer on this shot as a function of time. We observe that for times less than 175 ns, the protons have carried away, or accounted for, about 25 to 30% of the absorbed energy.

Table 5-8. Experimental results of α -particle spectrometer

Shot No.	Laser power (TW)	System	Target parameters		α -yield		E_{av} (MeV)	FWHM (keV)	T_{ion}^c (keV)
			Diam (μM)	Fill (mg/cm^3)	At detector	At target ($\times 10^8$)			
36120702	3.0	P (90°) ^a	107	1.71	220 ± 15	2.8 ± 0.6	3.30	415	5.5
36120703	3.2	P	147	1.87	370 ± 20	4.7 ± 0.9	3.17	415	5.5
36120910	3.0	EM (45°) ^b	88	3.10	690 ± 25	7.6 ± 1.5	3.24	405	5.2
36120910	3.0	P	88	3.10	460 ± 20	5.8 ± 1.2	3.36	350	3.9
					3-TW average		3.27	400	5.0
36120906	4.5	EM	89	3.44	1190 ± 35	13.0 ± 2.6	3.33	440	6.2
36120906	4.5	P	89	3.44	1280 ± 40	16.3 ± 3.3	3.36	560	10.0
36120911	3.8	EM	86	2.48	730 ± 30	8.0 ± 1.6	3.34	370	4.4
					> 3-TW average		3.34	460	6.7

^aThe permanent magnet system at 90° with respect to the north laser beam direction.

^bThe electromagnetic deflection system at 45° with respect to the laser direction.

^cUpper limit to the plasma ion temperature.

Fig. 5-63. α -particle time-of-flight data for Hyperion target at 4.5 TW, showing the α -particle energy loss invariance with angle.

By measuring the polarization state of the scattered $1.06\text{-}\mu\text{m}$ light, we have obtained direct evidence of short scale lengths near the critical density region. The degree of depolarization of the scattered $1.06\text{-}\mu\text{m}$ light was measured both for a one-sided irradiation and a highly asymmetric irradiation (6 J/41 J for the south/north beams) of SiO_2 microshell Hyperion targets on the Argus facility. By comparing the measurements with calculations of the effect of a plane wave incident upon a density gradient with a scale length $L = n_{cr}(n/z)^{-1}$, L was determined to be of the order $1\text{ }\mu\text{m}$ or less. The measurements and the calculations are discussed in detail elsewhere.

The symmetry of the thermonuclear burn region was investigated by imaging the α -particle emission

region using both pinhole and zone-plate-coded imaging techniques. In both cases, the thermonuclear fuel region was measured to be confined to within about $25\text{-}\mu\text{m}$ -diam region, with a FWHM distribution diameter of about $15\text{ }\mu\text{m}$, implying volume compressions of the order of 50 to 100. Within the resolution of the measurements (spatially about $9\text{ }\mu\text{m}$ for the zone-plate-coded images and about $13\text{ }\mu\text{m}$ for the pinholes, temporally unresolved), we observed very little deviation from a spherically symmetric burn region. (See also Section 3 for the measurements, techniques, and a detailed discussion of the results.)

In addition to all the experiments performed on Hyperion-type exploding pusher targets, forerunner experiments were carried out to set a data and

Table 5-9. Laser fusion experiment diagnostics

Measurement	Instrument	Record
Neutron count	<ul style="list-style-type: none"> 1 Cu activation counter 1 time-of-flight detector (2 fluor-PM) 2 fluor-PM systems (6 detectors) 	Special coincidence counter system 6 traces + 8 CAMAC channels 12 traces
X-ray spectrum	<ul style="list-style-type: none"> Active-gypsum flat crystal RAP bent crystal CAR carbon reflector Lead stearate bent crystal 7 K-edge filtered channels 4 K-edge filtered channels 	Ditigized image from reticon array Film Film Film 7 CAMAC channels 3 traces + 1 CAMAC channel
X-ray spatial distribution	<ul style="list-style-type: none"> 1 axisymmetric x-ray microscope 2 x-ray microscopes (4 channels each) 1 zone plate imaging system 	Film 2 Film (8 images) Film
X-ray temporal character	<ul style="list-style-type: none"> 4 LEXD Filtered x-ray streak camera 	4 traces Film (10 images)
X-ray calorimetry	<ul style="list-style-type: none"> 4 SiSB detectors 3 TA foil x-ray calorimeters 	4 CAMAC channels 3 chart records
α -spectrum	<ul style="list-style-type: none"> 1 Quadrupole triplet spectrometer 2 Magnetic-TOF spectrometers 1 Pin hole camera 1 Zone plate imaging system 	3 traces 6 traces Film Film
Ion energy spectrum	<ul style="list-style-type: none"> 2 Magnetic spectrometers 1-4 channel CN detector 	4 traces 4 Films
Ion spatial distribution	<ul style="list-style-type: none"> 8 Faraday cups 11 differential calorimeters 1 pin hole camera 	12 traces 11 chart records Film
Electron energy spectrum	Magnetic spectrometer	9 CAMAC channels
Second harmonic conversion efficiency	2 PIN diodes	2 CAMAC channels
Laser temporal and spatial distribution both incident and scattered	<ul style="list-style-type: none"> 2 Target plane multiple image cameras 2 Target plane streak camerss Forward and backscatter streak camera 2 forward and backscatter multiple image cameras 	2 Films (50 images) 2 Films (6 images) 1 Film (3 images) 2 Films (10 images)
Optical energy balance	<ul style="list-style-type: none"> North and south incident calorimeters North and south forward and backscatter calorimeters 40 PIN diodes 10-1.06 μm calorimeters or box calorimeter 	Computer (2 channels) Computer (2 channels) 40 CAMAC channels 10 chart records 6 chart records

Table 5-9. (Continued)

Measurement	Instrument	Record
Laser system performance	Oscillator streak camera	1 trace
	Switched-out pulse energy diode	1 trace
	Pulse train monitor	1 trace
	Spark gap timing monitor	1 trace
	Prepulse monitor	1 trace
	7 interstage calorimeters	Computer (7 channels)
	6 nearfield beam photos	6 Films
	Flashlamp current monitors	20 traces
	Faraday rotator field monitors	10 traces
Total for one shot:		
	85 oscilloscope traces	
	82 data channels from computerized acquisition system	
	105 photographic images	
	24 chart records	
	1 digitized image (1024 data at computer output)	
	1 coincidence counter output

Shot 36111113

Laser energy	99 J
FWHM	49 ps
D-D protons	$8.6 \pm 4.3 \times 10^5$
D ³ He protons	$1.7 \pm 0.2 \times 10^6$
Temperature	$5.7^{+1.9}_{-0.9}$ keV

Fig. 5-64. D³He experiment measuring the thermonuclear fuel temperature.

Fig. 5-65. X-ray spectrum for 0.4- and 2-TW experiments.

physics base for the high-density ($\geq 10 \text{ g/cm}^3$) experiments we plan to perform in 1977. These two series of experiments have significantly extended our data base and our understanding of laser-induced thermonuclear implosions and the basic laser plasma interaction physics from the 0.4 TW, $< 5 \times 10^{16} \text{ W/cm}^2$ level on Janus to the 4 TW, $< 10^{18} \text{ W/cm}^2$ level on Argus.

References

41. E. K. Storm et al., "The Effects of Fill Pressure and Pulse Simultaneity on the Laser Driven Implosion of DT Filled Glass Microshells," *Bull. Am. Phys. Soc.* **20**, No. 10, 1266 (1975).
42. R. L. Lerche, L. W. Coleman, J. W. Houghton, D. R. Speck, and E. Storm, *DT Ion Temperature Determined from the Neutron Energy Spectrum of Laser Fusion Targets*, Lawrence Livermore Laboratory, Rept. UCRL-78430 (1976).
43. V. W. Slivinsky et al., *Phys. Rev. Lett.* **35**, 1083 (1975).
44. K. R. Manes et al., *Laser Plasma Interaction Studies at LLL*, Lawrence Livermore Laboratory, Rept. UCRL-78771 (1976), to be published in *J. Opt. Soc. Am.*
45. H. G. Ahlstrom et al., "Plasma Experiments with 1.06- μm Lasers at the Lawrence Livermore Laboratory," Lawrence Livermore Laboratory, Rept. UCRL-77943 Rev. 1 (1976), to be published in *Laser Interaction and Related Plasma Phenomena, Vol. IV* (Plenum Publishers, New York).
46. E. K. Storm et al., *Exploding Pusher Experiments Utilizing a 4 π Illumination System*, Lawrence Livermore Laboratory, Rept. UCRL-78730 (1976), to be published in *J. Appl. Phys.*
47. K. R. Manes et al., *Spherical Microshell Targets Irradiated by the Janus 4 π Illumination System*, Lawrence Livermore Laboratory, Rept. UCRL-78449 (1976), to be published in *Plasma Phys.*
48. V. C. Rupert et al., *Particle and X-Ray Energy Measurement in Laser Plasma Interaction Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-78439 (1976), to be published in *J. Appl. Phys.*
49. D. W. Phillion et al., *Scattered Light Evidence for Short Density Scale Heights at Critical Density in Laser Irradiated Plasma*, Lawrence Livermore Laboratory, Rept. UCRL-78444 Rev. 2 (1976), to be published in *Phys. Fluids*.
50. S. S. Glaros et al., *Measurement of High Energy Ions*, Lawrence Livermore Laboratory, Rept. UCRL-78427 Rev. 1 (1976), submitted to *Rev. Sci. Instrum.*

Fig. 5-66. X-ray spectrum for Hyperion-type targets.

Janus
0.4 TW

$E_{x\text{-ray}} = 1.5 \text{ keV}$

Argus
2 TW

Fig. 5-67. X-ray micrographs are symmetrized with increasing incident intensity.

Shot 36120702: Incident energy: 153 J, 37 ps
Neutron yield: 2.8×10^8

Fig. 5-68. Irradiation of microshells with $f/1$ focusing lenses show a strong polarization dependence of the scattered light as well as the particle and x-ray energies.

Shot 36100812, 96 J, FWHM 40 ps

Fig. 5-69. Ion wide band spectrometer data for an exploding pusher target.

5-3.3 Spatial Resolution of Thermonuclear Burn in Laser Fusion Targets

The alpha particle emission from laser-compressed DT-filled targets has been successfully imaged using two complementary diagnostic tools: a pinhole camera (PC) and a zone-plate-coded imaging (ZPCI) camera. The experimental details associated with setting up the cameras are provided elsewhere; here, we are interested in the imaging data recorded by the cameras. The data consist of images of alpha particles emitted from laser-compressed Hyperion targets irradiated at the Argus facility.

Alpha-particle images of the reacting DT fuel were recorded for a number of laser-imploded targets using both the pinhole camera and zone plate coded imaging techniques. The pinhole cameras for the experiments consisted of arrays of 10- μm and 25- μm -diam pinholes in 12- μm -thick tantalum; the zone plate camera used a free-standing micro-Fresnel zone plate (100 zones, 5- μm -thick gold, narrowest zone 5.3 μm wide) as a coded aperture. The radiation collection solid angle subtended by the pinhole cameras ranged from about 5×10^{-6} sr (a single 25- μm pinhole) to an effective value of about 1.2×10^{-5} sr (an array of two 10- μm and two 25- μm pinholes). The zone plate coded aperture subtended a solid angle of about 2×10^{-2} sr. The nominal resolution of the pinhole cameras was about 12.5 and 31 μm for images recorded using 10- μm and 25- μm pinholes, respectively. The zone plate camera had a 10- μm nominal resolution. Figure 5-70 presents pinhole and zone plate camera alpha image data derived from laser shot 36111611. View (a) is a direct alpha image recorded through a 25- μm -diam pinhole. View (b) is a coded alpha image recorded through the zone plate coded aperture on the same experiment. These images are representative of the raw data of the alpha imaging experiments. Each is an array of microscopic holes etched through a 6- μm -thick cellulose nitrate layer. Each hole is the result of an alpha particle track in the cellulose nitrate. (Details on the use of cellulose nitrate as a high-resolution alpha particle detector are contained in Section 3.) The number of alpha tracks in the images recorded by the two cameras (~ 125 tracks for PC; $\sim 5 \times 10^5$ tracks for ZPCI)

Author
E. Storm

Major Contributors

H. G. Ahlstrom
M. J. Boyle
D. E. Campbell
L. W. Coleman
S. S. Glaros
H. N. Kornblum
R. A. Lerche
D. R. MacQuigg
D. W. Phillion
F. Rainer
F. Rienecker
V. C. Rupert
V. W. Slivinsky
D. R. Speck
C. D. Swift
K. G. Tirsell

were in excellent agreement with that expected from the alpha yield ($3.1 \pm 0.6 \times 10^8$) on shot 36111611.

Figure 5-71 presents the processed alpha imaging data for laser shot 36111611. (Information about the Hyperion targets, laser performance, and ther-

monuclear yield for all the shots discussed in this article is presented in Table 5-10). In Fig. 5-71(a) the pinhole camera data [of Fig. 5-70(a)] were plotted as a histogram using annular segments, 20 μm wide in the image plane. The data were transformed into the object plane using Eq. (42) from Section 3 :

$$R_0 \approx \left(\frac{a}{b} \right) \left[R_P - R_{Ph} \frac{(b + a)}{a} \right].$$

Fig. 5-70. Raw data from alpha imaging experiment: (a) direct pinhole image for shot 36111611; (b) zone-plate-coded image for shot 36111611.

Application of this transformation indicates that on the 36111611 target shot, 90% of the imaged particles originated within a compressed core approximately 30 μm in diameter. Figure 5-71(b) shows alpha image data for target shot 36111611 reconstructed from the zone plate coded image presented in Fig. 5-70(b). Figure 5-71(b) is a two-dimensional contour map of the reconstructed alpha image. Each contour represents a locus of constant alpha emission density (time-integrated intensity); the incremental change in the density between successive contours is approximately 1.5×10^5 alphas/ μm^2 (measured at the source). Also presented in Fig. 5-71(b) are line out data, showing relative alpha emission density along horizontal and vertical lines through the image center. Generally, the ZPCI data for target shot 36111611 show an ovoid region of thermonuclear burn with a diameter roughly one-third that of the original target. Contour map dimensions are roughly 29 μm and 26 μm along the vertical and horizontal axes, respectively, with a common FWHM $\sim 16 \mu\text{m}$. An estimate of the alpha emission originating outside the contour map regions of Fig. 5-71(b) was made by counting the alpha track density in the appropriate penumbra region of the shadowgraph. We concluded that no more than 4% of the total alpha emission could have originated outside the designated contour map region.

The PC and ZPCI alpha data for target shot 36111611 are consistent and in good agreement with the measured thermonuclear yield. This may be illustrated by a crude but reasonable calculation of the anticipated yield using the measured burn dimensions. The thermonuclear burn region is modeled as a constant-temperature, equimolar DT mixture compressed to the burn region dimensions

Fig. 5-71. Processed alpha imaging data for shot 36111611: (a) pinhole camera data plotted as a histogram; (b) reconstructed zone-plate-camera image.

Table 5-10. Target, laser, and thermonuclear burn data for three target shots

Parameters	Shot		
	36111611	36120906	36120910
Target diameter, μm	86	88.5	88
Target wall, μm	0.64	0.88	0.88
DT fill, mg/cm^3	1.58	3.44	3.10
Laser power, TW	2.4	4.2	3.9
Pulse width (FWHM), ps	50	38	27
Yield, 10^8 neutrons	3.1 ± 0.6	1.4 ± 0.3	8 ± 1

Table 5-11. Parameters and results of a crude calculation of the thermonuclear yield using alpha imaging results

Parameters	Shot 36111611
Ion temperature, keV	5.6
Ion density ($N_D = N_T$), 10^{21} cm^{-3}	5.6
Reaction rate, $10^{26} \text{ cm}^{-3} \text{ s}^{-1}$	6.3
Burn time, ps	36
Calculated yield, 10^8 neutrons	2.6
Measured yield, 10^8 neutrons	3.1 ± 0.6

shown in Fig. 5-71(b). The effective temperature is obtained from alpha and neutron time-of-flight spectrometer data; ion density is assumed equal to the original fuel density multiplied by the volume compression ratio; and the burn time is taken as the ratio of burn region diameter to mean ion sound velocity. The parameters and results of this simple calculation for target shot 36111611 are presented in Table 5-11. The calculated thermonuclear yield is in good agreement with the measured value.

Additional alpha imaging results are presented in Figs. 5-72 and 5-73. Figure 5-72 presents data recorded using a two-pinhole array camera (two 25- μm pinholes) on target shot 36120906. The two-pinhole data was plotted as a histogram in the image plane, transformed into the object plane,* and combined to yield the emission profile presented in Fig. 5-72. The transformed data indicate that 90% of the imaged particles were generated within a compressed core 25 μm in diameter.

*This transformation does not imply a 1:1 mapping between angular segments in the image and object planes. It merely allows the reader to evaluate the source size in the object plane.

Figure 5-73 presents ZPCI data on Hyperion target shot 36120910. A two-dimensional contour map of the reconstructed image along with line out data are presented. The thermonuclear burn region, measured from the outermost contour, is 26 and 22 μm along the vertical and horizontal axes with a

Fig. 5-72. Alpha imaging data for shot 36120906 derived by a two-pinhole array camera.

Fig. 5-73. Reconstructed zone-plate-imaging data for shot 36120910.

FWHM of 18 and 15 μm , respectively. The number of alpha tracks in the penumbra of the coded image showed that on target shot 36120910 no more than 10% of the total alpha emission could have originated outside the contour map region of Fig. 5-73.

Alpha imaging data, derived from two independent and complementary imaging techniques, have provided explicit confirmation that the thermonuclear burn produced by laser-driven implosions does indeed occur within a compressed core of the imploded target.

5-3.4 Spatial Resolution of Plasma Energy

The polarization dependence previously suggested by sparse data gathered at the Janus facility has been confirmed for f/1 focusing with the more powerful Argus system, and we have obtained evidence of inhibited conduction. Moreover, we have shown that the plasma from the target stalk strongly modifies the energy flux distribution and accounts for low energy peaks observed in charge collector data.

Preliminary indications of polarization-dependent energy flux were obtained at the Janus facility where targets were irradiated at power levels of 10^{15} W/cm^2 with two f/1 lenses.⁵¹ These results have been confirmed with the Argus laser system, where better beam quality and a larger number of detectors provide more reliable data. Figure 5-74 depicts the standard coordinate system used; typical data obtained with a ball target at constant polar angle are shown in Figs. 5-75 and 5-76.

Authors

K. M. Brooks
N. M. Ceglio

Major Contributors

V. W. Slivinsky
H. Kornblum
E. Storm
L. Coleman
H. G. Ahlstrom

Fig. 5-74. Polar angles are measured with respect to the beam axis (west beam at Janus and Cyclops, north beam at Argus). Azimuthal angles are measured counterclockwise in a plane normal to this axis. Zero azimuth corresponds to the upward-pointing vertical.

From the data obtained below the horizontal plane,* we see that the particle and x-ray energies measured close to the plane of the light's E vector are larger than those measured normal to this plane. From Figs. 5-75 and 5-76, the relative value of the in- and out-of-plane polarization fluxes at a polar angle of 127.5° or 105° is approximately 17%. These results were consistent over a number of shots at power levels of about 2 to $5 \times 10^{16} \text{ W/cm}^2$ and were independent of the location of the detectors. Since the detectors measure both particle and low energy x-rays, the asymmetry in particle energy is larger than 17%. Indeed, estimates of the x-ray

energy indicate that as much as 15% of the absorbed energy is reemitted in this form. Since the x-ray flux is nearly isotropic, the asymmetry in particle energy flux is about 20%.

Such distributions together with the scattered light distributions, which display a minimum in the E vector plane, confirm the importance of polarization-dependent absorption mechanisms, particularly resonance absorption.⁵² In addition, as discussed below, they are a sign of inhibited electron conduction.

The deviation from azimuthal symmetry observed in the scattered light distributions⁵³ is considerably larger than that seen by the plasma calorimeters. Two effects contribute to this difference. Part of the asymmetry in the light distribution can be due to Brillouin sidescattering which

*The shape of the curve above the horizontal plane is discussed later.

Fig. 5-76. Same as Fig. 5-75 but at a polar angle of 105°. Incident energy was 95.9 J (2.4 TW). Shot 36100812.

thermal conduction.* As discussed elsewhere,⁵⁴ magnetic fields generated both by the thermoelectric current and as an intrinsic part of the resonance absorption phenomenon⁵⁵ result in a strong inhibition of electron conduction. These fields and possibly anomalous conduction resulting from two-stream instability⁵⁴ can be responsible for maintaining the anisotropy of the energy flux.

*Evidence of these phenomena are also seen in x-ray micrographs.⁵⁴

The polar as well as the azimuthal dependence of the energy flux was measured at Argus. Figure 5-77 shows the polar dependence of flux both in the polarization plane and normal to this plane. The ratio of in- to out-of-plane fluxes varies with polar angle.

The differences observed in the data are also simply explained in terms of absorption efficiency. At the high incident power flux used in these experiments, absorption occurs primarily through parametric instabilities and resonance absorption.^{56,57} Both phenomena depend strongly on the

Fig. 5-77. The ratio of in- and out-of-plane polarization fluxes depends on the polar angle. These data were obtained at azimuthal angles of 214° ("out") and 281° ("in"). The polarization plane lies at 104° to 284°. Shot 36120702.

angle of incidence, and one-dimensional simulations⁵² show the latter peaking around 20°. Our measurements reflect the larger influence of resonant absorption near an incidence angle of 30° compared to 50° (calorimeter location 52.5° and 75°).

In addition to the asymmetry due to resonance absorption, Figs. 5-75 and 5-76 show an effect from the stalk used to hold the target. A minimum in the energy distribution consistently occurs near $\phi = 0$ and is much more pronounced at a polar angle of 75° than 52.5°. Simulation of the three-dimensional expansion in this region is very difficult to perform, so that only a qualitative picture of the blowoff can be drawn. Since the stalk is heated not only by conduction and refracted or scattered radiation from the target but also directly by the (spatial) tail of the laser pulse, a significant part of it is ionized and expands in the surrounding vacuum. Symmetry considerations show that this expansion will have its major component normal to the axis of the stalk. The microshell ions expanding towards $\phi = 0$ will interact with the low-energy but high-density stalk plasma and be slightly deflected away from this

region, resulting in the heart-shaped distribution shown in Figs. 5-75 and 5-76. This pattern was also confirmed using Faraday cups. A number of these instruments were placed at various azimuthal angles but at constant polar angle. Only the data obtained in a direction normal to the stalk exhibited a low energy (≈ 100 eV/a.m.u.) peak. The experiment was repeated, placing the cups at constant azimuth and various polar angles. Again the low-energy peak occurred consistently in all probes whose lines of sight were within 11° from the normal to the stalk. Figure 5-78 shows two typical traces with and without the low energy peak.

Less than 1% of the total ion energy is included in the low energy peak so that its absence would not be detectable with the plasma calorimeters. Thus the energy measured by the calorimeters is not modified by the stalk plasma, but the distribution of the energy is.

Figure 5-79 compares polar flux distribution in and normal to the polarization plane of the incident radiation as in Fig. 5-77, but here the presence of the stalk further depresses the distribution in the E vector plane, since the out-of-plane data were taken near the stalk. Such comparisons emphasize the need for caution when extrapolations are performed with a limited or arbitrary choice of detector locations.

*Numerous mechanisms can be invoked which would modify the location of the peak.

Fig. 5-78. Charge collector data show a very slow plasma component in the plane normal to the target stalk. The cylindrically expanding plasma from the stalk yields no component at 46° from the stalk. Shot 36071408.

Fig. 5-79. Same as Fig. 5-77 but the out-of-plane data were obtained at an azimuth of 11° . Shot 36080611.

References

51. V. C. Rupert et. al., "Energy Absorption by Laser Fusion Targets Determined by Ion Calorimetry," *Bull. Am. Phys. Soc.* **20** (10), 1286 (1975).
52. K. G. Estabrook, E. J. Valeo, and W. K. Kruer, "Two Dimensional Relativistic Simulation of Resonance Absorption," *Phys. Fluids* **18** (5), 1151 (1975).
53. D. W. Phillion, R. L. Lerche, V. C. Rupert, and M. J. Boyle, "Scattered Light Evidence for Short Density Scale Heights at Critical Density in Laser Irradiated Plasmas," *Bull. Am. Phys. Soc.* **21** (9), 1046 (1976).
54. J. T. Larsen, J. J. Thomson, and C. E. Max, *Electron Transport Inhibition in Spherical Microshell Target Irradiation*, Lawrence Livermore Laboratory, Rept. UCRL-78467 (1976).
55. J. J. Thomson, C. E. Max, and K. Estabrook, *Magnetic Fields Due to Resonance Absorption of Laser Light*, Lawrence Livermore Laboratory, Rept. UCRL-76690 (1975).
56. K. R. Manes et. al., *Laser Plasma Interaction Studies at the Lawrence Livermore Laboratory*, Lawrence Livermore Laboratory, Rept. UCRL-78771 (1976). Also, W. L. Kruer, *Theoretical Interpretation of Enhanced Laser Light Absorption*, Lawrence Livermore Laboratory, Rept. UCRL-76529 (1975).
57. J. J. Thomson, private communication.

Author	Major Contributors
V. C. Rupert	S. R. Gunn J. F. Holzrichter

5-3.5 Argus Postshot Calculations and Analysis

We chose a representative target irradiation experiment (36080611) for comparison to LASNEX computer code calculations. The target parameters and focusing scheme are shown in Fig. 5-80. The schematic representation of the target (8649) is the initial Lagrangian mesh used in the LASNEX calculation. The target ball was a 0.97- μm -thick glass microshell 83 μm in diameter filled with equimolar DT at an initial density of 2.5 mg/cm^3 . This target was irradiated with two opposing 1.06- μm laser beams whose total energy was 58 J. The pulse duration was 47 ps; total power on the target was 1.35 TW. The spatial intensity distribution of the laser beam in the calculation was adjusted to approximate the Argus laser beam profile.

Many diagnostic measurements are expected to be strongly correlated with various aspects of the target physics. For example, the angular distribution of the scattered light often correlates with details of the beam-plasma interaction, i.e., spatially inhomogeneous laser beams, irregular focusing schemes, and magnetic field or other effects leading

Fig. 5-80. Calculational representation of target geometry and laser beam profile.

to inhibited electron transport. The neutron yield and alpha-particle spectrum help determine some of the relevant implosion characteristics such as the $\rho\Delta R$ of the shell, peak DT ion temperature, and, most importantly, the thermonuclear nature of the DT reactions. The integrated x-ray energy indicates the energy absorbed and thermalized in the target (i.e., not lost by fast ions). The spectral distribution of x-ray energy above 2.5 keV provides information about both the conduction of thermal electrons in the target and the distribution of superthermal electrons generated near the laser light absorption radius by means of the laser-plasma anomalous absorption processes. Additional interesting features of the implosion are often obtained from the x-ray micrographs, which, though time-integrated, show details of the implosion such as the center of convergence and local thermal differences, and can sometimes be used to obtain a very rough estimate of peak DT density.

Table 5-12 is a comparison of the calculations and experimental measurements. Agreement is very good not only for neutron production but also for the DT ion temperature and density, the implosion velocity, the radiated x-ray energy, and the absorbed energy. Note that the measured peak DT ion

Table 5-12. Experimental results compared with calculation

	Measured	Calculated
Fusion events, 10^8	4	3.6
DT ion temperature, ^a keV	5	4.6
DT density, ^a $\text{g} \cdot \text{cm}^{-3}$	~ 0.2	0.16
Implosion velocity, ^a 10^7 cm/s	5	4.5
Integrated x-ray energy, J	~ 2	~ 2
Energy absorbed, J	12	13.5

^aDerived from measurement.

temperature was derived from the energy spread of the alpha and neutron spectra. An estimate of the peak density was obtained from the experimental x-ray micrograph, and the implosion velocity was found from sound speed and electron temperature estimates derived from the x-ray spectrum.

Fig. 5-81. Comparison of experimental and calculational results of light scattered from target.

Fig. 5-82. Comparison of experimental and calculated x-ray spectra.

The measured scattered light distribution is compared to LASNEX in Fig. 5-81. Note that LASNEX is axisymmetric and cannot treat polarization effects.

The agreement between the calculated and measured x-ray spectra is quite good, as Fig. 5-82 shows. For this calculation a value of 9 was used for the superthermal spectral parameter α , where

$$f(v_e) \sim \exp - \left(\frac{1/2 n_e v_e^2}{\alpha k T_e} \right). \quad (1)$$

The two temperatures associated with the thermal and superthermal portions of the spectrum are 0.96 keV and 21.8 keV. (The magnetic field was included in the calculation.)

Author
A. R. Thiessen

5-4 EXPLODING PUSHER TARGETS: D³He FUEL, ARGUS SYSTEM

5-4.1 Design and Simulation Experiments

We have proposed, designed, and analyzed laser implosion experiments with D³He fuel to determine the fuel ion temperature. The experiments are also a sensitive indicator of a nonthermonuclear burn component. Experimental evidence for thermonuclear DT reactions in a laser-compressed target was first obtained in May 1975.⁵⁸ The experiments used a time-of-flight spectrometer to measure the energy distribution of the alpha particles from the D(T,n) α reaction.⁵⁹

The time width of the Gaussian distribution is proportional to the square root of the ion temperature of the reactants.⁶⁰ However, the width is also increased by Doppler energy loss and finite size effects. In the experiments, these effects produced a

spreading comparable to that of the thermal effect and thus, a temperature could only be determined with LASNEX estimates of the various corrections. The resulting ion temperature of about 2.0 keV agrees well with the LASNEX ion temperature.⁶¹

With the completion of the ARGUS facility, about four times the power and energy obtainable from Janus were now available for implosion experiments. LASNEX calculations indicated that ion temperatures in the range of 6 to 10 keV would be attained and hence, the reaction rates would be about 100 times greater than those achieved with JANUS. At these temperatures, the thermal spreading is dominant, and thus, the temperature could be directly determined.

In addition, with the Argus laser system it became feasible to make independent measurements of temperature via the ³He(D,p)⁴He and D(D,p)T reactions. These reactions yield 14.7- and 3-MeV

protons, respectively. A comparison of the reaction rates for the DD and D³He reactions⁶² revealed that their slopes are quite different at about 5 keV (Figs. 5-83 and 5-84). Hence, the ratio of the number of reactions provides an independent measurement of the temperature. In particular, this ratio would be

$$\frac{\frac{1}{4} N_D^2 \bar{\sigma v}_{DD}}{N_D N_{He^3} \bar{\sigma v}_{DHe^3}} \quad (2)$$

where $\bar{\sigma v}$ is the total DD reaction rate. Note that DT and DD have about the same slope in the 1- to 20-keV range so that the ratio of the DT/DD reactions is a poor measure of temperature. In addition, at temperatures of 6- to 8-keV, the reaction rates are sufficient to produce about 10⁶ protons from both DD and D³He fusion, enough to produce detectable signals.

Fig. 5-83. Values of $\bar{\sigma v}$ for the three important reactions are based on Maxwellian distributions. The slopes of the reaction rates for the DT and DD reactions are the same for the kinetic temperatures achieved in the experiments; however, the D³He reaction differs markedly.

Fig. 5-84. Reaction rate ratio for a Maxwellian temperature is indicated by the lower scale and a deuteron particle kinetic energy by the upper scale. Actual quantities plotted are $1/4 (\bar{\sigma v}_{DD}/\bar{\sigma v}_{DHe^3})$ and $1/4 (\sigma_{DD}/\sigma_{D^3He})$, respectively.

LASNEX pre-experiment simulations were run on a 100- μ m-diam microsphere with a 0.8- μ m wall filled with equimolar deuterium and ³He imploded by a 2-TW, 30-ps FWHM laser pulse. A peak D³He ion temperature of 7.8 keV and 25% absorption were calculated; in addition, the reaction-rate weighted average was 6.9 keV. The predicted yields were 8.3×10^6 DD protons and 2.5×10^6 D³He protons.

There exists the possibility of a significant non-thermonuclear component in the D³He fusion. If a significant number of deuterium or ³He ions are accelerated out of the thermal distribution to tens-of-kiloelectronvolt kinetic energy, the ions will react more rapidly in a beam target manner. Figure 5-84 shows the ratio of the reaction rates for Maxwellian-averaged nuclear cross sections at a kinetic temperature shown on the lower scale and for nuclear cross sections at a deuteron beam energy indicated on the upper scale.

Should this nonthermonuclear component exist in sufficient strength, a higher apparent temperature will result from the D^3He implosion than from the same DT implosion. Conversely, if we find that these two temperatures are approximately the same, then the possibility of a significant nonthermonuclear component will be eliminated. In addition, the temperature measurements by alpha and neutron time-of-flight spectrometers will be corroborated.

References

58. V. W. Slivinsky, H. G. Ahlstrom, K. G. Tirsell, J. T. Larsen, S. S. Glaros, G. B. Zimmerman, and H. D. Shay, *Phys. Rev. Lett.* **35**, 1083 (1975).
59. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), pp. 409.
60. H. Brysk, *Plasma Phys.* **15**, 611 (1973).
61. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), pp. 279.
62. S. L. Green, Jr., *Maxwell Averaged Cross Sections for Source Thermonuclear Reactions on Light Isotopes*, Lawrence Livermore Laboratory, Rept. UCRL-70522 (1967).

Author

J. Larsen

5-4.2 Experimental Results

We first used D^3He fuel to measure ion temperature at the 10^6 DT reaction level with the Janus laser,⁶³ where we obtained DT temperatures in the 1 to 3 keV range. Nuclear emulsions, used to detect 14.7-MeV protons, were placed 5 cm from the target to achieve a large solid angle. Based on a null result, an upper limit of 3 keV was placed on the DT ion temperature for those early experiments. Because counting tracks in emulsions is time-consuming, it is advantageous to use an active detector, a fluor-photomultiplier, located several meters from the target. The increased reaction yields from higher temperatures achieved with the Argus laser offsets the reduction in solid angle.

The 3.0-MeV DD protons are routinely measured on each experiment with the same time-of-flight spectrometer used to measure the DT alpha parti-

cles (see Fig. 5-85).⁶⁴ A magnetic field bends the protons out of the direct line of sight into the fluor-photomultiplier to shield the detector from the intense x-ray and light flux coming from the targets. The solid angle for that detector is 5.76×10^{-5} sr. To measure the 14.7-MeV protons, we used a large, 110-mm-diam fluor coupled to an Amperex 2041 photomultiplier (see Section 3). The detector was placed at the end of a long evacuated pipe to temporally separate the x-ray signal from the proton signal. No magnet was used to bend these protons; the detector looked directly at the target. A 0.30-mm-thick tantalum filter was placed 4 cm in front of the detector to reduce the x-ray signal. The proton energy loss in the filter was calculated to be 9.2 MeV, while proton energy loss in the target was calculated to be negligible. The fluor was purposely selected to be thin (0.25 mm) to reduce the x-ray signal, but it was thick enough to be a large fraction of the proton range. This detector solid angle was 1.56×10^{-3} sr. The time-of-flight distance to the tantalum filter was 247 cm. Figure 5-86 shows the experimental configuration.⁶⁵

Four experiments were carried out, three with targets containing D^3He and one with deuterium only. Each target was a microsphere about 85 μm in diameter with a wall thickness of 0.5 to 0.7 μm . The gas fills were 1.3 mg/cm³ 3He and 0.9 mg/cm³ deuterium. Experimental parameters are listed in Table 5-13.

An oscilloscope trace from experiment 36111113 (Fig. 5-86) shows that the x-ray pulse is off scale, but the system recovers in time to record the D^3He protons. Figure 2 also shows the results of experiment 36111606 where the fuel in the target ball was deuterium only. No signal was observed at the correct arrival time for the D^3He protons, and we conclude that fewer than 8×10^3 were produced at the source. The results of all four shots are shown in Table 5-13. Two of the experiments yielded temperatures of 5.7 and 5.8 keV while experiment 36111508 yielded a much higher temperature of 9.3 keV.

The major source of uncertainty in these experiments is in the DD proton measurement. Three to four DD protons were measured at the detector. (The number of D^3He protons was much larger because of the large detector solid angle.) This introduces a 50% statistical error on the number of DD protons. The uncertainty in the ion temperatures due to this error is shown in Table 5-13. A

Table 5-13. Experimental parameters

Shot	Laser energy (J)	Target diameter (μm)	Wall thickness (μm)	Absorbed energy (J)	Pulse width (ps)	DD protons	D, ³ He protons	Measured temperature (keV)	Calculated temperature (keV)
36111113	100	87	0.68	22	49	8.6×10^5	1.7×10^5	5.7 ^{+1.9} -0.9	6.4
36111508	113	86	0.60	26.5	43	7.3×10^5	4.3×10^5	9.3 ⁺³ -1.6	7.8
06111511	52	88	0.65	11	31	7.6×10^5	1.6×10^5	5.8 ^{+1.9} -0.9	5.5
36111606	132	89	0.54	26	48	7.0×10^5	$<8 \times 10^3$

Fig. 5-85. Experimental configuration.

Fig. 5-86. (a) Oscilloscope trace from D^3He experiment 36111113. (b) Oscilloscope trace from background experiment 36111606. 500 mV/division, 20 ns/division.

second source of error is the uncertainty of the initial gas fill, estimated to be $\pm 20\%$. A third uncertainty arises from the DT neutrons (from residual tritium in the filling procedure) which arrive at the detector within 1 ns of the arrival time of the D^3He protons. It is very difficult to shield against this neutron background. However, the thin-fluor detector is fairly insensitive to the neutrons. The neutron yields were measured independently for each experiment and were between 5×10^5 to 2×10^6 (Section 3). The neutron sensitivity of the D^3He proton detector is known from previous higher yield shots (with DT-filled microspheres) which imply that neutrons in these experiments contribute less than 3% to the D^3He proton signals. This estimate was confirmed in the background experiment where no signal was observed at the 14.1-MeV neutron arrival time. Other errors such as measured distances, detector calibrations, etc. were all very small compared with the 50% statistical error in counting the DD protons.

References

63. H. N. Kornblum and J. D. Eckels, Lawrence Livermore Laboratory, private communication (1967).
64. V. W. Slivinsky, H. G. Ahlstrom, K. G. Tirsell, J. Larsen, S. Glaros, G. Zimmerman, and H. Shay, *Phys. Rev. Lett.* **35**, 1083 (1975).
65. V. W. Slivinsky, H. G. Ahlstrom, J. H. Nuckolls, J. T. Larsen, B. W. Weinstein, K. G. Tirsell, E. K. Storm, G. R. Leipelt, *Implosion Experiments with D^3He Filled Microballoons*, Lawrence Livermore Laboratory, Rept. UCRL-78450 Rev. 2 (1977). Submitted to *Journal of Applied Physics*.

Author

V. W. Slivinsky

Major Contributors

H. G. Ahlstrom
E. Storm
G. Leipelt

5-4.3 Comments on D^3He Experiments

In the preceding article, temperatures inferred from the ratios of the number of DD and D^3He

protons were found to range from 5 to 10 keV with an uncertainty in each particular experiment of ± 1 to 2 keV. This is the same temperature range predicted by LASNEX calculations and measured in experiments with DT fuel via neutron and alpha time-of-flight spectrometers.

The agreement between these various temperature measurements and calculations provides very strong evidence that most of the fusion is thermonuclear. It is difficult if not impossible to imagine nonthermonuclear possibilities yielding the observed numbers of DD, DT, and D^3He reactions plus the simultaneous observed shift in alpha energy, temporal spreading of the alpha and neutron pulses, and alpha imaging of the burn region.

However, in view of the fast-ion data, it would be surprising if no small fraction of the fusion was nonthermonuclear. In principle, it is possible to estimate the size of the nonthermonuclear component from the temperature difference between D^3He fusion and DT fusion. However, the data obtained so far are not sufficient to allow a useful estimate. There is a moderately large spread in our observed temperatures as well as a substantial uncertainty in measurements by the three methods. In addition, we have not used both the time-of-flight and the D^3He methods to determine the temperature of the same implosion.

As we scale up to larger exploding pusher targets to match the higher power lasers coming on line, the optimum wall thickness and the ρR of the compressed fuel will increase; the DT burn temperature will also increase to the optimum range (10 to 20 keV). Under these conditions, the relative size of any nonthermonuclear component and the effect on the observed burn efficiency should decrease. For high density targets, the implosion is sufficiently isentropic and of such high ρR that the predominant nonthermonuclear fusion should be that which is inherent in the fusion itself (e.g., multi-MeV knockon tritons and deuterons generated by 14-MeV neutron scattering may react in flight with the thermal deuterons and tritons).

Author

J. Nuckolls

Major Contributor

J. Larsen

5-5. EXPLODING PUSHER TARGETS: SUMMARY

5-5.1 Experimental Data

As part of the ongoing effort to understand the physics of laser-imploded targets, a series of experiments examining a wide range of irradiation geometries and intensities have been performed over the last two years, both at Livermore and other laboratories.⁶⁶⁻⁸⁶ At Livermore these include experiments designed to study the basic laser plasma interaction phenomena⁷⁵⁻⁷⁸, as well as experiments specifically designed to map out and understand the parameter space and physics of laser-induced compressions of thermonuclear fuel.⁷⁹⁻⁸⁶ This section discusses the experimental results obtained with DT-filled SiO_2 microshell exploding pusher⁸⁷⁻⁸⁹ targets at the Lawrence Livermore Laboratory using the Janus, Cyclops, and Argus laser facilities in both one- and two-beam configurations. The experiments were performed using $f/1$ and $f/2.5$ lenses as the lens-elliptical-mirror-spherical illumination system at power levels ranging from 0.2 to 4.5 TW.

We employed two different focusing schemes. Using the $f/1$ lenses on Janus and Argus and the $f/2.5$ lenses on Cyclops, the converging beams from the lenses were adjusted such that at the equatorial plane of the target, the beam diameter at about the $1/3$ intensity points equalled the target diameter. Preliminary experiments indicated that for simple lenses, this maximized the implosion symmetry, compression, and neutron yield. Figures 5-87 through 5-89 are examples of high-power beam profiles showing the time-integrated energy density at the equivalent target plane for the three laser systems. This "tangential" focusing scheme was followed for most of the simple lens irradiation target experiments. For the spherical illumination system this scheme was also used; however, we also varied the position of the foci with respect to the target center to examine the effect of resonance absorption. The focusing results for the spherical illumination system are described in § 5-1.2.

On Janus, experiments were performed in one- and two-beam configurations at the 0.2- to 0.4-TW level using both $f/1$ lenses and the spherical illumination system described in § 5-1.2. The experiments with the $f/1$ lenses were the first series of ex-

ploding pusher experiments performed. The purpose was to explore the first phase of the parameter space of this type of target. The parameters varied were the SiO_2 microshell diameter, the shell wall thickness, the density of the DT gas in the target, and the time separation of the two laser beams focused on the target. Two goals of the experiments on Janus using the spherical illumination system were to study the effect on target performance due to increased compression symmetry expected from the more uniform target illumination and to study the absorption as a function of the focal positions with respect to the center of the target.

The experiments using the Cyclops laser system were performed to study the effect of higher f -No. lenses. Argus, operating at up to 4 TW with two beams, was used to extend the power and energy regimes from those available on Janus and to confirm our understanding of the physics of exploding pushers. The experiments on Cyclops and Argus using $f/2.5$ and $f/1$ lenses, respectively, and Janus using the spherical illumination system, are discussed in more detail in § 5-1.1 through 5-4.3. The experiments on Janus using $f/1$ lenses were first reported in the 1975 Annual Report.

Table 5-14 summarizes the experimental configurations and lists representative data obtained from experiments using the respective facilities. Various laser plasma interaction aspects of these experiments have been discussed in separate articles both in this report and in the 1975 Annual Report. This article, however, attempts to synthesize the results from the point of view of exploding pusher target performance.

With the absorption fraction indicated in the table, the targets produced between 10^4 and 1.5×10^9 fusion reactions (neutrons and α -particles) with the yield scaling as the specific absorbed energy — all other parameters being the same. (A derivation of simple scaling rules is developed in § 5-5.3.) Of the absorbed energy, roughly 7% was radiated as x rays between 0.2 to 20 keV. Since the very fast ion peak observed in the Faraday Cup traces is partly due to fast protons (see Refs. 90 and 91 for details), then assuming $A/Z = 2$ for the remaining ions, we find that approximately 25% of the absorbed energy is detected in ions with energies exceeding 60 keV/a.m.u. The remaining fraction of

Janus east beam, high power 80- μm inside f/1 focus

Shot 75060202 235 GW $B = 4.3$

Fig. 5-87. Laser beam characteristics in the target plane: Janus laser.

the absorbed energy is found in a broad distribution of lower energy ions associated with the expansion of the thermal plasma. Measurements of the polarization state of the laser light reflected by the plasma, significant polarization dependence of the scattered $1.06\text{-}\mu\text{m}$ radiation, together with polarization-dependent asymptotic plasma energy distribution, are consistent with density steepened scale lengths of a few microns and resonance absorption. These latter measurements are

described in Section 3 and Refs. 92 and 93. Time-of-flight measurements of the energy distribution of the nominal 3.5-MeV α -particles⁹⁴ and the 14.1-MeV neutrons⁹⁵ from the DT reaction indicate that the reaction products are of thermonuclear origin and are produced from the compressed DT fuel with an effective ion temperature of 1.5 to $8\ \text{keV}$, depending upon laser and target parameters. Time-integrated x-ray microscope data together with time-resolved x-ray pinhole⁹⁶ pictures and α

imaging⁹⁷ data all indicate volume compressions $30 \lesssim C \lesssim 100$ for neutron producing experiments. X-ray pinhole streak camera data measure mean SiO_2 pusher velocities of 2.5 to 3.5×10^7 cm/s. Similar estimates of the pusher implosion velocity, were obtained from the beam delay experiments described in the 1975 Annual Report.

A typical example of an exploding pusher experiment with $f/1$ lenses is shown in Figs. 5-90 and 5-91. Figure 5-90 shows the target and laser input specifications together with a summary of experimental results and computer code predictions.

Figure 5-91(a) shows the continuum x-ray spectrum from this target. The typical "two-temperature" behavior characteristic of high intensity laser plasma interaction is evident. The portion of the spectrum between 2.5 and 7.5 keV is representative of a thermal emission with the slope being related to the plasma electron temperature in the overdense region, and the portion of the spectrum above 7.5 keV is due to the suprathermal electrons generated by the collective absorption processes. The computer code simulation⁹⁸ of the x-ray spectrum is also shown in this figure. Figure 5-91(b)

Fig. 5-88. Laser beam characteristics in the target plane: Cyclops laser.

Argus north beam, power on target 2.8 TW

Time-integrated 117- μm inside f/1 focus

Radial average

Streak record

Shot 4 12/10/76

90 J

Fig. 5-89. Laser beam characteristics in the target plane: Argus laser.

shows x-ray micrographs of the implosion with emission from the 0.8 to 2.5 keV region of the spectrum, highlighting the fact that the majority of the high-energy thermal x-ray emission comes from the stagnation region where the pusher converts its kinetic energy into thermal energy of the glass and the DT fuel. The imprint of the illumination from the two f/1 lenses and the resulting asymmetric implosion, compression, and heating of the fuel and pusher are indicated by the emission geometry in

these time-integrated micrographs. The heated regions are confined approximately to the areas where the angle of incidence of the illumination is less than or about equal to 45° . We take this data as evidence for angle dependent absorption and inhibited thermal conductivity. Using Spitzer's⁹⁹ expression for the thermal conductivity and assuming a temperature of 1.5 keV at the critical region, we find that classical conductivity would diffuse the absorbed energy over approximately 300 μm in the

time scale (73-ps FWHM) of the laser pulse. Calculations show that thermoelectrically generated magnetic^{100,101} fields and magnetic fields produced by resonance absorption effects^{102,103} can reach megagauss values. Fields of this magnitude could

reduce the conduction lengths to the order of 10 μm , a value consistent with the data in Fig. 5-91(b). The question of inhibited thermal transport will be discussed further in "Absorption" below (also see Section 4 and § 5-5.2).

Table 5-14. Summary of experimental results

Facility	Janus	Janus	Cyclops	Argus
Output power level, TW	0.2-0.4	0.2-0.4	0.4-0.7	1-4
Pulsewidth, ps	75 $\pm$ 25	75 $\pm$ 25	80 $\pm$ 10	25 - 200
Focusing geometry	f/1 lenses	Spherical illumination system, f/0.47 lenses and elliptical mirrors	f/2.5 lenses	f/1 lenses
Target and experimental configuration	Diam: 40-100 μm Wall: 0.6-1 μm DT fill: 0.5-8 mg/cm^3 Vary delay between incident beams from 0 - ∞ ps	Diam = 60-120 μm Wall: 0.4-1 μm DT fill $\approx$ 2 mg/cm^3 One- and two-sided illumination	Diam $\approx$ 80 μm Wall $\approx$ 0.8 μm DT fill $\approx$ 2 mg/cm^3 One- and two-sided illumination	Diam $\approx$ 80-140 μm Wall $\approx$ 0.7-1.2 μm DT fill $\approx$ 2 mg/cm^3 One- and two-sided illumination
Absorption, %	27 $\pm$ 4	20 - 30 Focusing geometry dependent	13 $\pm$ 4	22 $\pm$ 4
Neutron yield	10 ⁴ - 6 $\times$ 10 ⁶ Depending upon beam delay and target configuration	10 ⁴ - 1.5 $\times$ 10 ⁷ Target and focusing geometry dependent	Maximum yield 4 $\times$ 10 ⁶ at 0.54 TW, 67 ps	10 ⁶ - 7 $\times$ 10 ⁸ Target, power, and pulsewidth configuration dependent
Main experimental results	<ul style="list-style-type: none"> Initial experiments exploring the parameter space of exploding pushers First observation of polarization dependent 1.06-μm scattered light First observation of improved thermal conduction at higher intensities and higher specific energy First measurement of DT ion temperature and proof of thermonuclear burn 	<ul style="list-style-type: none"> Spherical compression increases yield by $\sim$ 2.5 X-ray pinhole/streak gives r-t implosion diagram Verification of angle dependent absorption mechanisms 	<ul style="list-style-type: none"> Studied the effect of high f-No. on absorption Zone plate coded images of x-ray emission Polarization dependent heating observed in x-ray images 	<ul style="list-style-type: none"> High power performance Conclusive evidence for polarization dependent absorption DT ion temperatures determined from N and α TOF and D³He proton measurements Imaged α-particles Indication of density profile steepening by polarimetry measurements

Experimental results

Shot 5 on 6/24/75

Total energy on target: 28.3 J

Pulse width (FWHM): 73-ps

Energy absorbed: 7.4 J

Thermonuclear yield: $N(n) = (2 \pm 0.4) \times 10^6$
 $N(\alpha) = (1.3 \pm 0.5) \times 10^6$

DT ion temperature from
 α time-of-flight: $T_{\text{ion}} \lesssim 2.5$ keV

Integrated x-ray emission
($0.3 \text{ keV} \lesssim h\nu \lesssim 17 \text{ keV}$): $E_x \sim 0.4$ J

Marginal rays of
focused laser beams
from f/1 lenses, where
intensity $\approx 25\%$ of
peak intensity.

14.5 J

13.8 J

LASNEX simulation

Energy absorbed: 7.5 ± 0.4 J

Neutron yield: $(3.7 \pm 2) \times 10^6$

DT ion temperature: 1.7 ± 0.2 keV

Integrated x-ray emission

($h\nu > 0.3 \text{ keV}$) 0.52 ± 0.03 J

Target diam = $85.7 \mu\text{m}$
Wall thickness = $0.64 \mu\text{m}$
DT fill = 2 mg/cm^3

Fig. 5-90. Typical exploding pusher performance.

The reasonably close agreement between the LASNEX calculations and the experimentally observed values in Figs. 5-90 and 5-91 is not fortuitous. Throughout the entire experimental series, numerous simulations were performed to "pin down" the relevant physics and determine as many as possible of the adjustable parameters in the code. This was also aided by basic plasma physics work and code development to model the specific laser plasma interaction experiments described in this and last year's annual report. The success of this

cooperation between experiment-code simulation-plasma physics and back to experiment again, is demonstrated by the fact that a consistent set of parameters in the LASNEX code now produces agreement to within a factor of two or better with most experimental observables over the entire 0.2- to 4.5-TW range. This agreement between the experiments and the code calculations, and more specifically, the occasional disagreement, teaches us more about the physics of laser-induced implosions. This is discussed more thoroughly in § 5-5.2.

Fig. 5-91. (a) Continuous x-ray spectrum for the experiment shown in Fig. 5-90. The calculation is from Ref. 98. (b) Time-integrated x-ray microscope images in the 0.8- and 2.5-keV region of the x-ray spectrum. Both the initial target diameter and the final imploded state are clearly visible.

Shot 75062405, $\Delta t = 0$, $h\nu \approx 2.5 \text{ keV}$

Shot 75062405, $\Delta t = 0$, $h\nu \approx 0.8 \text{ keV}$

In the rest of this section, we summarize and synthesize the results from all the experimental facilities and the various focusing geometries and power levels, in terms of various physical phenomena. Thus, we address the question of absorption, discuss pusher dynamics, and deal with the neutron yield and thermonuclear burn regions.

Absorption

The fraction of incident 1.06- μm light that is actually absorbed in the laser plasma interaction experiment is one of the more controversial questions in the literature. Values ranging from 20 to 80% for simple targets and irradiation levels from 10^{13} to 10^{17} W/cm² have been reported^{76,92,103-105}. Using the box calorimeter (see the 1975 Annual Report for details), we have made absolute measurements of the total amount of 1.06- μm light that is *not* coupled to the target — is in good agreement with 1.06- μm optical energy balance measurements and with plasma calorimeter measurements made at numerous discrete points around the target when the box calorimeter is absent and extrapolated to a full 4π coverage. Figures 5-92(a) and (b) show the absorption results for the exploding pusher targets plotted

as a function of the *f*-No. of the focusing optics and solid angle covered by the converging laser beams. All the data are for the tangential focusing scheme discussed above. The data points plotted are the average of at least five experiments (in most cases more than 10) with the one exception shown. The error bars show the rms standard deviation, or variation, in the experiments.

Data from the box calorimeter, 1.06- μm optical energy balance, and plasma calorimetry are in good agreement. All the data are for DT-filled SiO₂ microspheres approximately 80 μm in diameter and 0.7 μm thick. The absorption as a function of focusing geometry for the spherical illumination system was discussed in § 5-1.2. All absorption data is in good agreement with plasma simulation results as evidenced both by the data shown in those sections and the data shown in Fig. 5-93. Here we plot absorbed energy as a function of microsphere target diameter for the Janus experiments, using *f*/*l* lenses at about 0.4 TW. The fraction of absorbed energy is seen to vary from about 23 to 28%. Using an absorption model that included the effects of resonance absorption and absorption due to parametric decay instabilities, J. J. Thomson of Livermore computed the expected absorption as a function of target diameter.¹⁰⁶ This is shown as the

Fig. 5-92. (a) Absorption data for exploding pusher targets as a function of focusing geometry data plotted as a function of solid angle of the focusing optics. (b) Data are for 70- to 85- μm -diam SiO₂ microspheres. Data points are offset horizontally for clarity. Open symbols are for ~0.4 TW. Closed symbols are for > 2 TW. Error bars give the rms deviation from the mean, except where indicated.

Fig. 5-93. Comparison of experimental and theoretical absorption values for exploding pusher targets of varying initial diameter. The experimental points are from Janus using f/1 lenses at ~0.4 TW. The calculation is from Ref. 106.

solid line in Fig. 5-93. The reasonable agreement between the simulation and the measurements is additional evidence for the existence and the importance of collective absorption mechanisms for this regime of laser plasma interaction experiments. (We note that calculations of absorption due to inverse bremsstrahlung result in less than one-fifth of the actual absorbed energy.)

There can no longer be any doubt that classical inverse bremsstrahlung is insufficient to explain the absorption data measured not only on the glass microspheres, but on a series of simple targets such as Parylene disks and glass disks doped with a variety of high-Z materials. This statement is supported by the experimental data shown in Fig. 5-94. Here we plot the fraction of absorbed energy as a function of incident intensity for Parylene disks and glass disks doped with Pb and W. The two colored bands in the figure are the result of a simple model by Kruer¹⁰⁷ of the absorption expected from inverse bremsstrahlung in the absence of profile modification. If the absorption at 10^{13} W/cm² is attributed to inverse bremsstrahlung alone and the equation in Fig. 5-94 is solved for the gradient scale length L , we arrive at a value of $L \sim 2 \mu\text{m}$, a number which is consistent with the polarization measurements of the scattered $1.06\text{-}\mu\text{m}$ light mentioned in § 5-7.2. It seems clear that collective absorption mechanisms and density profile modification by light pressure are extremely important for these experiments. In addition, experimental data consistent with the existence of both Brillouin side and backscattered light, and resonance absorption has been measured at LLL and other laboratories. At Livermore, all the data we have taken on laser plasma interaction experiments using photodiodes and plasma energy

Fig. 5-94. Absorbed energy fraction for parylene ($\langle Z \rangle \sim 3$) and tungsten glass ($\langle Z \rangle \sim 25$) disks as a function of incident intensity. Data are from the Janus, Cyclops and Argus lasers. The colored bands are based on theoretical predictions from Ref. 107.

$\langle Z \rangle = 25$
 $\langle Z \rangle = 3$

Fig. 5-95. Continuous x-ray spectra for exploding pusher targets at ~0.4 to ~4 TW and f/0.07, f/1 and f/2.5 lenses using the Janus, Cyclops, and Argus lasers.

calorimeters to measure both the scattered 1.06- μm light distribution and the plasma energy distribution has shown a marked difference in and out of the plane of polarization. Figure 5-68 shows a very good example of this phenomenon. The top graph shows the scattered light distribution in and out of the plane of polarization. The fact that more light is scattered out of the plane of polarization than in the plane of polarization is consistent with both stimulated Brillouin side scatter and resonance absorption. The fact that the ratio is as high as 4:1 indicates that both processes may exist at the same time. However, that data alone are not sufficient to distinguish between the two. As we look at the plasma blowoff energy distribution in the lower part of the figure, we notice an asymmetry in and out of the plane of polarization there also. However, in this picture there is more plasma energy seen in the plane of polarization than out of the plane of polarization. The ratio here is only about 15 to 20% higher in the plane of polarization, but that data in conjunction with the scattered light distribution is consistent with the existence of a polarization dependent absorption mechanism such as resonance absorption. (In March of 1977, a series of experiments were concluded on the Janus laser facility using Parylene disk targets that positively showed the existence of angle- and polarization-dependent absorption mechanisms consistent with resonance absorption.) By measuring the amount of depolarization of the scattered light with polarimeters and comparing this with calculations for 1.06- μm light incident upon a linear density profile, Phillion⁹³ has estimated that density profile steepening, producing scale lengths of the order of 1 μm , exists in the exploding pusher experiments. The existence of such scale lengths, which can be generated by the laser radiation pressure present at these high intensities, is consistent with the large absorption attributed to collective absorption processes.

The important role played by collective absorption mechanisms is also clearly evident from the presence of a superthermal component in the spectrum of x rays, electrons, and ions. Figure 5-95 shows an example of the x-ray spectra from exploding pusher targets illuminated with 0.3 to 4 TW using all three focusing geometries. The increase in amplitude, both with absorbed energy and power, is evident. Equally obvious is the hardening of the superthermal portion of the spectrum ($h\nu \lesssim 10 \text{ keV}$) with increasing intensity. This latter effect is more

clearly demonstrated in Fig. 5-96, where we plot the "temperature" associated with the superthermal component of the x-ray spectrum as a function of the incident intensity times the laser wavelength squared. Data are shown both for 1.06- μm experiments and the 10.6- μm experiments. Although the spread in data is reduced with this scaling, the variation of the superthermal temperature with target material and target geometry indicates that the subject of superthermal x-ray scaling is not a closed book.¹⁰⁸ Figure 5-97 shows two examples of the electron spectrum for a typical 80- μm diam, 0.8- μm wall-thickness glass microsphere that has been irradiated with approximately 0.4 and 4 TW. The hardening of the spectrum or conversely the shift of the peak to higher energies with increasing laser intensities is obvious and consistent with the data shown in Fig. 5-96. Figure 5-98 shows another example of the electron spectrum, this time for a series of 80- μm -diam microspheres illuminated on the Janus facility, using one or two beams at about 0.2 TW per beam. The electron spectrum is shown as a function of delay between the two beams incident upon the target. The apparent hardening of spectrum as one beam was delayed 42 ps, then 84 ps, and then infinity ps, with respect to the other, is not well understood at present.

The existence of superthermal, or very fast, ions has long been well known. Measurements of these fast ions using the wide-band ion spectrometer has been discussed in Section 3 and Ref. 91. Referring to Fig. 5-69, we note the existence of protons with energies in excess of 0.5 MeV. The existence of such high energy protons is clearly in agreement with the existence of high energy electrons as evidenced both by the superthermal x-ray spectrum in Figs. 5-95 and 5-96 and the electron spectra in Figs. 5-97 and 5-98. The question of the fraction of absorbed energy carried away by fast ions with kinetic energies in excess of 60 keV/a.m.u. has already been discussed above.

The effect of absorption is also evident in the thermal portion of the x-ray spectrum; Fig. 5-99 shows an example of the "temperature" associated with this thermal portion of the x-ray spectrum as a function of the specific total absorbed energy. This is defined as the total absorbed energy divided by the total target mass. The increase in this temperature with the increase in specific absorbed energy is in general in agreement with the predictions of this behavior discussed in § 5-5.2.

Fig. 5-96. Observed and calculated superthermal x-ray tail slope, θ_h , scales with the incident intensity times the wavelength squared. Data are shown for both 1.06- and 10.6- μm laser plasma interaction experiments from several laboratories.

Fig. 5-97. Electron spectrum for exploding pusher targets as a function of incident power for $f/1$ lenses. Both shots for $\sim 80\text{-}\mu m$ -diam, $\sim 0.8\text{-}\mu m$ wall-thickness SiO_2 microspheres.

Fig. 5-98. Electron spectra for exploding pusher targets as a function of delay between the two beams incident upon the target. Each beam had an ~ 15 J in ~ 70 -ps FWHM laser pulse.

The existence of inhibited electron conduction mechanisms has already been mentioned above. The fact that the heated areas on an x-ray microscope image of an irradiated microsphere are confined approximately to the areas where the laser beam heated the target may be taken as evidence for inhibited thermal conductivity. We mentioned above, that classical conductivity at temperature of about 1.5 keV would have differenced the energy over a distance appreciably larger than the target diameter in the time scale of the laser pulse. However, the existence of megagauss thermoelectrically generated magnetic fields, and magnetic fields produced by resonance absorption, is one mechanism that would have reduced this conduction length to $10 \mu\text{m}$ or less. This number would be consistent with the data shown in Fig. 5-91(b).

Figure 5-100 shows another example of the effect of inhibited electron conduction. Here we show an x-ray microscope image, in the 0.8-keV region, of an exploding pusher target irradiated from one side only. It is clear from the picture that the pusher did not traverse the entire target diameter before stagnating. The emission from the fluid dynamic convergence point (i.e., where the side that was heated by the laser converges and converts parts of its kinetic energy to thermal energy before it expands again) is quite distinct, and only a few

microns past the original target center. It is also equally clear that after convergence, the now expanding pusher only traversed about 60% of the original radial dimension before stagnation. A

Fig. 5-99. The "temperature" associated with the thermal portion of the x-ray spectrum for exploding pusher targets increases with total specific absorbed energy.

Fig. 5-100. X-ray micrograph of an exploding pusher target irradiated with one beam only. Shot 75062506 on Janus. 14.9 J in 75 ps-FWHM. Micrograph is in the 0.8-keV region of the x-ray spectrum.

reasonable hypothesis is that the back surface acquired sufficient energy to move in about 40% of the initial radius, but not sufficient energy to radiate enough energy in the 0.8-keV region to be measured. Again, if classical transport mechanisms were dominant, the energy would have had more than sufficient time to diffuse around to the back side of the target to heat it to a level where emission should have been observed. Detailed LASNEX calculations¹⁰ indicate that the rear surface of the target is initially heated to few eV by the transport of superthermal electrons produced in the laser-heated plasma. However, this is an insufficient temperature for an isothermal expansion to proceed to the 40% stagnation point, which is indicated in the x-ray microscope image. The calculations indicate that inhibited thermal electron transport from the absorption region through the glass shell raises the temperature to a few tens of eV, giving it a mean velocity of about 3×10^6 cm/s, which is sufficient to produce the effect seen in Fig. 5-100. This experiment also provides us with more information concerning the nature of inhibited thermal transport in

these targets. In § 5-1.4, we discussed LASNEX calculations of a similar one-sided experiment that show the effects of the inhibited conduction.

An apparent reduction in the conduction inhibition mechanisms was observed in the Argus experiments, as compared with the Janus experiments, as the incident intensity was increased above 10^{16} W/cm², keeping the target size fixed at about 85 μ m in diameter. This reduced inhibition was deduced from the increased symmetry of the x-ray emission in the x-ray microscope images, indicating that thermal conduction was able to produce more uniform heating of the target. Figure 5-67 shows an example of this effect. Similar observations were made in the experiments on the Janus laser by keeping the incident power fixed and decreasing the target diameter. This is shown in Fig. 5-60.

The information in this latter figure clearly raises the question whether the effect observed is mainly due to the about sixfold increase in specific absorbed energy and incident intensity caused by the about sixfold decrease in target mass, or the about two-and-a-half-fold decrease in target size. Figure 5-101 presents data relevant to this question. Here we show x-ray microscope images of four targets irradiated at about 1.2, 0.4, 1.9, and 2.8 TW, respectively. For the Janus shot, 75062405, the incident intensity and specific absorbed energy was 1.7×10^{15} W/cm² and 0.20 J/ng, respectively. For the three Argus experiments, the values are (4.1×10^{15} W/cm², 0.19 J/ng), (9×10^{15} W/cm², 0.27 J/ng), and (1.2×10^{16} W/cm², 0.44 J/ng) for shots 36091310, 36091408, and 36101203, respectively. For the experiments shown in Fig. 5-6, we have to increase the specific absorbed energy (and the incident power) by a factor of at least three to observe an appreciable effect. Referring to Fig. 5-101 and comparing shots 75062405 and 36091408, we observe the same increase in the x-ray emission symmetry for an about fivefold increase in intensity, although the specific absorbed energy has only increased by 35%. The shot 36091310, with a 109- μ m-diam ball, has nearly the same specific absorbed energy as the Janus shot and shows an x-ray image with the same lack of symmetry although the intensity is up by a factor of approximately 2.5. This shows the effect of increased target size on the conduction process. The shot 36101203, with about seven times the intensity and twice the specific absorbed energy of the Janus shot, shows the much increased x-ray emission symmetry obtainable at

75062405

Janus

$$D = 85 \mu\text{m}, w = 0.64 \mu\text{m}$$

$$E = 28.3 \text{ J}, \tau = 73 \text{ ps}$$

$$I = 1.7 \times 10^{15} \text{ W/cm}^2$$

$$E_A/M = 0.20 \text{ J/ng}$$

360913010

Argus

$$D = 109 \mu\text{m}, w = 0.9 \mu\text{m}$$

$$E = 53.9 \text{ J}, \tau = 35 \text{ ps}$$

$$I = 4.1 \times 10^{15} \text{ W/cm}^2$$

$$E_A/M = 0.19 \text{ J/ng}$$

36091408

Argus

$$D = 83 \mu\text{m}, w = 0.77 \mu\text{m}$$

$$E = 53 \text{ J}, \tau = 28 \text{ ps}$$

$$I = 9 \times 10^{15} \text{ W/cm}^2$$

$$E_A/M = 0.27 \text{ J/ng}$$

36101203

Argus

$$D = 87 \mu\text{m}, w = 0.65 \mu\text{m}$$

$$E = 82 \text{ J}, \tau = 29 \text{ ps}$$

$$I = 1.2 \times 10^{16} \text{ W/cm}^2$$

$$E_A/M = 0.44 \text{ J/ng}$$

Fig. 5-101. An increase in the total specific absorbed energy, the incident intensity, or reduction in characteristic scale, improves the symmetry of the x-ray emission and compression. Examples of x-ray micrographs (in the 2.5-keV region) from Janus and Argus using f/1 lenses are shown for varying intensity and specific absorbed energy. E_A is the absorbed energy and M is the mass of the fuel ball.

higher intensities. As mentioned earlier and discussed both in the next section and in Section 4, the lack of uniform heating in the low power experiment on Janus could be caused by thermoelectrically generated megagauss fields inhibiting the electron thermal conduction. The data from Fig. 5-6, Fig. 5-67, and Figs. 5-100 and 5-101 seem to indicate two conditions: (1) at higher intensities, and/or specific absorbed energy, we either have generated a sufficiently high temperature to increase the conduction scale lengths to a point where the energy has time to symmetrize the heating, or (2) based upon the shot 36101203 in Fig. 5-101, where the pulse length was only 29 ps and yet we have a very symmetric image, the increased conduction at early times in the pulse may prevent the magnetic fields from growing sufficiently large to impede the thermal conduction. Clearly more experiments at different power levels and using different target sizes, coupled with measurements of the time-dependent thermoelectrically generated magnetic fields are needed before a definitive answer of the relative importance of the various effects can be determined.

Finally, the asymmetry in and out of the plane of polarization in the plasma blowoff energy distribution (already discussed in connection with collective absorption mechanisms and shown in Fig. 5-68) is also corroborative evidence for inhibited thermal conduction. The fact that, even at a distance of about 10^4 times the target dimension, the signature of the polarization-dependent absorption is observed by preferential plasma energy emission in the plane of polarization suggests the existence of strong thermal conduction inhibition mechanisms.

Pusher Dynamics

The first measurements giving an indirect measure of the implosion time scales, and consequently mean pusher velocities, were the beam-delay experiments on Janus described in the 1975 Annual Report. One of the beams irradiating the standard about 80- μ m-diam microspheres was delayed 42 and 84 ps with respect to the other beam, and finally, the target was exposed to one beam only. Both the variation in neutron yield with beam delay and the motion of the stagnation region away from the original target center in these experiments indicated implosion time scales of 120-150 ps, or conversely, mean implosion velocities of 2.0 to 2.7

$\times 10^7$ cm/s.* These implosion time scales were also corroborated by x-ray streak camera measurements during these series of experiments.⁸⁵

A more complete picture of the implosion dynamics, however, was obtained on Janus using the spherical illumination system. Here a series of space, time, and space-time-resolved x-ray data were obtained on a target of differing diameter.^{83,84,86} Figures 5-102 through 5-104 show data from the x-ray microscope, x-ray streak camera, and x-ray pinhole/x-ray streak camera from these experiments.

The x-ray microscope image (in the 2.5-keV region of the spectrum) in the upper left corner of Fig. 5-102 shows the x-ray emission from the initial surface area of an about 120- μ m-diam SiO_2 microsphere. The "imprint" of the laser beam, from the 81.5° focusing optics, associated with angle-dependent absorption, is clearly visible. This emission is associated with the heating of the pusher prior to the explosion and subsequent inward implosion and compression. The central emission region of this image is interpreted as resulting from the conversion of pusher kinetic energy to thermal energy as the pusher stagnates. Thus, although the x-ray microscope image is time integrated, the nature of the explosion/implosion, in effect, generates a time-resolved image. To the right of the x-ray microscope image, we have data from the x-ray streak camera, also in the about 2.5-keV region. The double-peaked trace is the result from a typical target shot, with the first peak again associated with the laser heating of the pusher, and the second peak ascribed to the conversion of kinetic energy to thermal energy at stagnation time. The drop in emission immediately following the first peak, as well as the absence of emission between the outer ring and the central spot in the x-ray microscope picture, is a signature of a target whose mass is large enough to cause the heating prior to the explosion to take an appreciable fraction of the total absorbed energy. The time delay between the two peaks is a measure of the implosion time for this target. Finally, the lower left picture in Fig. 5-102 shows data obtained with a x-ray pinhole/x-ray streak camera combination. Basically the data are obtained by using an x-ray pinhole camera to image the x-ray emission

*The pusher for an 80- μ m-diam target typically travels 30 to 32 μ m before stagnating.

Shot No.	76073002	76082002
Diameter (μm)	125	105
Wall (μm)	0.86	0.75
Laser Power (TW)	0.45	0.28
Pulse FWHM (ps)	79	100

Fig. 5-102. Space- and time-resolved x-ray emission from large ($>100 \mu\text{m}$) exploding pusher targets. Experiments were done on Janus with the spherical illumination system.

from the target onto the slit-shaped photocathode of an x-ray streak camera.⁸⁶ These experiments are described in detail in § 5-1.3. It is sufficient here to point out the consistent behavior demonstrated in this r-t diagram. At early times we observe the heating of the shell at two points separated by the initial target diameter. As the shell explodes and expands both inward and outward, the emission drops below the detectable level, and it is not until approximately 160 ps later that we observe the emission from the stagnation region.

In contrast, Fig. 5-103 shows data from a much smaller target. In the upper left corner we show the x-ray microscope image of this smaller target. Here the target explodes much earlier in the irradiation pulse, and consequently the stagnation of the imploding pusher occurs while the laser power is still increasing. This causes a continuing increase in the x-ray emission during convergence. We also note the enhanced electron conduction for this target as evidenced by the much more symmetric x-ray emission at the equator of the target where the laser

Fig. 5-103. Space- and time-resolved x-ray emission from small ($< 70 \mu\text{m}$) exploding pusher targets. Experiments were done on Janus with the spherical illumination system.

beam was not efficiently absorbed and did not directly heat the target. The corresponding x-ray streak camera and x-ray pinhole/x-ray streak camera data are displayed on the upper right and lower left corner of Fig. 5-103, respectively. The continuing increase in x-ray emission during the implosion is evident in both pictures, as well as the shorter implosion time scale associated with the smaller target.

In Fig. 5-104 we show data from a target that did not perform successfully. The right side of Fig. 15 shows the time-resolved x-ray streak camera data

for this experiment. We observe that the second peak, the stagnation emission peak is absent. On this shot, the target was exposed to a few-millijoule prepulse about 1 to 2 ns prior to the arrival of the main pulse. This prepulse level is above the damage threshold for these targets.¹¹⁰ In this case, the target has partially disassembled before the main laser pulse arrives. We observe a peak in the emission caused by absorption and heating of the disassembled target, but the integrity of the target has been destroyed, and consequently, there is no material that is effectively accelerated inward to compress

the fuel. In addition, this target produced no detectable neutrons, providing additional evidence for our interpretation of the x-ray data. The picture on the left side of Fig. 5-104 shows the time-integrated x-ray microscope image of this target shot. The target was originally about 40 μm in diameter. Yet the outer edges of the image in Fig. 5-104 are greater than 60 μm in diameter, in contrast to the data obtained for a no-prepulse shot where the x-ray microscope image equals the initial size of the target. In addition, we observe the rather "fuzzy" appearance of the image. The interpretation is that the small prepulse caused the glass shell to shatter, but clearly did not heat it up sufficiently to cause any radiation in the keV x-ray region. The main

pulse arrived about 1 to 2 ns after the prepulse and heated up the expanding target fragments. The "expansion velocity" of a 10^5 to 10^6 cm/s obtained from this data is consistent with the target mass and the energy in the prepulse. The absence of a well-defined compression or stagnation emission peak is consistent with both the time-resolved data and our interpretation.

The complementary picture obtained from these three diagnostics is quite satisfactory and in substantial agreement with the behavior of an exploding pusher contained in Section 4 and § 5-5.2 and 5-5.3. Together with the beam-delay series in Janus, they have also given a consistent set of values for the pusher implosion velocities.

Shot No.	<u>75060406</u>	<u>76081802</u>
Diameter (μm)	41.2	103
Wall (μm)	1.29	0.96
Laser power (TW)	0.49	0.41
Pulse width (ps)	63	71
Prepulse (mJ)	>5	~2

Fig. 5-104. Space- and time-resolved x-ray emission from an exploding pusher target that was destroyed by a few mJ-prepulse, a few nsec prior to the main laser pulse.

Neutron Yield

The neutron yield is a very sensitive indication of the success of an exploding pusher experiment. As shown in Section 4 and § 5-5.3, the neutron yield scales as $< \sigma v > T_{\text{ion}}^{-1/2}$ for targets with identical diameter, wall thickness, and DT fill. In the region of $1 \text{ keV} \lesssim T_{\text{ion}} \lesssim 10 \text{ keV}$, this means that the neutron yield will scale as T_{ion}^α with $2.5 \lesssim \alpha \lesssim 5$. From the discussion of the behavior of an exploding pusher in the introduction above and in Section 4 and § 5-5.3, it is clear that the final DT ion temperature is strongly dependent upon both the absorbed energy and the rate at which this energy is coupled to the target. Figure 5-105 shows this behavior where we plot the neutron yield as a function of total absorbed power. Data from all three facilities and all four focusing geometries are included. Data points are only plotted if the prepulse level was below the damage threshold and if the temporal behavior of the focused laser pulse was not significantly distorted by beam breakup. Data are from Hyperion targets with about 2 mg/cm^3 of DT fill. The general trend of increasing neutron yield with increasing power is obvious. However, equally obvious is the fact that there is no unique scaling rule that would fit the data. This is because in this way of plotting the yield, no allowance is made for variation in the target diameter, the target wall thickness, and the matching of the laser pulse-width to the target implosion time scale.

Figure 5-106 shows another way of plotting the data and one step further toward defining the proper scaling parameter. Here we plot the neutron yield normalized with $r^{10/3}$ and $w^{2/3}$ as a function of ϵ , the total absorbed energy divided by the mass of DT-filled glass microshell. (The mass of the DT fuel is always $\ll$ the mass of the glass microshell.) As shown in Section 4 and discussed in § 5-5.3, the neutron yield should scale as

$$N \sim r^{10/3} w^{2/3} < \sigma v > T^{1/2} \quad (3)$$

for targets with constant DT fill. If we assume T is proportional to the total specific absorbed energy and match the temperature to a mean of the experimentally observed values, we can construct the solid line in Fig. 5-106. Although this is clearly a more appropriate way of plotting the data,

measured in terms of deviations from an observable trend, there are still a few points that deviate significantly from this otherwise obvious trend. These data points are from target experiments with a total absorbed energy and pulse length that were not optimally matched to the target diameter and wall thickness. The concept of useful specific energy and a derivation of simple scaling rules that fit all the data better is discussed in § 5-5.3.

By selecting the peak target performance from each set of experiments on the various laser facilities we obtain another interesting scaling result. This is shown in Fig. 5-106(a) where we plot the yield efficiency, defined as the ratio of the thermonuclear yield to the incident laser energy, as a function of peak incident power. We observe that by optimum matching of the target with the focusing characteristics and incident power, the neutron yield scales approximately as the peak power squared.

The variation of neutron yield with target diameter is discussed in § 5-5.3. A strict comparison of neutron yield versus target diameter is not meaningful because the pulse length, target wall thickness, and useful specific absorbed energy varied sufficiently for the different target sizes that were irradiated at the different facilities and different power levels.

The variation of neutron yield with the time delay between the two beams irradiating the target and the variation of neutron yield with initial DT fill, or pressure, was discussed in the 1975 Annual Report. Similar experiments were not carried out as a parameter study on the Cyclops and Argus facilities. Figures 5-107 and 5-108 show results from the Janus experiments for completeness. Figure 5-107 shows the neutron yield as a function of beam delay, indicating the obvious trend of decreasing neutron yield with the decreasing compression symmetry caused by the beam delay. It is interesting to note that the same reduction in neutron yield can be obtained even when the pulses are coincident in time if the energy in one beam is reduced with respect to the other. Thus an experiment where the energy in one beam was reduced by a factor of 10, gave approximately the same reduction in neutron yield as a beam delay of 84 ps. Figure 5-108 shows the variation of neutron yield with initial DT fill. It is clear that for no DT fill the neutron yield is zero. Increasing the fill from a low value, we are simply to "first order," providing more thermonuclear fuel to burn, causing the yield to increase. However, for

Fig. 5-106. Neutron yield normalized with radius and wall thickness as a function of useful specific absorbed energy.

fixed laser energy on target, a point comes when the increased amount of fuel is offset by the decrease in compression and, consequently, also in DT ion tem-

perature, and the yield decreases with increasing fill. Figure 5-108 also gives results from a one-dimensional LASNEX simulation,¹¹¹ showing that

the code predicts basically the experimental results. This is also discussed in more detail in § 5-5.2 for targets irradiated at a different power level.

Thermonuclear Burn and Compression

As discussed in detail in Section 3 and § 5-3.2 and 5-6.3, the fuel-averaged DT ion temperatures at the time of peak neutron production have been measured using neutron and α -particle time-of-flight techniques. A measurement of the temporal distribution of the thermonuclear reaction products at a detector station can be unfolded to produce the energy distribution of the particles in the actual thermonuclear burn region. For the case of the neutrons, broadening corrections are negligible. For the α -particles, however, interactions of the α -particles with the fuel and the pusher broaden the observed distribution. In this case, relating the FWHM of the α -particle energy spectrum to the

fuel-averaged DT ion temperature, leads to an upper bound for this temperature. Table 5-8 and Figs. 5-62 and 5-63 give examples of results from the neutron and α -particle time-of-flight measurements from the Argus experiments. Average temperatures of up to 8 keV have been observed for the high neutron-producing experiments. Figures 5-107 and 5-108 show results from neutron and alpha-particle time-of-flight measurements as a function of absorbed power and total specific absorbed energy. We plot the measured FWHM, in keV, of the time-of-flight distribution of the thermonuclear particles. The conversion from FWHM of the energy distribution to ion temperature, as given by ΔE (FWHM in keV) = $177\sqrt{T}$ (keV) is shown on the right-hand side of the figures, as an indication of the upper limit of the ion temperature. We note that this expression assumes not only negligible broadening corrections, but also that the fusion products result from interactions of two Maxwell-Boltzmann distributions of deuterons and tritons at the temperature T .

Fig. 5-107. Neutron yield is severely reduced by a temporal mismatch between the two laser beams irradiating an exploding pusher target.

Fig. 5-108. Neutron yield as a function of initial DT gas density. Solid line is from Ref. 110.

Another measure of the thermonuclear burn temperature can be found by filling the microspheres with a mixture of D_2 and 3He . A measurement of the ratio of the 3.0-MeV protons produced from the D-D reaction to the number of the 14.7-MeV protons from the D 3He reaction is a very sensitive indication of the fuel temperature in the 1- to 10-keV temperature range. These measurements were performed on the Argus laser and are discussed in detail in § 5-4.1 through 5-4.3. The results from those experiments are also shown on Figs. 5-109 and 5-110, indicating the agreement between the different methods.

Direct information about the condition of the DT fuel at the time of thermonuclear burn has been obtained by imaging the α -particles. These measurements were performed using both pinhole and zone-plate-coded imaging techniques, as discussed in Section 3 and § 5-3.3. In both cases, the thermonuclear

fuel region was measured to be confined within a 25- to 30- μ m-diam region, implying volume compressions of the fuel about 25 to 40. Within the resolution of the measurements (about 9 μ m for the zone-plate-coded images and about 13 μ m for the pinholes), we observed no deviation from a spherically symmetric burn region. Volume compressions of the order of 25 to 50 are also obtained from the x-ray microscope and x-ray pinhole/streak camera data if the width of the emission region from the stagnated SiO_2 pusher is taken as a measure of the fuel boundary at peak compression.

References

66. G. Charatis, et al., *Plasma Phys. and Controlled Nucl. Fusion Res. 1974, Vol. II, Session VIII*, pp. 317-335.
67. P. M. Campbell, G. Charatis, and G. R. Montry, *Phys. Rev. Lett.* 34, 74 (1975).

68. F. J. Mayer and D. C. Slater, *Bull. Am. Phys. Soc.* **21**, 1120 (1976).
69. I. Pelah, E. B. Goldman, and B. Yakobi, *Phys. Rev. Lett.* **37**, 829 (1976).
70. B. Yakobi, I. Pelah, and J. Hoose, *Phys. Rev. Lett.* **37**, 836 (1976).
71. B. H. Ripin et al., *Phys. Rev. Lett.* **34**, 1313 (1975).
72. B. H. Ripin, J. A. Stamper, and E. A. McLean, *Bull. Am. Phys. Soc.* **21** 1083 (1976).
73. D. V. Giovanelli, J. F. Kephart, and A. H. Williams, *J. Appl. Phys.* **47**, 2907 (1976).
74. D. V. Giovanelli, *Bull. Am. Phys. Soc.* **21**, 1047, (1976).
75. K. R. Manes, H. G. Ahlstrom, R. A. Haas, and J. F. Holzrichter, *Light Plasma Interaction Studies with High Power Glass Lasers*, Lawrence Livermore Laboratory, Rept. UCRL-78771 (1976).
76. R. A. Haas, W. C. Mead, W. L. Kruer, D. W. Phillion, H. N. Kornblum, J. D. Lindl, D. MacQuigg, V. C. Rupert, and K. G. Tirsell, *Irradiation for Parylene Disk with 1.06- μ m Laser*, Lawrence Livermore Laboratory, Rept. UCRL-77930 (1976).
77. H. G. Ahlstrom, J. F. Holzrichter, K. R. Manes, E. K. Storm, R. A. Haas, D. W. Phillion, V. C. Rupert, M. J. Boyle, and K. M. Brooks, *Plasma Experiments with 1.06- μ m Lasers at the Lawrence Livermore Laboratory*, Lawrence Livermore Laboratory, Rept. UCRL-77943 (1976).
78. J. T. Larsen, E. K. Storm, C. E. Max, and J. J. Thomson, *Absorption and Conduction in Spherical Laser Targets*,

Fig. 5-109. FWHM of the energy distribution from neutron and α -particle time-of-flight measurements for exploding pusher targets. Data are plotted as a function of total absorbed energy divided by the mass of the DT fuel ball. Data from the D^3He experiments are also plotted.

Fig. 5-110. FWHM of the energy distribution from neutron and α -particle time-of-flight measurements for exploding pusher targets. Data are plotted as a function of total absorbed power. Data from the D^3He experiments are also plotted.

- Lawrence Livermore Laboratory, Rept. UCRL-77901 (1976).
79. V. W. Slivinsky, H. G. Ahlstrom, K. G. Tirsell, J. T. Larsen, S. Glaros, G. B. Zimmerman, and H. Shay, *Phys. Rev. Lett.* **35**, 1083 (1975).
 80. J. F. Holzrichter, H. G. Ahlstrom, D. R. Speck, E. K. Storm, J. E. Swain, L. W. Coleman, C. D. Hendricks, H. N. Kornblum, F. D. Seward, V. W. Slivinsky, Y. L. Pan, G. B. Zimmerman, and J. H. Nuckolls, "Implosion Experiments with an Asymmetrically Irradiated Laser Fusion Target," *Plasma Physics* **18** 675, (1976).
 81. E. K. Storm, J. F. Holzrichter, H. G. Ahlstrom, D. R. Speck, J. E. Swain, L. W. Coleman, C. D. Hendricks, H. N. Kornblum, F. D. Seward, and V. W. Slivinsky, *The Effects of Fill Pressure and Pulse Simultaneity on the Laser Driven Implosion of DT Filled Glass Microshells*, Lawrence Livermore Laboratory, Rept. UCRL-77083 (1975); also *Bull. Am. Phys.* **20** 1266 (1975).
 82. E. K. Storm, H. G. Ahlstrom, and J. F. Holzrichter, *Exploding Pusher Targets Illuminated Using f/1 Lenses at ~0.4 TW*, Lawrence Livermore Laboratory, Rept. UCRL-78729 (1976).
 83. E. K. Storm, H. G. Ahlstrom, J. A. Monjes, J. E. Swain, V. C. Rupert, and D. W. Phillion, *Exploding Pusher Experiments Utilizing a 4 π Illumination System*, Lawrence Livermore Laboratory, Rept. UCRL-78730 (1976).
 84. K. R. Manes, D. T. Attwood, J. M. Auerbach, J. T. Larsen, D. W. Phillion, and J. E. Swain, *Spherical Microshell Targets Irradiated by the Janus 4 π Illumination System*, Lawrence Livermore Laboratory, Rept. UCRL-78449 (1976).
 85. D. T. Attwood, L. W. Coleman, J. T. Larsen, and E. K. Storm, *Phys. Rev. Lett.* **37**, 449 (1976).
 86. D. T. Attwood, L. W. Coleman, M. J. Boyle, D. W. Phillion, J. E. Swain, K. R. Manes, and J. T. Larsen, *Phys. Rev. Lett.* **38**, 282 (1977).
 87. G. H. Dahlbacka and J. H. Nuckolls, *Laser Driven Isothermal Implosion*, Lawrence Livermore Laboratory, Rept. UCRL-75885 (1974).
 88. J. H. Nuckolls, *Outlook for Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-76395 (1975).
 89. See Section 3 of this report.
 90. See § 5-5.1 through 5-5.3 of this report.
 91. S. S. Glaros, K. G. Tirsell, V. C. Rupert, H. C. Catron, and V. W. Slivinsky, *Measurement of High Energy Ions*, Lawrence Livermore Laboratory, Rept. UCRL-78427 (1976).
 92. V. C. Rupert, S. R. Gunn, J. F. Holzrichter, S. S. Glaros, and J. R. Severyn, *Particle and X-Ray Energy Measurement in Laser-Plasma Interaction Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-78439 (1977), submitted to *J. Appl. Phys.*

93. D. W. Phillion and R. L. Lerche, *Scattered Light Evidence for Short Density Scale Heights at Critical Density in Laser-Irradiated Plasma*, Lawrence Livermore Laboratory Rept. UCRL-78444 (1977), submitted to *Phys. Fluids*.
94. K. G. Tirsell, H. C. Catron, S. S. Glaros, and V. W. Slivinsky, *Laser Fusion Burn Diagnostics Using Several Alpha Time-of-Flight Spectrometers*, Lawrence Livermore Laboratory, Rept. UCRL-78487 (1976).
95. R. A. Lerche, L. W. Coleman, J. W. Houghton, D. R. Speck, and E. K. Storm, *Laser Fusion Ion Temperatures Determined by Neutron Time-of-Flight Techniques*, Lawrence Livermore Laboratory, Rept. UCRL-79375 (1977), submitted to *Phys. Rev. Lett.*
96. D. T. Attwood, L. W. Coleman, M. J. Boyle, J. T. Larsen, D. W. Phillion, and K. R. Mancs, *Space-Time Implosion Characteristics of Laser Irradiated Fusion Targets*, Lawrence Livermore Laboratory, Rept. UCRL-78784 Rev. 1 (1977).
97. V. W. Slivinsky, K. M. Brooks, H. G. Ahlstrom, E. K. Storm, K. N. Kornblum, and G. R. Leipelt, *Pinhole Imaging of Laser Implosion Thermonuclear Alpha Particles*, Lawrence Livermore Laboratory, Rept. UCRL-78879 (1976), submitted to *Appl. Phys. Lett.*
98. J. T. Larsen, *Computer Simultaneity of Laser Driven Implosion of DT Filled Glass Microballoons* Lawrence Livermore Laboratory, Rept. UCRL-77040 (1975).
99. L. Spitzer, *Physics of Fully Ionized Gases* (Interscience Publishers, New York, 1962), 2nd ed., 43.
100. J. A. Stamper and B. H. Rippin, *Phys. Rev. Lett.* **34**, 138 (1975).
101. J. J. Thomson, C. E. Max, and K. Estabrook, *Phys. Rev. Lett.* **35**, 663 (1975).
102. J. A. Stamper and D. A. Tidman, *Phys. Fluids* **16**, 204 (1973).
103. B. H. Rippin, *Appl. Phys. Lett.* **30**, 134 (1977).
104. N. G. Basov, A. A. Kologrivov, O. N. Krokhin, A. A. Rupasov, G. V. Sklizkov, and A. S. Shikanov "Observation of Compression of Hollow Microspheres by Laser Radiation," *JETP Lett.* **23**, (8), 428 (1976).
105. N. G. Basov, O. N. Krokhin, V. V. Pustovalov, A. A. Rupasov, V. P. Silin, G. V. Sklizkov, V. T. Tikhonchuk, and A. S. Shikanov, *Sov. Phys. JETP* **40** (1), 61 (1975).
106. J. J. Thomson, Lawrence Livermore Laboratory, private communication (May 1976).
107. W. L. Kruer, R. A. Haas, W. C. Mead, D. W. Phillion, and V. C. Rupert, *Collective Behavior in Recent Laser-Plasma Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-77730 (1976).
108. H. D. Shay, R. A. Haas, W. L. Kruer, M. J. Boyle, D. W. Phillion, V. C. Rupert, H. N. Kornblum, F. Rainer, V. W. Slivinsky, L. N. Koppel, L. M. Richards, and K. G. Tirsell, *Interaction of 1.06 μ m Laser Radiation with Variable Z Targets*, Lawrence Livermore Laboratory, Rept. UCRL-19438 (1977), submitted to *Phys. Fluids* (1977).
109. J. T. Larsen, Lawrence Livermore Laboratory, private communication (October 1975) and § 5-1.4 and 5-5.2.
110. J. F. Holzhrichter, R. Speck, and J. Swain, "Plasma Development in Low Z Laser Fusion Targets," *Bull. Am. Phys. Soc.* **19**, 855 (1974).
111. J. T. Larsen, Lawrence Livermore Laboratory, private communication (December 1976).

Author

E. K. Storm

Major Contributors

Scientific and technical personnel of the Laser Plasma Interaction Group and the Diagnostics Development Group of the Fusion Experiments Program.

5-5.2 Comparing LASNEX with Experimental Data

The previous article synthesized the data obtained from the LLL glass lasers to show the variation of key target parameters with illumination optics and power. In this article, the experimental results are compared with LASNEX calculations.

Figure 5-111 compares the calculated and measured absorption as a function of the f-number of the illumination optics. The reduced absorption with high f-No. occurs because with the f/1 and f/2.5 lenses the beam was focused tangentially onto the target ball to optimize the neutron yield. Hence, more of the light intercepts the sphere at large angles, which have smaller absorption coefficients. This effect is stronger for f/2.5 focusing so that the absorption is least. With the clamshell system, a sufficiently large fraction of the surface area was illuminated so that focusing could be adjusted to give maximum absorption without degrading the neutron yield as a result of an asymmetric implosion. The agreement of calculations with experiments supports the angle-dependent resonance absorption model derived from plasma simulation codes.

Figure 5-112 compares the measured and calculated superthermal x-ray "temperatures" (derived from the slope of the high energy portion of the x-ray spectrum) as a function of the laser intensity. The results confirm the hot electron model derived from plasma simulation code calculations.

Figures 5-113(a) and (b) compare the measured history of the position and velocity of the glass-DT interface with LASNEX calculation. Agreement is well within the experimental uncertainties. However, it should be noted that the position of the interface must be inferred from gradients in the diagnostic data. Consequently, the uncertainty is somewhat large. This comparison provides a crucial test of the LASNEX calculations of exploding

Fig. 5-111. Comparison of measured and LASNEX calculated absorption vs focusing optics. Variation with f -No. and power are correctly predicted by LASNEX using angle-dependent absorption parameters derived from calculations with LLL plasma simulation codes. Data are for 70- to 85- μ m-diam SiO_2 microspheres. Data points are offset horizontally for clarity. Open symbols are for ~ 0.4 TW, closed symbols for ≥ 2 TW.

pushers. This agreement would not occur (1) if absorption were mainly by inverse bremsstrahlung rather than resonance absorption, (2) if the implosion were ablative rather than exploding pusher, or (3) if a strong superthermal electron component were not present.

The characteristic signature of the LASNEX calculations of near-optimum exploding pusher capsules is an initial acceleration of the glass shell by a shock followed closely by explosion of this shell due to penetration by superthermal electrons. Figure 5-114 shows these effects. Finally, there is significant energy transport through the glass by the superthermal electrons that, in turn, accelerate the glass DT interface during most of the implosion.

Fig. 5-112. Comparison of experimental and LASNEX calculated superthermal bremsstrahlung temperature as a function of the peak laser intensity. The LASNEX superthermal prescription, derived from calculations with LLL plasma simulation codes, is in good agreement with the experimental data.

Fig. 5-113. Implosion history (position and velocity vs time) of the glass pusher shows a smooth acceleration and compression. The hatched areas are the measured quantities with uncertainties and the solid line is the LASNEX simulation.

The interface reaches maximum velocity when the pressure on the DT side of the interface becomes as large as the pressure on the glass side. Any energy absorbed from the laser after this time has no effect on the DT implosion and burn. Although the electron temperature in the DT may be affected, the DT ions are so strongly decoupled from the electrons that small changes in the electron temperature have no effect on the burn. These effects are illustrated in Fig. 5-115, which shows the effect on the implosion and burn of truncating the laser pulse at various times during the implosion.

Figure 5-116 compares the experimental and calculated variation of DT ion temperature with specific absorbed energy. At high ion temperatures agreement is good and meaningful. Good agreement at low ion temperatures is not so meaningful because there are uncertainties in interpretation of the experimental data because of large corrections that can only be determined by LASNEX calculations. Those experiments did not measure ion temperature, but instead the spread in the velocities of the reacting particles. At few keV temperatures there are large corrections because of the fluid Doppler effect and to energy loss in traversing the finite size target.

Fig. 5-114. The radial profiles of thermal electron temperature, ion temperature, and density in the vicinity of the glass shell is shown at the time of initial interface acceleration. Note shock and thermal electron front are moving together as inside of glass is reached. Hence, glass is compressed, then exploded. This behavior is typical of near-optimum exploding pusher designs.

Fig. 5-115. The calculated target performance is most sensitive to the first half of the laser pulse. The Gaussian temporal profile is shown as the dotted curve with three cutoff times A, B, and C. The interface velocity for three cases is plotted as a function of time, as indicated by the different broken lines. The solid line indicates the history for the case using the entire pulse, with the table showing the fractional quantities compared to this case.

The average energy loss suffered by the alpha particles in traversing the glass pusher is determined from the α time-of-flight. Janus experiments showed α -particle energy losses in the range of 250 keV, and Argus experiments have shown $100 \leq E_{\alpha} \leq 300$ keV. However, Argus experiments have a wide range of specific absorbed energy. The resulting temperature differences in the glass significantly affect the α energy loss. Calculations of

low and high power Argus experiments show the ρR of the glass to be approximately constant, but the glass temperature at the time of α -particle production varies by a factor of two or more. In addition, the electrostatic correction has not been experimentally or theoretically determined. Consequently, even though the observed and calculated α energy losses are consistent, the interpretation is not definitive.

Fig. 5-116. Comparison of experimental and calculated variation of DT ion temperature with specific absorbed energy. At temperature ≥ 4 keV, which were measured by α TOF, the corrections due to DT finite size, Doppler shift, etc., are so large that the temperature cannot be determined from experimental data without use of LASNEX to estimate correction factors. At higher temperatures the correction term is relatively small, and in addition measurements are possible with neutron TOF. However, since the neutron yield varies with such a high power of ion temperature in the few keV range, correct calculation of the neutron yield strongly implies correct calculation of the ion temperature.

Fig. 5-117. Comparison of observed and LASNEX-calculated neutron yields for Hyperion exploding pusher targets. Neutron yield is scaled by the inertial and mass dependent factors derived in § 4-1.2 and is plotted vs specific absorbed energy (which is approximately proportional to the DT ion temperature). Agreement is good.

Figure 5-117 compares the measured and calculated neutron yields. As has been noted, agreement is good over a wide range. The neutron yield has been divided by the temperature-independent factor derived in § 4-1.2 and is plotted against the temperature-related factor, specific absorbed energy. Since the neutron yield depends so sensitively on ion temperature, correctly predicting the neutron yield strongly infers correct calculations of the ion temperature.

The most important target parameter that has not been measured directly is the density of the imploded DT. An attempt to do this is described in a following article. In addition, the magnetic field and density — temperature distributions in the corona (including the density step from self steepening) are not well defined experimentally. Finally a great deal remains to be done to measure and interpret the spatial shape of the implosion and burn.

In summary, LASNEX has correctly calculated key parameters of the exploding pusher implosion and burn, both in specific cases and across a broad range in incident laser power and focusing solid

angle. We have done this without normalization to experiment by using classical fluid dynamics and transport physics in combination with models derived from plasma simulation code calculations of the effects of plasma turbulence and instabilities.

Author
J. Larsen

Major Contributor
J. H. Nuckolls

5-5.3 Exploding Pusher Scaling Model

A laser-irradiated target is said to operate in the exploding pusher mode¹¹²⁻¹¹⁴ when the pusher significantly decompresses in the process of compressing the fuel. The exploding pusher mode is characterized by a high rate of energy addition to

the pusher that causes a supersonic (or near supersonic) thermal wave propagation. Shock compression of the fuel ions and heat addition by electron thermal conduction from the laser energy-absorption region produce a large entropy change in the fuel. This results in a limited density increase, compression, and heating of the fuel. Of course, the laser pulse length is involved in determining the target dynamics; however, even if the pulse duration is long compared to the fluid dynamic implosion time, the pusher may still have exploded due to a high energy deposition rate. The determination of the fraction of the laser energy in a Gaussian pulse that contributes to the inward motion of the pusher and to the heating of the fuel is a central issue in exploding pusher scaling.

Articles 5-5.1, 5-5.2, and 5-1.2 cover experimental data and LASNEX calculations of exploding pusher targets. As has been shown with a variety of experimental configurations, two-dimensional LASNEX simulations produce excellent agreement with experimental data.

Each one-dimensional, exploding-pusher LASNEX calculation requires several minutes of CDC-7600 computer time. By reviewing many calculations of exploding pusher targets irradiated with temporally Gaussian pulses, we have noticed trends that provide estimates of quantities ultimately calculated by LASNEX. In this section, several trends are assembled into a scaling model that provides an estimate for one of the more sensitive indicators of target performance — the thermonuclear yield. In addition to providing a quick estimate of yield, this model suggests the variables against which the results of exploding pusher experiments should be plotted.

Scaling Laws for Exploding Pushers

The number of thermonuclear neutrons produced by a DT plasma, neglecting fuel depletion, is assumed to be given by

$$N = \int dt \int d^3r n_D n_T \langle \sigma v \rangle. \quad (4)$$

In general, this integral must be carried out over all time and space where n_D and n_T are deuterium and tritium number densities, and $\langle \sigma v \rangle$ is the Maxwell averaged DT cross section. Although not strictly correct, an estimate for the neutron yield of an inertially confined plasma may be made by assuming that the ions are isothermal at an ion temperature T and isotropic in a volume V for the duration of the burn time $\Delta\tau$. Consequently, we have

$$N \cong n_D n_T \langle \sigma v \rangle V \Delta\tau. \quad (5)$$

The fuel densities and volume prior to the laser-driven implosion are related to these parameters during the burn by the volume compression C . For an equimolar mixture of DT, $n_D = n_T = (n_0/2)C$, where n_0 is the initial fuel number density. Similarly,

$$V = \frac{4}{3} \pi r_0^3 / C,$$

where r_0 is the initial uncompressed fuel radius. An estimate for the burn time, $\Delta\tau$, arises from the assumption that the confinement reaction time is proportional to the time required for a rarefaction wave to traverse the fuel*; i.e., $\Delta\tau$ is approximately proportional to the compressed radius divided by the ion sound speed:

$$\Delta\tau \propto \frac{V^{1/3}}{a} \propto \frac{r_0}{C^{1/3}} \sqrt{\frac{m_{\text{ion}}}{\gamma k T}} \propto \frac{r_0}{C^{1/3} T^{1/2}}.$$

The Maxwell-averaged DT reaction cross section is accurately approximated¹¹⁵ by

*In this model, we have assumed that the reaction time is determined by the fluid dynamic disassembly of the fuel; in § 4-1.2, J. Nuckolls discusses some other phenomena which may determine $\Delta\tau$.

$$\langle \sigma v \rangle = 3.8 \times 10^{-12} T^{2/3}$$

$$\exp(-19.02/T^{1/3}) \text{ (Ref. 4),}$$

for $T \leq 10$ keV. Inserting these relations into Eq. (5) leads to

$$N \propto n_0^2 r_0^4 C^{2/3} T^{-7/6} \exp(-19.02/T^{1/3}). \quad (6)$$

To proceed, expressions must be found which relate the compression, C , and the final ion temperature, T , to the initial target parameters and the target irradiation history. Perhaps the simplest approach is to consider the compression determined when the density of the imploding half of the pusher shell equals the compressed density of the fuel. Because the pusher can hardly be expected to have a uniform density at stagnation, this can be a proportionality at best, i.e.,

$$\frac{\rho_s w r_0^2}{r_0^3} \propto C \rho_0,$$

so

$$C \propto \frac{w}{r_0} \frac{\rho_s}{\rho_0},$$

where ρ_s is the initial density of the pusher shell, w is its thickness, and ρ_0 is the initial fuel density. For a fixed-shell composition and initial fuel density, therefore, $C \propto w/r_0$.

The more difficult task is to relate the final ion temperature, T , to the energy and pulse shape incident on the target. The DT ion temperature is assumed to be approximately proportional to the useful portion of the specific energy deposited in the pusher. For most LASNEX calculations, this is found to be a good assumption. This is equivalent to the assumption of an effective specific heat for the exploding pusher target process. By evaluating the target dynamics from a large number of LASNEX simulations, a prescription has been

evolved that yields T , given the incident laser and target pulse characteristics. The heating of the target by temporally Gaussian laser pulses has been extensively simulated and divides into two phases. Initially, laser energy is deposited at the outer surface of the pusher until the inner surface implodes violently at a time t_c . Next, the pusher fuel interface is accelerated inward until it has moved a distance

$$\Delta r \cong 0.27 r_0$$

at a time t_c . Beyond this distance, LASNEX simulations (in which the implosion time and the Gaussian pulse width are well matched) suggest that laser energy deposited in the target corona does not contribute to the compression and heating of the fuel. Consequently the portion of the incident laser energy that is useful for fuel heating is given by

$$E = \int_{-\infty}^{t_c} P(t) dt, \quad (7)$$

where $P(t)$ is the laser power at the target. Absorption measurements on a wide variety of targets with several illumination geometries have shown that the absorption fraction, η , depends primarily on illumination geometry and only weakly on intensity. Therefore, the final ion temperature, T , is proportional to the useful specific energy absorbed, ϵ_c , up to t_c ; i.e., $T \propto (2f\eta E/M) = \epsilon_c$, where M is the target mass* and $f \cong 1/8$. The "explosion time," t_c , and the "cutoff time," t_c , are found as follows:

$$\int_{-\infty}^{t_c} a_p(t) dt \cong 10w,$$

where $a_p(t)$ is the average speed of sound in the pusher. By making a flux-limited absorption assumption, which will be discussed below, and normalizing to LASNEX,

*In exploding pushers, approximately half the pusher mass implodes and half explodes.

$$\int_{-\infty}^{t_c} \left(\frac{\eta P(t)}{4\pi r_0^2} \right)^{1/3} dt \cong 0.8w . \quad (8)$$

Given the absorption fraction, η , for the illumination system (for $f/1$ lenses focused tangentially $\eta = 0.27 \pm 0.03$); the wall thickness, w , in micrometers; the initial target radius, r_0 , in micrometers; and the laser pulse shape, $P(t)$ in TW, the calculation of t_c in picoseconds is straightforward. Once t_c has been found, t_e is calculated by solving

$$\int_{t_c}^{t_e} v_p(t) dt = \Delta r \cong 0.27 r_0 , \quad (9a)$$

where it is assumed that the instantaneous pusher/fuel interface velocity, v_p , is given by

$$v_p(t) = \left[\int_{-\infty}^t \frac{2f\eta}{M/2} P(t') dt' \right]^{1/2} . \quad (9b)$$

The value of the constant f was found to be about $1/8$ by referring once again to LASNEX simulations. By solving first Eq. (8) and then Eq. (9), t_c is determined. Given t_c , Eq. (7) yields the incident laser energy, E , useful for fuel heating and therefore ϵ_c . Finally T is found from the relation

$$T \cong 42.5 \epsilon_c \text{ keV} , \quad (10)$$

where the constant factor comes from normalization to experimental results.

Even with a value for T , the neutron yield is only determined by Eq. (6) as a proportionality. To obtain a numerical value for the proportionality constant, one last normalization to experimental data or a LASNEX calculation is required. By means of this chain of approximations, several parameters of interest are calculated culminating in the neutron yield. Combining Eqs. (6) and (10) and holding both the initial fuel and pusher densities constant gives

$$N \cong A r_0^{10/3} w^{2/3} \epsilon_c^{-7/6} \exp(-5.45/\epsilon_c^{1/3}) , \quad (11)$$

where ϵ_c is in J/ng, r_0 and w are in micrometers, and the proportionality constant A is obtained by normalizing to LASNEX or to experiment. In the following section, the scaling predictions in this expression are compared with experimental results and LASNEX simulations.

Comparison of Scaling Law with Experimental Data and LASNEX Simulations

The scaling law presumes that the incident laser power pulse shape is Gaussian in time with a full width at half maximum of τ ; i.e.,

$$P(t) = P \exp [-(1.66 t/\tau)^2] .$$

A tabulated probability distribution, $F(z)$, provides a convenient way to express t_c , t_e , and ϵ_c . The probability integral, $F(z)$, is defined by

$$F(z) = \int_{-\infty}^z \frac{1}{\sqrt{2\pi}} e^{-u^2/2} du .$$

The pusher explosion time, t_e , can be found using Eq. (8):

$$F(1.36 t_e/\tau) = \frac{w}{\tau} \left(\frac{r_0^2}{\eta P} \right)^{1/3} .$$

Given t_c , the cutoff time, t_e , is obtained by a numerical integration of Eq. (9a):

$$\int_{x_c}^{x_e} \sqrt{F(x)} dx = 0.572 \frac{\Delta r}{\tau} \left(\frac{r_0^2 w}{\eta P \tau} \right)^{1/2} ,$$

where $x_c = 2.35 t_c/\tau$, $x_e = 2.35 t_e/\tau$, and use has been made of the fact that the mass of a SiO_2 pusher in nanograms is given by $M \cong 3.14 \times 10^{-2} r_0^2 w$. Having found x_e , the useful specific energy is determined by Eq. (7):

$$\epsilon_c = \frac{0.266 \eta P}{M/2} F(x_e) .$$

Finally, the neutron yield is calculated with Eq. (11).

The scaling predicted by Eq. (11) has been compared to LASNEX one-dimensional calculations by normalizing to a LASNEX simulation of a 100- μm -diam microsphere with a 0.7- μm wall thickness filled with 2 mg/cm³ of equimolar DT and irradiated uniformly with a 2-TW pulse, 65 ps in duration. The proportionality constant, A, in Eq. (11) is equal to 7.35×10^7 in this case. Figure 5-118 compares LASNEX one-dimensional calculations of neutron yield to the scaling law for a variety of target diameters and wall thicknesses irradiated with 0.5- to 20-TW as a function of laser pulse length τ . The scaling law tracks these LASNEX calculations within a factor of two over six decades in neutron yield. Figure 5-119 shows predictions for the neutron yield as a function of target diameter. Once again, agreement between the scaling law and LASNEX is obtained within a factor of two.

In practice, experimental geometries on Janus and Argus have rarely provided uniform illumination of the target. As is well known, this loss of spherical symmetry results in a reduced neutron yield. Complete two-dimensional LASNEX calculations accurately predict target neutron yield but require more than 30 min of CDC 7600 computer time. The scaling law tracks the measured neutron yield with remarkable accuracy and is a simple tool. To make up for the break in symmetry, the scaling law was normalized to experiment shot No. 75060402, and then used to predict the neutron yields of the experimental shots listed in Fig. 5-120. In this case the value of the proportionality constant, A, was 8.8×10^6 . Figure 5-121 shows a compilation of our exploding pusher target neutron yields using f/1 lenses, the spherical illumination system, and f/2.5 lenses (for which absorbed energies and accurate laser pulse widths are available). Shots were rejected where the laser parameters produced significant small-scale beam breakup or were accompanied by prepulses larger than a few tens of μJ . The neutron yield has been adjusted by $r_0^{10/3} w^{2/3}$ as suggested by Eq. (11) and plotted versus ϵ_c . Ion temperatures estimated by the scaling law are indicated. Again agreement is good. Finally, Fig. 5-122 shows the experimental neutron yield for targets irradiated by f/1 lenses normalized by the scaling-law predicted yield plotted against target diameter. Although there is a great deal of scatter in this data, a least squares fit produces a

curve that is indistinguishable from the scaling-law prediction.

The agreement achieved between the scaling law and both the LASNEX simulations and experimental results suggests that the picture of an exploding pusher on which the scaling arguments were based is a useful one.

Validity of Scaling Law

Implicit in the exploding-pusher scaling law described above is the presumption that the implosion process consists of three distinct phases. If the initial conditions of any given event are such that one of these phases is too exaggerated or absent, the scaling law will not be useful. The range of validity of the scaling law can be discussed by reviewing each phase in turn.

Explosion Phase. The early or "explosion" phase is characterized by heating of the pusher by superthermal electron and ion energy deposition, conduction from the critical density region, and the shock wave that may precede the thermal conduction wave. The explosion phase lasts from $t = -\infty$ to $t = t_e$, where t_e is the time when the shock wave generated by the absorption of the incident 1.06- μm light, and driven by the resulting thermal wave, breaks through the shell and the shell "explodes." The distance from the critical density to the pusher/fuel interface is about 10 w at the time that the shock wave enters the fuel region in several LASNEX calculations run without ponderomotive force profile modification. Simulations show that the pusher/fuel interface only acquires a substantial velocity when the shock wave breaks through the pusher. Until then, the expansion of the pusher is due to volume heating from superthermal electron and ion deposition and to heating from the thermal wave from the critical region, neither of which imparts substantial fluid motion to the pusher. To estimate the time when the pusher explodes, t_e , solve

$$\int_{-\infty}^{t_e} a_p(t) dt \approx 10 w, \quad (12)$$

where the assumption has been made that the shock wave Mach number is about 1 so that the speed of sound, $a_p(t)$, in the pusher can be substituted for the shock velocity. Since the pusher temperature, T_p ,

20 TW, $D = 400 \mu\text{m}$, $w = 2 \mu\text{m}$
50% absorption

20 TW, $D = 200 \mu\text{m}$, $w = 2 \mu\text{m}$
50% absorption

5 TW, $D = 150 \mu\text{m}$
 $w = 1 \mu\text{m}$

2 TW, $D = 80 \mu\text{m}$
 $w = 0.7 \mu\text{m}$

--- LASNEX
— Scaling law
All for 25% absorption,
except where indicated.

1 TW, $D = 80 \mu\text{m}$, $w = 0.7 \mu\text{m}$

0.5 TW, $D = 80 \mu\text{m}$, $w = 0.7 \mu\text{m}$

0.5 TW, $D = 40 \mu\text{m}$, $w = 0.4 \mu\text{m}$

will already have reached several eV by the time the shock wave propagates, $a_p(t) = \sqrt{\gamma RT_p}$, where γ is the ratio of specific heats and R is the gas constant.

The electron-ion equilibration time remains short during this phase so that the electron and ion temperatures are almost equal. The further assumption

that the electron temperature in the pusher is a constant fraction of the temperature at the critical density region is made. This "constant" is, in reality, a function both of time and position in the pusher. A flux limit argument relates the absorbed intensity to the temperature in the critical density region:

Fig. 5-119. Neutron yield calculated by one-dimensional LASNEX simulations for a range of target diameters is compared to the scaling law. Except where indicated, the absorption fraction, η , was set at 0.25.

	Shot No.	Power (TW)
A	76081002	0.28
B	75080803	0.30
C	76082002	0.21
D	75050603	0.44
E	75062405	0.39
F	75060402	0.40
G	76030507	0.43
H	36060904	1.01
I	36091603	1.67
J	36101204	2.45
K	36120910	4.00
L	36120906	4.44

○ Experiment:

Error bar is due to uncertainty
in neutron yield.

Scaling rule:

Error bar is due to uncertainty
in absorbed energy.

Fig. 5-121. Normalized neutron yield was plotted vs useful specific energy for a large number of target shots. Vertical error bars indicate uncertainty in neutron yield, while horizontal error bars reflect uncertainty in the absorbed energy. The solid curve is the scaling law normalized to one experimental point.

$$\eta I(t) = 2 \times 10^{-7} F n_{cr} (kT_e)^{3/2}, \quad (13)$$

where I is the intensity and F the flux limiter. Combining Eqs. (12) and (13) gives

$$\int_{-\infty}^{t_c} \left(\frac{P(t)}{4 I_0^2} \right)^{1/3} dt = \frac{10 W F^{1/3}}{\alpha^{1/2}},$$

where α contains the ratio of T_e at the critical density surface and T_e inside the pusher. The constants are adjusted by referring to the LASNEX simulations of § 5-1.2 with Eq. (8) as the result.

These assumptions obviously break down for very long heating pulses where the initial phase is ablative rather than explosive. A slowly ablating pusher would be even farther from isothermal, and in the isentropic limit, no shock wave even exists. In

Fig. 5-122. Although the data are scattered, the scaling law provides an estimate for the normalized neutron yield versus target diameter, which is negligibly different from a least squares fit to the data.

the opposite extreme of very short pulses, the scaling law breaks down for other reasons. To hold the specific energy absorbed constant as $\tau \rightarrow 0$, the peak incident power must increase. This intensity increase enlarges both the fraction of the absorbed energy, which appears in the superthermal electron distribution, and the effective temperature, θ_h , of these electrons. Hardening of the electron distribution results in a lower coupling efficiency between these electrons and the pusher, an increase in the production of radially directed very high energy pusher ions, and fuel preheat. The scaling law as stated can cope with none of these contingencies and so cannot be relied upon for an accurate prediction of neutron yield far from the parameter range covered in Figs. 5-118 through 5-122. The limits on w , r_0 , and P within which the scaling law is accurate have not been quantitatively established.

Acceleration Phase. During the second or "acceleration" phase, the pusher/fuel interface achieves its peak velocity. The DT ion temperature increases primarily because of the compressional work done by the accelerating pusher. The fuel electrons are continuously heated by electron thermal conduction, but the electron-ion equilibration time rises to between 50 and 100 ps shortly after t_c . The fuel ions are therefore effectively uncoupled from the fuel electrons. The acceleration phase is assumed to last from $t = t_c$ to $t = t_e$, where t_e is defined by the requirement that the pusher/fuel interface has moved in a distance $\Delta r \cong 0.27 r_0$. Some time is required for energy deposited at the critical density surface to affect the DT ion temperature. Laser energy reaching the absorption region after t_c is presumed to be felt by the fuel after stagnation, and therefore, to be ineffective for neutron production. For the 70- μm -diam, 0.4- μm -thick target exposed to 0.45 TW in a 5-ps FWHM pulse described in § 3-1.2, this condition appears to have been reached when the pusher/fuel interface had moved in a total of about 32% of the initial radius. This is shown by the LASNEX simulation data shown in Fig. 5-123. The horizontal axis is the time when the Gaussian input pulse is truncated. The dashed curve, and the right-hand vertical axis show the position of the pusher/fuel interface at any given time, t . The solid curve and the left-hand vertical axis give the neutron yield produced if the LASNEX simulation is allowed to continue after the input pulse has been truncated at time t , divided by the maximum neutron yield produced when the

Fig. 5-123. "Cutoff" time, t_c , was chosen from LASNEX simulations of a 70- μm diam, 0.4- μm wall target irradiated by a 0.45-TW pulse with a 45 ps FWHM. The peak of the pulse is at $t = 0$.

entire input pulse is used. The point marked "cutoff" time, when $N \sim 2/3 N_{\max}$, represents the knee on the curve, when the fuel appears to be uncoupled from the input laser pulse and further absorption. Since at the end of the explosion phase for that target, the interface had moved in about 6% of the radius; this implies a cutoff condition of

$$\int_{t_c}^{t_e} v_p(t) dt = 0.26 r_0 = \Delta r \quad (14)$$

for that experiment.

LASNEX simulations indicate that the ratio $\Delta r/r_0$ should decrease as the absorbed laser intensity drops below about 10^{15} W/cm^2 . The relationship between absorbed peak intensity and $\Delta r/r$, shown in Fig. 5-124, can be used to extend the useful range of the scaling law to lower intensities.

Fig. 5-124. LASNEX simulations suggest that the useful range of the scaling law may be extended by allowing the cutoff condition to decrease with absorbed intensity.

Figure 5-125 shows a graphic example of this prescription for finding useful absorbed energy and a comparison of the resulting pusher/fuel interface trajectory with the LASNEX one-dimensional simulation. The solid curve is the one-dimensional result when the Gaussian input pulse is truncated at the time when the shell has moved in 32% of the initial radius. The dashed lines show the result of applying the scaling law outlined above. If t_c is never reached, confidence in the scaling law's accuracy declines. Reasonable limitations on both t_c and t_e are shown in Fig. 5-126.

Compression Phase. The final or "compression" phase is that in which the imploding one-half of the pusher mass compresses (and heats) the DT fuel as it stagnates. In the above, the compression, C , was estimated from

Fig. 5-125. Velocity and v - t trajectory inferred from the scaling law are compared with a corresponding LASNEX simulation.

$$t_e \leq t_e^* = -0.54 \tau \quad \text{so} \quad \int_{-\infty}^{t_e^*} P(t) dt = 0.1 \quad \int_{-\infty}^{\infty} P(t) dt$$

$$t_c \leq t_c^* = +0.54 \tau \quad \text{so} \quad \int_{t_c^*}^{\infty} P(t) dt = 0.1 \quad \int_{-\infty}^{\infty} P(t) dt$$

Fig. 5-126. Limits on t_e and t_c are shown here. If $t_e > t_e^*$, then more than 10% of the laser energy will have reached the target before the end of the explosion phase. If $t_c > t_c^*$, then more than 90% of the laser energy will have reached the target prior to the achievement of the cutoff condition. In either case, confidence in the scaling law prediction declines.

$$C \propto \frac{w}{r_o} \frac{\rho_s}{\rho_o}$$

Comparing this relationship with the tabulated compressions in § 4-1.1 yields

$$C \cong (6.6 \pm 0.92) \frac{w}{r_o} \frac{\rho_s}{\rho_o} \quad (15)$$

Several attempts were made to arrive at an expression for C that depended upon such parameters as the ratio of the thermal energy in the pusher and fuel at stagnation to the useful energy absorbed or the energy losses during compression of the spdv work on the fuel assuming a variety of thermodynamically defensible paths. The resulting expressions, however, failed to agree as well with LASNEX simulations as did Eq. (15). Nevertheless, it is indefensible to assume that the DT ion temperature would be independent of the compression in isentropic experiments.

In § 4-1.2 Nuckolls shows that the DT ion temperature is weakly dependent on compression when the maximum implosion velocity is not much greater than the implosion velocity, which sets the initial trajectory in pressure-density space.

If the dependence on n_0 had been retained, Eq. (11) would have become

$$N = B n_0^{4/3} v_0^{10/3} w^{2/3} \epsilon_c^{-7/6} \exp [-5.45/\epsilon_c^{1/3}]$$

Although the yield must certainly increase from zero as the initial DT number density n_0 increases from zero, it must finally decrease as n_0 becomes large enough to lower the final DT ion temperature. Changing n_0 affects the electron-ion collision time and thus the relative importance of electron conduction losses during the compression. It is clear that the scaling law as formulated above does not properly account for n_0 , and the model is thus limited to a constant DT fill for any experimental or LASNEX normalization.

A more realistic description of the compression must be formulated in which the partition of energy between pusher, fuel ions, fuel electrons, and the radiation field is properly accounted for as a function of the laser and target parameters.

Conclusions

A simple model has been developed which, when normalized by experiment or LASNEX calcula-

tions, can be used to scale neutron yields for variations in pulse length, wall thickness, target radius, and laser input conditions. The model also elucidates several important processes occurring in these experiments. It does not, however, produce the proper functional relationship between initial fuel density and thermonuclear yield, and fails when electron decoupling or DT ion quenching, among other transport processes, become significant.

References

112. K. Boyer, R. Hirsch, and J. Nuckolls, *Status of Laser Fusion Research*, Lawrence Livermore Laboratory, Rept. UCRL-50600-71-5 (1971) (title U, report SRD). Report presented to the President's Scientific Advisory Committee on December 15, 1970 and to the AEC General Advisory Committee, December 16, 1970.
113. G. H. Dahlbacka and J. H. Nuckolls, *Laser Driven Isothermal Implosions*, Lawrence Livermore Laboratory, Rept. UCRL-75485 (1974).
114. J. H. Nuckolls, *Outlook for Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-76395 (1975), presented at 2nd Orbis Scientiae Conf., U. of Miami, January 1975.
115. K. A. Brueckner and S. Jorna, *Rev. of Mod. Phys.* **46**, 2 (1974).

Authors

E. K. Storm
J. T. Larsen
K. R. Manes

Major Contributors

H. Ahlstrom
J. Nuckolls
J. Trenholme

5-6 SUPER LIQUID DENSITY TARGETS: JANUS-CLAMSHELL SYSTEM

5-6.1 Target Design

Numerous laser-initiated fusion implosion experiments using DT-filled glass microspheres have been conducted in recent years at many laboratories under a variety of conditions. Microscope images of the x rays emitted by the glass have been used to diagnose implosion characteristics. High compressions or densities have been inferred from the spot

sizes of these temporally unresolved and unidirectional x-ray microscope data.¹¹⁶ The reliability of these inferences is, however, open to question on at least two grounds:

(1) Effects of the time variations and three-dimensional implosion asymmetries have not been determined experimentally;

(2) Effects of possible glass-DT mixing have been ignored. Therefore, density determinations

without these shortcomings are desirable. For example, measurements of spectral line broadening of atoms or ions could be used to determine the compressed plasma densities.¹¹⁷ We have chosen to diagnose the peak density achieved in implosion experiments using DT- and neon-filled microspheres by measuring the broadening of neon x-ray line emission in the 1 keV region. Our target design and simulations of proposed experiments which reach liquid densities are discussed here.

We present the results of design calculations for targets which:

- Can compress DT and neon mixtures to a peak average-density of about 1 g/cm³ using the 0.5-TW, Nd:glass laser facility, Janus,¹¹⁸ at LLL with the two-beam clamshell focusing system. For densities in this range, we need a spectrometer having an energy resolution of about 1 eV to measure the neon x-ray line width.

- Can be fabricated by filling DT and neon in available glass microspheres. However, note that oxygen (which has a bound-free edge at about 870 eV) and other high-Z materials in the glass microsphere wall (Si, Na, Ca) increase the x-ray background in the 1-keV region. Therefore, the advantages of using available components are offset by the increased difficulty of measuring neon line emissions.

- Allow experimental determination of peak ρR achieved by measuring the alpha-particle energy loss (ρ is fuel density, R is radius of the compressed region). Approximately 10^5 DT reactions in the target are required to produce a detectable signal in the alpha-particle time-of-flight detector which has an energy resolution of about 150 keV.¹¹⁹

Given a relatively low energy laser system without pulse-shaping capabilities, the limiting factor in compressing fuel to high densities is the electron preheat effect. The preheat of the glass and fuel can be reduced by increasing the wall thickness of the glass microsphere, by extending the laser pulse duration, or by lowering the laser power used. However, using these alternatives will decrease the strength of the neon line-emission signal as well as the DT reaction yields. Thus, the ideal target should be optimized to simultaneously give sufficiently high density and DT reaction yield as well as sufficiently strong neon line-emission with respect to the background.

Our target design calculations have been performed using the LASNEX MHD code with laser ab-

sorption due to classical as well as plasma instability processes.¹²⁰ To simulate the laser absorption due to plasma instabilities, we assume that if the laser radiation penetrates to or beyond a density of $0.8 \rho_c$, where ρ_c is the critical density for the laser radiation, then 25% of the laser energy is placed in the suprathermal electrons.¹²¹ The suprathermal electron spectrum is characterized by a temperature that is six times the thermal electron temperature. Laser absorption due to inverse bremsstrahlung is reduced by a factor of 5 to simulate density profile steepening effects.¹²¹ Using these parameters, we have been able to obtain good agreement between experimental and LASNEX simulation results for several different targets.¹²²

The clamshell focusing system can illuminate a spherical target in a moderately uniform manner. Thus, one-dimensional (1D) LASNEX simulation calculations yield reasonably satisfactory results. Within the design constraints, we find that strong neon line signals, high densities, and high DT reaction yields can be obtained with glass microsphere targets filled with DT fuel seeded with 10% (by mole fraction) of neon to an initial density of 2×10^{-3} g/cm³. The results do not depend strongly on the quantity of neon introduced.

Figures 5-127 and 5-128 show the 1D simulation results for a 60- μ m-diam, 3.2- μ m-thick glass microsphere irradiated with a 100-J laser pulse of varying pulse length, an optimistic upper limit on Janus system performance. A Gaussian temporal pulse shape is assumed in all cases. As expected, we find that the peak average-fuel-density is inversely proportional to its temperature, its thermonuclear yield, and the laser power used. Shock heating of the DT ions from the exploding glass microsphere, which causes the electron and ion temperatures to diverge as the pulse width is reduced (i.e., as laser power is increased), is apparent. The results for the same target using the three-temperature (3T) model where suprathermal electrons do not exist are shown in Fig. 5-127 to demonstrate the effect of preheat. As can be seen, preheat strongly degrades compression and neutron yield.

As noted above, approximately 10^5 DT reactions are required by the α -particle time-of-flight detector. From Fig. 5-127, we see that this requirement can be satisfied by a 100-J laser pulse with a width of less than 200 ps. Figure 5-129 shows the effects of laser irradiation energy on the peak average-density and neutron yield for a 200-ps Gaussian temporal

Fig. 5-127. 1D LASNEX results (peak average-fuel-density and neutron yield vs pulse length) for a 60- μ m-diam, 3.2- μ m-thick glass microsphere target irradiated by a 100-J, 1.06- μ m laser pulse.

pulse. Not surprisingly, the neutron yield drops rapidly with reduced laser energy. However, the peak average-fuel-density of about 1 g/cm³ is insensitive to the large incident energy variations.

We have also tried to design a 60- μ m-diam glass microsphere target which can compress fuel to peak-average-densities of about 1 g/cm³ using 50 J of laser energy and a pulse length of about 200 ps. This is a more realistic estimate of the performance of the Janus laser. Our calculations indicate that we cannot obtain a peak average-fuel-density of 1 g/cm³ and 10⁵ DT reactions using a 50-J laser pulse. However, Fig. 5-130 shows the relationship between the electron temperature in the fuel and the neon line-emission strength vs x-ray background in the 1 keV region. The target is a 60- μ m-diam, 1- μ m-thick glass microsphere irradiated with a 50-J laser pulse of varying duration. Since the neon line-emission strength can vary with time, a steady state calculation can lead to serious errors. We have, therefore, used a time-dependent calculation.¹²³ The attenuation of the neon x-ray line emission by the glass has not been included in these calculations. We estimate the neon line attenuation by the glass shell for the targets to be less than a factor of 2. Conservatively, a minimum electron temperature of about 400 eV in the fuel or a line/background ratio

Fig. 5-128. 1D LASNEX results (peak average-fuel-density, peak electron and ion temperatures vs pulse length) for a 60- μ m-diam, 3.2- μ m-thick glass microsphere target irradiated by a 100-J Gaussian temporal laser pulse.

Fig. 5-129. 1D LASNEX results (peak average-fuel-density and neutron yield vs incident laser energy) for a 60- μ m-diam, 3.2- μ m-thick glass microsphere target irradiated by a 200-ps (FWHM) Gaussian temporal laser pulse.

Fig. 5-130. 1D LASNEX results (peak electron temperature in the fuel and the ratio of the neon line emission to x-ray background in the 1-keV range vs incident laser pulse length) for a 60- μ m-diam, 1.0- μ m-thick glass microsphere irradiated by a 50-J laser pulse.

of about 4 is desirable for the observation of the neon line emission with a 1- μ m-thick glass microsphere. Because of this, experimental verification of a peak average-fuel-density of greater than about 1 g/cm³ using a 50-J, 200-ps laser pulse and a 60- μ m-diam glass microsphere is improbable.

To increase the target performance with reduced laser input energy, we reduced the microsphere diameter to 40 μ m. Two-dimensional (2D) LASNEX calculations used geometrical ray tracing to calculate the focal, refractive, and reflective properties of the laser radiation. Magnetic field effects were also included. An example of the laser spatial profile used in these calculations is shown in Fig. 5-131. Table 5-15 shows the results of these 2D simulations for a 40- μ m-diam, 1- μ m-thick glass microsphere irradiated by a 100-ps, 50-J Gaussian pulse. The focusing offset is varied. These results are in good agreement with those obtained from 1D simulations and show that a peak density of about 1 g/cm³ can be achieved and experimentally verified. The results are insensitive to small variations in the clamshell focusing positioning.

Thus, LASNEX simulation results indicate that with 40- μ m-diam capsules, fuel at an initial density

of 2×10^{-3} g/cm³ can be compressed to peak average densities of about 1 g/cm³ using 50 J of incident 1.06- μ m laser energy. More importantly, the attainment of these densities can be verified by neon line width broadening measurements, and ρR determinations can simultaneously be made by the α -particle time-of-flight detector. As the Janus performance falls below 50 J, the experiment becomes increasingly marginal.

References

116. G. Charatis, R. R. Johnson, D. Sullivan, *Bull. Am. Phys. Soc.* **19**, 909 (1974); P. M. Campbell, G. Charatis, and G. R. Montry, *Phys. Rev. Lett.* **34**, 74 (1975).
117. A. Vinogradov, I. I. Sobelman, and E. A. Yukov, *Spectroscopic Methods for Diagnostics of Superdense Hot Plasmas*, Lebedev Physical Institute, Laboratory of Quantum Radiophysics, Moscow, Preprint N 173 (1973); G. G. Chapline and H. E. DeWitt, *X-Ray Line Broadening As a Compression Diagnostic for Laser-Induced Implosions*, Lawrence Livermore Laboratory, Rept. UCRL-76272 (1974).
118. J. F. Holzhrichter and D. R. Speck, *J. Appl. Phys.* **47**, 2459 (1976).

Fig. 5-131. Example of the assumed beam spatial profile used in 2D LASNEX calculations. The angle θ is measured from the positive Z axis. The laser beam is assumed to be symmetrical about the X and Z axes.

Table 5-15. Results of 2D LASNEX calculations of implosion of 40- μm -diam, 1- μm -thick target with 50-J, 100-ps laser pulse

Offset (μm)	Peak average-DT density (g/cm^3)	DT reaction yield	X-ray emission (keV/keV)			Alpha-particle energy loss (keV)	
			Neon line	Back- ground	Line BG	DT	SiO_2
3.5	1.3	4.5×10^6	8.2×10^{15}	9.4×10^{14}	8.7	250	285
6.5	1.1	2.3×10^6	8.4×10^{15}	9.4×10^{14}	8.9	210	240
-0.5	1.1	2.8×10^6	5.4×10^{15}	8.2×10^{14}	6.6	125	290

119. V. W. Slivinsky, H. G. Ahlstrom, K. G. Tirsell, J. T. Larsen, S. Glaros, G. Zimmerman, and H. Shay, *Phys. Rev. Lett.* **35**, 1083 (1975).
120. G. Zimmerman, *Numerical Simulation of the High Density Approach to Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-75173 (1973).
121. K. Estabrook, E. Valeo, W. Kruer, *Phys. Fl.* **18**, 1151 (1975).
122. Y. L. Pan, *Bull. Am. Phys. Soc.* **20**, 1266 (1975); *Analysis of the Ball-Plate Laser Fusion Target Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-77044 (1975).
123. D. S. Bailey and E. Valeo, *Calculation of Emission from Hydrogenic Ions in Super Liquid Density Plasmas*, Lawrence Livermore Laboratory, Rept. UCRL-78473 (1976); *Bull. Am. Phys. Soc.* **21**, 1134 (1976).

Author
Y. L. Pan

5-6.2 Neon Line-Width Calculations

In this section, we discuss various sources for line broadening, and show the results of our calculations applied to a LASNEX simulation of a super-liquid-density implosion experiment.

Different broadening mechanisms affect both the line width and shape, so that in principle they may be separated. However, this requires both that the spectrometer resolution be much better than the widths expected and that the line signal-to-noise ratio be much larger than unity. Unfortunately, neither requirement is possible for the present experiment, so we must rely on the gross line width for a diagnostic. The mechanisms we have considered are the following:

- **Directed mass motion.** The implosions reach a peak speed of about 3×10^7 cm/s corresponding to a Doppler shift of about 1 eV. In the compression phase, the fuel is opaque to the neon line, so that only the material on the observer's side is visible. In the expansion phase, velocities are much lower. Therefore we expect to see part of the line red shifted about 1 eV, but of low intensity, since densities are low during the compression phase. Most of the line emission occurs after the stagnation point when the fuel density is near maximum. Examination of the velocities in the DT fuel region during this time suggests a symmetric Doppler broadening of about 0.2 eV.

- **Ion temperature Doppler widths.** Besides the directed velocities due to gross mass motion, there is random thermal motion of the ions. The ions and electrons are effectively uncoupled during compression, and the ion temperature (T_i) may be significantly higher than the electron temperature (T_e). The FWHM Doppler width for the Ne^{+9} 1s - 2p line is $\omega_D^{(eV)} \approx 0.65\sqrt{T_i}(\text{keV})$. Typical ion temperatures reach 1 to 2 keV, so that $\omega_D \approx 0.65\text{--}0.92$ eV.

- **Fine structure.** The $n = 2$ fine structure width is 0.45 eV, and is essentially additive. Figure 5-132 shows this effect.

- **Stark broadening.** Stark broadening comes from two sources, perturbation due to the quasi-static ion background and to fast electron impacts. Figure 5-133 shows the broadening from the ion background as a function of the perturbation strength

Fig. 5-132. Unshifted neon Lyman α line-shape after convolution with a Doppler profile. The histogram indicates the relative intensities and energies of the $j = 1/2$ and $j = 3/2$ components of an isolated stationary ion.

$$\Sigma \equiv \frac{eF \int_0^\infty dr r^3 R_{21}(r) R_{20}(r)}{\Delta_{jj}}, \quad (16)$$

where F is the Holtzmark field strength, R_{21} and R_{20} are the hydrogenic $n = 2$ radial-wave functions, and Δ_{jj} is the fine structure splitting. For neon, $\Sigma = 7.7 \times 10^{-14} N_i^{2/3}$. For $10^{21} < N_i < 10^{22}$, Σ is in the range 7.7 to 36.0. We see from Fig. 5-133 that the linear Stark components produce line wings that are from 5 to 20 eV wide over this range, reducing intensity by a factor of 10 and making them too faint to see. Hence, the only observable broadening is from electron collisions. Using the impact approximation, we find a (FWHM) width for Ne^{+9} 1s - 2p of $\omega_s = 1.1 \times 10^{-24} N_e / \sqrt{T_e}$, or 0.3 eV at $N_e = 2 \times 10^{23}$ and $T_e = 550$ eV.

It should be noted that this width may be a factor of 2 too low. At densities such as we are considering, the ion plasma frequency is about that of the Stark width. Griem¹²⁴ suggests that the low frequency plasma oscillations give an additional width of the same magnitude as the electron impact width.

Fig. 5-133. Intensities of the $n = 2$ hydrogen Stark components as a function of the reduced electric field Σ .

(A factor-of-2 increase in width was found experimentally.¹²⁵)

• *Optical transfer effects.* In these experiments, we expect an optical depth of about 10 to 100; thus we need to consider the line profile modification from radiation transfer. The transfer calculations depend on the line profile. Doppler broadening gives a Gaussian profile, while Stark effects give a Lorentzian profile. The convolution of these two is called a Voigt profile. Fine structure splitting and asymmetric Doppler shifting tend to further modify the line. Thus the opacity broadening depends on the relative mix of all the broadening mechanisms.

As a guide, we have done the transfer calculations for the Gaussian and Lorentzian profiles separately and simply added the widths. In the future, the spectral line post-processor (Section 4) will be modified to handle the Voigt profile.

Next, we discuss a particular LASNEX simulation, a 40- μm glass microsphere, with a 1- μm -thick wall, and filled to $2 \times 10^3 \text{ g/cm}^3$ (90% DT and 10% Ne by mole fraction). The laser pulse has 30 J in 100 ps (FWHM), which is a possible configuration for the density experiments described below. The results of a one-dimensional LASNEX simulation of this experiment yielded a peak fuel density of 1.8

g/cm³, a peak electron temperature of 0.55 keV and a peak ion temperature of 1.7 keV. Figure 5-134 shows the time histories of fuel electron density, T_e , and T_i . With these parameters given, we can evaluate the ionization states and line emission of a given seed material. Using the post-processor described in Section 4, we show in Fig. 5-135, the time history of a neon seed. As discussed in Section 6.7.1 of the 1975 Annual Report, an ionization state has appreciable population only when $\chi_n/T_e \approx 3$, where χ_n is the n th ionization potential. If the electron temperature is too low, the n th ionization state is not reached; if it is too high, the state is burned out. Since the last two ionization potentials of neon

are 1.2 and 1.36 keV, we expect to see neon H-like and He-like lines in the electron temperature region 300-500 eV. As Fig. 5-133 shows, by peak compression, the 550-eV electron temperature has significantly lowered the H-like population. However, with the 10% neon fill chosen, we still have enough hydrogenic neon left to reach an optical depth of 10 to 100 as shown in Fig. 5-136. Note that we do not expect much $\text{Ne}^{+8} 1S^2 - 1S2P$ emission.

Figure 5-137 shows the resulting emitted line profiles. As a rough guide, the Doppler width of 0.65 eV is about doubled, and the Stark width of about 0.3 eV is about tripled. Thus, their effect is

Fig. 5-134. Time history of fuel temperatures and electron density for sample problems.

Fig. 5-135. Time history of last four ionization states of the 10% neon fill in the fuel region of sample problems.

Fig. 5-136. Neon Lyman α series line-center optical depth in fuel as a function of time.

Fig. 5-137. Time-integrated Doppler (a) and Lorentz (b) line profiles for neon Lyman α series emitted from DT core region.

Fig. 5-138. Neon Lyman α series (optically thick) emission power from DT core as a function of time.

about equal and, together with the fine structure, yields a total width of 2.5 eV, larger than the calculated spectrometer resolution width of about 1 eV. Figure 5-137 also shows the estimated continuum background, which is about 30% of the peak line intensity. Figure 5-138 shows the time history of the line intensity.

In summary, this example shows that the neon line should be visible, with a peak/continuum ratio of about 3, and a width sufficiently large for the spectrometer to resolve. Since the Doppler and Stark widths are about equal, it would be difficult to make any unique density or temperature estimate from a similar experiment.

References

124. H. R. Griem, *Broadening of the Lyman-Alpha Lines of Hydrogen and Hydrogenic Ions in Dense Plasmas*, University of Maryland, to be published.
125. K. Grutzmacher and B. Wende, *Phys. Rev.* **16A**, 243 (1977).

Authors

D. S. Bailey
J. J. Thomson

5-6.3 Neon Line Measurement Experiment

Calculations discussed in the previous section indicated the suitability of measuring compressed fuel density and/or temperature by using the N_e^{19} 1S-2P line emitted from the fuel region. Although experiments with neon-seeded glass microspheres have been performed elsewhere,¹²⁶ hydrogen and helium-like emission from the neon was never observed in a single-laser pulse compression experiment.¹²⁶ We have undertaken to experimentally observe a broad neon line from fuel compression to demonstrate the feasibility of this method as a density diagnostic.

The targets we used were glass microspheres, nominally 40, 60, and 80 μm in diameter. The wall thicknesses ranged from about 0.5 to about 1.0 μm . The fill gas was 45% deuterium, 45% tritium, and 10% neon, by mole fraction, at densities in the range 2 to $3 \times 10^{-3} \text{ g/cm}^3$.

The targets were irradiated with the Janus laser system and the ellipsoidal 4π illumination system, which is discussed in Section 3. This system produces sufficient uniformity of illumination on the target sphere to produce the desired implosion densities. Beam foci overlapped the center of the microsphere by about 20% of the target diameter to maximize absorption. The laser pulse width ranged from about 10 ps to about 300 ps, with energies ranging from 16 to 45 J. Longer pulses were not used because oscillator instabilities and prepulse suppression dye cells caused significant pulse shortening and steepening of the longer pulses.

Measurements taken on each shot are listed in Table 5-16. The only new instrument in the table is the miniature spectrometer, a small x-ray spectrometer that uses a flat rubidium acid phthalate (RAP) crystal mounted 10 cm away from the target. Its useful energy range is 800 to 1200 eV. A diagram of the spectrometer is shown in Fig. 5-139; the design and performance of the spectrometer is discussed in Section 3.

Figure 5-140 shows a schematic diagram of the spectral lines which appear on the spectrometer film. The two silicon lines are second-order Bragg reflections from the crystal plates and are useful for calibrating the film energy positions. The sodium and calcium lines occur because these elements are trace impurities in the glass (about 5%); the sodium line, in particular, is very useful for calibrating the

Fig. 5-139. Compression spectrometer.

Fig. 5-140. Compression spectrometer film record.

Table 5-16. Density measurement experiment diagnostics

Measurement	Instrument
Optical energy balance	Laser calorimeter
Temporal distribution of laser pulse	Optical streak camera
Spatial distribution of x-ray emission	X-ray microscope
Temporal distribution of x-ray emission	X-ray stream camera
Neon line spectra	Miniature x-ray spectrometer
Neutron yield	Neutron detector
Ion spatial distribution	Faraday cups
Ion energy	Ion calorimeter
Low energy x-ray spectra	Bent crystal spectrometer
X-ray spectra to 20 keV	Seven-shooter diode detector

resolution of the spectrometer. Since we expect the crystal rocking curve to dominate the spectrometer resolution, we transfer the observed width at the sodium line energy (1.12 keV) to the neon line energy (1.02 keV) by the Bragg relation

$$\frac{\Delta E}{E} = \frac{\Delta \theta}{\tan \theta_B},$$

assuming the sodium line width to be all instrumental. The narrow intrinsic line width of $\text{Na } ^{+9}\text{IS}^2\text{-IS2P}$ (less than 1 eV), together with small transfer effects, (line center optical depth of about 15) leads us to expect an observed width of less than 2 eV. We thus obtain an upper bound for the spectrometer instrumental width of 1.2 ± 0.2 eV, which is in good agreement with the design objective of 1 eV.

Another possible line which might appear on the film record is $\text{Ne } ^{+8}\text{IS}^2\text{-IS2P}$ at 0.92 keV. However,

we found this line was either very weak or non-existent. ($\text{Si } ^{+12}\text{IS}^2\text{-IS2P}$ has red satellites which might mask this neon line.) This suggests that the electron temperature at peak densities is sufficiently high to burn out the $\text{Ne } ^{+8}$, i.e., $T_e \gtrsim 0.35$ keV.

The IS-2P line of hydrogen-like neon was observed on six experiments. Of these, four were sufficiently strong to obtain width measurements. These lines were weak because of attenuation in the glass pusher and high film noise on the very sensitive Kodak 101 x-ray film used to record the data. The important parameters for these four shots are listed in Table 5-17. Note that two shots have line widths significantly larger than the instrumental width.

The x-ray microscope records of the experiments showed the effect of longer pulses as a means of achieving higher densities. Figure 5-141 shows color-enhanced x-ray micrographs of long- and short-pulse experiments with approximately the same energy on target. The much smaller dimension of the central x-ray region of the long-pulse experiment implies that a much higher fuel density was achieved.

LASNEX simulations of the four experiments for which neon line data is available require detailed information on the laser pulse incident on the microsphere. This information was provided by laser calorimeters, the optical streak camera, and ion calorimeters. The purpose of each of these diagnostics is given in Table 5-16. LASNEX simulations also require an estimate of the errors in each of these measurements. A very important measurement is the temporal shape of the laser pulse since the power profile of the pulse determines the magnitude of the preheat electron wave. Unfortunately, the dynamic range of the data is such that the low-power initial portion of the pulse incident on the target was not resolved. Variation in FWHM values based on scans of streak camera traces corresponding to different camera slit points was no more than 9% for short-pulse experiments and 13% for long-pulse experiments. However, the uncertainties about what laser pulse width to use in LASNEX calculations are somewhat larger. In addition, as mentioned earlier, there is some uncertainty about the shape of the leading edge of the pulse. Table 5-17 shows the laser pulse characteristics and errors for the four neon line experiments. Laser calorimeter measurements are accurate to $\pm 10\%$; ion calorimeter measurements are accurate to $\pm 5\%$.

Table 5-17. Experimental parameters

Shot	Target parameter			Laser parameters			Results	
	Outside diameter (μm)	Wall thickness (μm)	Fill (mg/cm^3)	Energy on target (J)	Pulse width (ps)	% energy absorbed	Neutron yield	Line width (eV)
76110506	42.6 ± 0.1	0.45 ± 0.05	1.7 ± 0.1	42 ± 4	135 ± 20	18 ± 5	< 1000	2.9 ± 0.3
76112302	42.0 ± 0.1	0.36 ± 0.05	3.6 ± 0.2	36 ± 4	205 ± 25	21 ± 5	< 500	1.0 ± 0.3
76120802	43.0 ± 0.1	0.53 ± 0.05	2.1 ± 0.2	39 ± 4	163 ± 20	20 ± 5	< 500	1.5 ± 0.3
76121703	43.0 ± 0.1	0.92 ± 0.05	2.3 ± 0.2	16 ± 2	52 ± 6	19 ± 5	$5.8 \pm 2 \times 10^5$	4.4 ± 0.3

Long pulse experiment
34.7 J 259 psec
60 μm ball target

Short pulse experiment
36 J 92 psec
80 μm ball target

Fig. 5-141. X-ray micrographs for short- and long-pulse experiments.

The seven-shooter x-ray spectrometer was used to record the x-ray spectrum on two experiments in which no neon lines were seen. Because of limited diagnostic access, this spectrometer was not ordinarily used. The spectra are shown in Fig. 5-142 and are consistent with those from other shots on microspheres at equivalent intensities. The suprathermal temperatures agree with the summary data presented in Figs. 5-90 and 5-91.

Figures 5-143 through 5-146 present graphical data for the four experiments for which neon lines were analyzed. Each figure shows the neon line profile along with one or two of the neighboring silicon lines, the temporal profile of the laser pulse on target, the temporal shape of the x-ray emission, and an x-ray micrograph of the microsphere. (Measured line widths are given in Table 5-17.) Note that all four x-ray micrographs suggest rather

Fig. 5-142. Seven-shooter x-ray spectrum.

Neon line profile

X-ray micrograph and intensity profile
3.5-keV channel

Shot data: 76110506

Target: B-598
Diam: 42.6 μm
Wall: 0.48 μm
Fill: 1.71 mg/cm³

Energy on target: 42.4 J
Laser pulse FWHM: 135 ps
Neutron yield: <500

Temporal profile of output laser pulses
on target

Temporal shape of x-ray emission
2.6-keV channel

Fig. 6-143. Data summary for experiment 76110506.

Shot data 7612302

Target: B-658
 Diam: 42.0 μm
 Wall: 0.38 μm
 Fill: 2.87 mg/cm^3

Energy on target: 32 J
 Laser pulse FWHM: 205 ps
 Neutron yield: <500

(a) Neon line profile

(c) Temporal shape of x-ray emission 2.9-keV channel

(b) Temporal profile of output laser pulse on target

(d) X-ray micrograph and intensity profile

Fig. 5-144. Data summary for experiment 76112302.

Shot data 76120801
 Target: B-671
 Diam: 43.0 μm
 Wall: 0.53 μm
 Fill: 3.33 mg/cm^3

Energy on target: 39 J
 Laser pulse FWHM: 163 ps
 Neutron yield: <500

(a) Neon line profile

(b) Temporal profile of output laser pulse on target

(c) Temporal shape of x-ray emission 2.6-keV channel

Fig. 6-145. Data summary for experiment 76120892.

Shot data: 76121703

Target: B-688
 Diam: 43.0 μm
 Wall: 0.92 μm
 Fill: 2.30 mg/cm^3

Energy on target: 15.5 J
 Laser pulse FWHM: 52 ps
 Neutron yield: $5.8 \pm 1.3 \times 10^5$

Neon line profile

Temporal shape of x-ray emission 2.9 keV channel

Temporal profile of laser pulse on target

X-ray micrograph and intensity profile 3.5 keV channel

Fig. 5-146. Data summary for experiment 76121703.

uniform spherical compression. However, since the micrograph is temporally and spatially integrated, the real sphericity cannot be accurately determined.

Experiments 76110506 and 76121703 produced the broadest neon lines. If we assume that this is an indication of higher compressions, it is interesting that the temporal x-ray emission and laser pulse histories are qualitatively different for these two shots and may also indicate higher compressions. When the compression is higher, the central portion of the shell may be exploded to low densities less rapidly and is imploded to a smaller radius. This denser plasma would have a higher intensity of x-ray emission. The x-ray emission will then appear to follow the temporal shape of the laser pulse for a longer time. This seems to be what is observed in the data of experiments 76110506 and 76121703. In experiment 76112302, the neon line is very narrow, implying that the shell exploded to lower densities at an earlier time^{127,128} relative to the main laser pulse. The same circumstances occur in the data of experiment 76120802 (Fig. 5-146). However, because small light leaks in the spectrometer were recorded on the highly sensitive film, each film record had a high film base and fog level. This film noise made it impossible to accurately determine the continuum x-ray emission.

The experiments have demonstrated that we can observe broadening of x-ray spectral lines from a low-intermediate Z gas used as a seed material in imploded fuel. Relating the line width to the fuel density and temperature is a complex task which will be discussed in the following section.

References

126. B. Yaakobi and L. M. Goldman, *Phys. Rev. Lett.* **36**, 899 (1976).
127. D. T. Atwood, L. W. Coleman, J. E. Swain, D. W. Phillion, K. R. Manes, D. S. Bailey, and Y. L. Pan, *The Correlation of X-Ray Temporal Signatures, Neutron Yields, and Laser Performance*, Lawrence Livermore Laboratory, Rept. UCRL-78739 (1976).
128. E. K. Storm, H. G. Ahlstrom, and J. F. Holzrichter, *Exploding Pusher Targets Illuminated Using F/1 Lenses at ~0.4 TW*, Lawrence Livermore Laboratory, Rept. UCRL-78729 (1976).

Author

J. Auerbach

5-6.4 Interpretation of Neon Line Measurement

In this section we discuss the two experiments that gave the largest neon line widths, shot 76110506 with width $\omega_N(\text{exp}) = 2.9 \pm 0.3$ eV, and shot 76121703 with width $\omega_N(\text{exp}) = 4.5 \pm 0.3$, -0.8 eV. Inside the compressed core, the line width is due to Doppler and Stark broadening. Since the core is optically thick to neon line radiation, opacity effects cause a significant amount of line broadening. We have used the spectral line post-processor (Section 4) to investigate opacity line broadening over a range of densities and temperatures relevant to this experiment. We find that the opacity broadening for both the Doppler and Stark components is relatively insensitive to exact fuel temperature and density. For the Stark effect, this is easy to see: opacity broadening is inversely proportional to line width, but increases with increasing density. Since the Stark line width is proportional to density, the two effects tend to neutralize each other. We find that opacity effects broaden the Stark component by a factor of 3.0 ± 0.6 .

The opacity of the Doppler component depends on the ground state population and on the Doppler line width. The ground state population is a function of electron temperature, which for these experiments is effectively decoupled from the ion temperature and fairly constant. The Doppler line width is proportional to $T^{1/2}$, varying by about 50% in our expected temperature range of 1.0 ± 1.5 , -0.6 keV. However, if the optical depth is between 10 and 100, as we expect, a 50% variation in opacity leads to about a 25% variation in the broadening factor. Therefore, we take the opacity broadening factor for the Doppler components to be 2.0 ± 0.5 .

A more complete analysis would involve the convolution of the two line shapes and a radiative transfer calculation for the emitted line. For our present purposes, however, this separation of the two line components gives a rough idea of experimental fuel densities and temperatures.

Since we can estimate the average ion temperature by the neutron yield, we will use the experimentally observed line widths to obtain fuel density limits. The neutron yield is proportional to $\rho \bar{\sigma} v_i$, where ρ is the density, r is the radius, $\bar{\sigma} v$ is the averaged product of cross section and velocity, and v_i is the ion thermal velocity. Ion temperatures

Table 5-18. Line width calculation

	Shot 76121703	Shot 76110506
Neutron yield	$(5.8 \pm 2.0) \times 10^5$	<500
Ion temperature, keV	1.5 - 2.5	0.5 - 0.7
Opacity-broadened Doppler width (ω_D), eV	1.8 ± 0.4	1.0 ± 0.3
Instrumental width (ω_i), eV	1.2 ± 0.2	1.2 ± 0.2
Fine structure splitting (ω_{FS}), eV	0.5	0.5
Observed line width (ω_o), eV	$4.4^{+0.3}_{-0.8}$	2.9 ± 0.3
Opacity-broadened Stark width ($\omega_o - \omega_i - \omega_{FS} - \omega_D$), eV	$0.9^{+0.5}_{-0.9}$	0.2 ± 0.5
Intrinsic Stark width, eV	$\sim 0.3 \pm 0.3$	$\sim 0.1 \pm 0.2$

less than about 2 keV may be accurately estimated from the neutron yield because $\bar{v}$ varies with ion temperature to the fifth power (or higher). Hence uncertainties in ρ do not significantly change the estimated temperatures.

In general, the observed line is a complex convolution of the various line components. The Stark component is a Lorentzian; convoluted with the Gaussian profile of the Doppler component gives a Voigt profile. Due to the fine structure splitting, the resulting profile consists of two Voigt profiles separated by 0.45 eV. This resulting profile is used for the opacity-broadening calculations, convoluted with the Lorentzian instrumental profile, and compared with the observed line width. In particular, from the neutron yield, we can obtain the ion temperature and find the Doppler width. The magnitude of the Stark component may then be varied until it agrees with experimental values. Here we choose a simpler path, which is, however, more uncertain: since the opacity corrections are approximately constant (as discussed above), we calculate the Stark widths by simple addition, i.e.,

$$\omega_o = \omega_s + \omega_D + \omega_{FS} + \omega_i,$$

where ω_o is the observed line width, ω_s is the opacity-broadened Stark width, ω_D is the opacity-broadened Doppler width, ω_{FS} is the fine structure splitting, and ω_i is the instrumental width.

Table 5-18 shows the resulting calculations. Unfortunately, the error ranges are too large to allow us to say much about density, except that the upper limit for shot 76121703 is 0.4 g/cm^3 , and the upper limit for shot 76110506 is about 0.2 g/cm^3 . These numbers are consistent with LASNEX simulations of similar experiments. In the future, we will use two-dimensional LASNEX simulations to reduce the uncertainty of the opacity calculations.

In conclusion, we have used the experimental line widths and neutron data to estimate both the temperature and density of the compressed core. These results show the feasibility of using seed gas line spectra as a diagnostic to directly measure the properties of the imploded fuel.

Authors

Y. L. Pan
D. S. Bailey
J. Thomson

5-7 ABSORPTION AND TRANSPORT STUDIES

5-7.1 Interaction of 1.06- μm Laser Radiation with Tungsten Glass and Parylene Disks

Recent theoretical and experimental studies¹²⁹ of the interaction of intense (10^{15} to 10^{17} W/cm²) 1.06- μm laser light with low-Z targets suggest that at high intensities absorption occurs by means of collective processes. Because future targets may be illuminated by lower intensities, we present results from a series of low intensity (10^{13} to 10^{15} W/cm²) 1.06- μm laser irradiation experiments.

Data from disk targets composed of Parylene (C₈H₈) and W-glass (0.75 W₂O, 0.25 P₂O₅) show little distinction in the laser light absorption and scattering characteristics between the Parylene and W-glass disks. The inhibition of inverse bremsstrahlung that this implies is evidence for density profile steepening by means of ponderomotive

forces. Polarimetry measurements provide additional evidence for the profile steepening. Anisotropies in the scattered laser-light angular distributions are consistent with the onset of Brillouin scattering or resonant absorption on a strongly rippled critical surface. Furthermore, hard x-ray and fast electron emission data strongly imply that most of the absorption occurred through collective processes. At comparable laser intensities, the suprathermal electron energy distribution was harder for W-glass than for Parylene. X-ray calorimetric data demonstrate that the W-glass radiative efficiency was very high (more than 50%) and suggest, therefore, that the W-glass coronal temperatures were clamped at lower values. Thus, the ratio of the electron oscillatory and thermal velocities, $\eta = v_{os}/v_{th}$, was lower for W-glass than for Parylene at a given laser intensity. The higher η promoted the generation of harder electron energy distributions.¹²⁹ Evidence of ponderomotively induced filamentation of the laser beam appears in x-ray micrographs.

Fig. 5-147. (a) Laser energy scattered per unit solid angle into, $p_{\perp}$, and perpendicular to, $p_{\parallel}$, the incident laser light polarization plane as a function of the scattering angle for: (solid line) W-glass (5.7×10^{14} W/cm², 181 ps) and (dash line) Parylene (5.3×10^{14} W/cm², 195 ps). The absorption fractions were (solid line) 27% and (dash line) 23%. (b) Fraction of the incident laser energy scattered azimuthally non-uniformly for W-glass at (e) about 300 ps and (o) about 200 ps and Parylene at (Δ) about 200 ps.

In these experiments the planar disks (650- to 950- μm -diam $\times$ 7- μm thickness) were supported in vacuum by slender glass stalks and irradiated with the Cyclops laser.¹³⁰ The target was oriented normal to the incident laser beam and located about 1000 μm inside the best focus of the $f/2.5$ aspheric focusing lens. The flux level was varied by changing the laser pulse length (150 to 400 ps) and energy on target (5 to 75 J). Target damage due to amplified spontaneous emission and prepulses was found to be unimportant. An extensive array of diagnostics¹²⁹ observed laser and plasma behavior during each experiment. The time-integrated laser energy distribution, in the target plane, was measured with an equivalent lens/multiple image camera system during each experiment. The focused laser beam, 250 to 300 μm FWHM in diam, exhibited a ring structure, rising about 50 to 100% above the central minimum. Small scale fluctuations, 30 to 40 μm in diam and 30 to 50% in relative intensity, were superimposed on these gross features. Interpretation of the experimental results was aided by using the code LASNEX,^{129,131} a two-dimensional, axisymmetric, Lagrangian, fluid dynamics code. The LASNEX laser-plasma interaction model has been detailed elsewhere.^{129,131}

The scattered laser energy distributions¹³² into, $p_{\parallel}$, and perpendicular to, $p_{\perp}$, the incident laser-light polarization plane exhibited several unusual characteristics indicative of the importance of collective processes. As shown in Fig. 5-147(a), the scattered laser light distributions for both target types were similar and strongly peaked in the backscatter direction. A substantial fraction of the scattered laser light appeared in the plane perpendicular to the plane of polarization of the incident laser light. In Fig. 5-147(b), the fraction of the incident laser energy scattered azimuthally nonuniformly ($\eta_p = \int (p_{\perp} - p_{\parallel}) d\Omega / \epsilon_i$) is plotted as a function of I_L . This quantity increases with intensity, is relatively insensitive to target composition, and greater for the long pulse-length experiments than for the short pulse-length experiments.

Although the azimuthally nonuniform scattering could result from resonant absorption on a strongly rippled critical surface, it is appealing to attribute it to Brillouin sidescatter since the asymmetries are larger than those expected from resonance absorption. The estimated threshold for Brillouin sidescatter in these experiments is approximately equal to 10^{14} W/cm^2 , consistent with the results shown in

Fig. 5-148. Fractional laser-light absorption measurements: (∇) photodiodes (PDS) — glass (about 270 ps), (Δ) PDS and (Δ) "box" cal.—Parylene (about 200 ps), ($\bullet$) PDS—W-glass (about 300 ps), ($\blacksquare$) PDS and ($\square$) "box" cal.—W-glass (about 200 ps).

Fig. 5-147(b). For a density profile that is locally steepened near critical density, n_c , Brillouin sidescatter occurs most strongly at densities of about 0.5 to 0.7 n_c . The azimuthally scattered light is then expected to refract out of the plasma at θ angles of about 135 to 150°, as observed. Sidescatter is expected to be more important in these experiments than previous ones¹²⁹ due to the larger focal spots and longer pulse lengths. Furthermore, at these intensities, induced scatter does not readily self-limit by modification of the plasma density.

Figure 5-148 shows the measured absorption $\eta_a = \epsilon_a / \epsilon_i$ as a function of intensity. Both target types absorbed comparable fractions. For the experiments at about 200 ps, η_a for W-glass varied from about 38% at $5 \times 10^{13} \text{ W/cm}^2$ to about 30% at $5 \times 10^{14} \text{ W/cm}^2$, and for Parylene from about 30% at $5 \times 10^{13} \text{ W/cm}^2$ to about 25% at $5 \times 10^{14} \text{ W/cm}^2$. The discrepancy between the photodiode and box calorimeter measurements is indicative of the accuracy¹²⁹ of the energy balance measurements, although the box calorimeter is expected to be more accurate since it subtended 0.92 (4π) sr around the

target. The laser light absorption fraction was also inferred by using several ion calorimeters surrounding the target. These calorimeters measured the emitted x-ray radiation and asymptotic convective energy of the plasma. They gave results that agreed, to within experimental uncertainties, with the optical energy balance measurements. For instance, in a specific W-glass irradiation experiment, at $5.7 \times 10^{14} \text{ W/cm}^2$, 28% absorption was inferred by the ion/x-ray calorimetry and 27% by photodiode measurements. On a comparable experiment, at $5.5 \times 10^{14} \text{ W/cm}^2$, 34% absorption was measured by the box calorimeter. The x-ray and ionic contributions to the calorimetry data were deconvolved with the aid of ion angular distributions deduced from Faraday detector data and x-ray angular distributions measured with pinhole cameras and x-ray microscopes. The x-ray emission greater than or equal to 100 eV was much larger for W-glass than for Parylene; at about 10^{14} W/cm^2 it was about $0.5 \epsilon_e$ for W-glass and 0.01 to $0.1 \epsilon_e$ for Parylene. Because of radiative losses, W-glass coronal temperatures, θ_e , about equal to 300 to 400 eV, inferred from low energy x-ray spectral data, were typically 2.5 times lower than Parylene temperatures.

The small role played by inverse bremsstrahlung in these experiments is consistent with the existence of strong density profile steepening near the critical density. Since most of the inverse bremsstrahlung occurs quite close to n_c ,¹³³ it is strongly reduced by the profile steepening. Local steepening of the density profile near n_c is consistent with polarimetry measurements.¹³² In these experiments the average degree of linear polarization, p , of the scattered laser light at ($\theta = 164^\circ$, $\phi = 45^\circ$) was measured to be 0.92 relative to the direction of polarization expected if the plasma reflected laser light as a perfectly conducting plane. According to detailed calculations,¹³² this value of p corresponds to a scale length of less than or equal to $4 \mu\text{m}$ for a plane wave incidence angle of 8° . The depolarization contributions due to the finite angular extent of the beam, plasma turbulence, critical surface steepening or breakup, and Faraday rotation were estimated¹³² using a reference polarimeter in the plane of polarization $\phi = 0^\circ$, of the incident laser beam.

Evidence for plasma filamentation seeded by a nonuniform laser beam appears in Fig. 5-149. This figure shows an x-ray micrograph¹³⁴ of the blowoff plasma produced by irradiation of a W-glass target

Fig. 5-149. X-ray micrograph, $\bar{E}_e \approx 2.5 \text{ keV}$, taken at a 45° angle from the front surface of a W-glass target at $5.7 \times 10^{14} \text{ W/cm}^2$.

at $5.7 \times 10^{14} \text{ W/cm}^2$. The presence of several pronounced nonuniformities (or hot spots) surrounded by less intense rings is clearly evident. The position of the x-ray hot spots correlates with hot spots on the incident beam.¹²⁹ The outer dimension of the low intensity ring, or halo, around each hot spot compares closely to the initial FWHM of the hot spot on the laser beam. Nonuniform heating was also observed on high-intensity Parylene irradiations, but the effect was not pronounced as for W-glass. No nonuniform heating was observed at intensities of 10^{14} W/cm^2 . The estimated¹³⁵ filamentation e-folding length for the conditions of Fig. 5-149 is about $12 \mu\text{m}$ for an about $20\text{-}\mu\text{m}$ diam inhomogeneity at n_e/n_c approximately equal to 0.5 compared to the plasma scale length of about $22 \mu\text{m}$ predicted by LASNEX. The halo about each hot spot is possible due to filamentation and conduction inhibition by self-generated magnetic fields.

The x-ray emission spectra plotted in Fig. 5-150 show further evidence of collective laser plasma interactions. Above 4 to 5 keV, the typical x-ray spectrum consisted of two parts each having a roughly exponential behavior: a low-energy ($> 10 \text{ keV}$) component due to line radiation and the tails of photo-recombination edges, and a high-energy component due to bremsstrahlung from energetic, nonthermal electrons. Figure 5-150 shows the intensity dependence of the x-ray intensity at 30 keV, normalized to the absorbed energy $f_e = dI_e/dE_e/\epsilon_e$, and the effective "temperature", θ_e , of the high energy x-rays;

$dI_e/dE \propto \exp(-E_e/\theta_h)$. Both quantities increase with I_e , indicating an increase in plasma coronal temperature. Furthermore, at a given intensity, f_e and θ_h are largest for the W-glass experiments. For equal fast-electron distributions, about 5 times as many hard x rays should be observed for W-glass as for Parylene. Instead, the hard x-ray spectra from W-glass irradiations are 30 to 40 times more intense than those from comparable Parylene experiments. These results indicate that at a given laser intensity the heated electron distributions were *harder* in the W-glass experiments. Electron emission data corroborate this point: typically 4 to 5 times as much energy in fast electrons ($\lesssim 30$ keV) was detected in W-glass irradiations as in Parylene.

Given the absorbed intensity, detailed two-dimensional LASNEX calculations including anomalous absorption reproduce the curves shown in Fig. 5-150 and show that the common denominator for relative suprathermal electron dis-

tributions in these experiments is the parameter η ($\eta = v_{os}/v_e$ as defined previously). Because of the high radiative efficiency of the W-glass plasmas, their thermal electron temperature was about 2.5 times less than that in the corresponding Parylene plasmas. Thus η was larger by a factor of about 1.5 in the W-glass experiments than in the experiments with Parylene at the same intensity. As indicated in Fig. 5-150, the hot electron temperature in the W-glass plasmas was larger by approximately this same factor.

We did not predict theoretically this experimental increase of the temperature of the heated electrons as the background temperature decreases. Indeed, simulations of resonance absorption in the wave-breaking regime indicate the opposite scaling,¹³⁶ i.e., that at a fixed intensity the hot electron temperature decreases as the background temperature decreases. Several possibilities may explain this anomaly. For example, in the higher-Z targets, heated electrons

Fig. 5-150. X-ray spectral-emission characteristics delineated according to target and pulse length: W-glass at (o) about 200 ps and solid circle about 300 ps, glass at (∇) about 270 ps, and Parylene at (Δ) about 200 ps.

are more frequently reflected back into the critical density surface and so are driven to a higher temperature. It is also possible that the energy conduction is more inhibited in the high-Z disks. Calculations with LASNEX using inhibition by self-generated magnetic fields and the two-stream instability do not reproduce this temperature scaling, but all the different inhibition mechanisms are not well understood.

References

129. W. L. Kruer *et al.*, "Collective Behavior in Recent Laser-Plasma Experiments," *Nobel Symp. Aspenasgarden, Lerum, Sweden, June 10-18, 1976*; W. C. Mead *et al.*, *Phys. Rev. Lett.* **37**, 489 (1976); R. A. Haas *et al.*, *Phys. Fluids* **20**, 322 (1977); K. R. Manes *et al.*, *Laser-Plasma Interaction Studies in High-Power Glass Lasers*, Lawrence Livermore Laboratory, Rept. UCRL-78771 (1977).
130. J. Glaze, *Opt. Eng.* **15**, 136 (1976).
131. G. B. Zimmerman and W. L. Kruer, *Comm. Plasma Phys.* **2**, 85 (1975) and G. B. Zimmerman, *Numerical Simulation of the High Density Approach to Laser-Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-74811 (1975).
132. D. W. Phillion, R. L. Lerche, V. C. Rupert, R. A. Haas, and M. J. Boyle, *Scattered Light Evidence for Short Density Scale Heights Near Critical Density in Laser-Irradiated Plasmas*, Lawrence Livermore Laboratory, Rept. UCRL-78444 (1977).
133. J. Dawson, P. Kaw, and B. Green, *Phys. Fluids* **12**, 875 (1969).
134. F. Seward, J. Dent, M. Boyle, L. Koppel, T. Harper, P. Stoering, and A. Toor, *Rev. Sci. Instr.* **47**, 464 (1976).
135. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **19**, 1151 (1975); D. W. Forslund, T. M. Kindel, K. Lee, and E. L. Lindman, *Phys. Rev. Lett.* **36**, 35 (1976); C. S. Liu, M. N. Rosenbluth, and R. B. White, *Phys. Fluids* **17**, 1211 (1974); A. Bruce Langdon and B. F. Lasinski, *Phys. Rev. Lett.* **34**, 834 (1975); P. Kaw, G. Schmidt, and T. Wilcox, *Phys. Fluids* **16**, 1522 (1973).
136. D. W. Forslund, *Bull. Am. Phys. Soc.* **21**, 1066 (1976). K. G. Estabrook, in Section 4 of this Annual Report.

Authors

R. A. Haas
H. D. Shay
W. L. Kruer

Major Contributors

M. J. Boyle
D. W. Phillion
F. Rainer
V. C. Rupert
H. N. Kornblum, Jr.

5-7.2 Scattered Light Evidence for Short Density Scale Heights Near Critical Density in Laser-Irradiated Plasmas

Direct evidence of short density scale lengths near critical density ($n_c = 9.85 \cdot 10^{20}$ electrons/cm³) has been obtained from measurements of the polarization of the light scattered by laser-fusion targets. Figure 5-151 shows the two extreme cases for a plane wave reflected by a plane-stratified plasma. In the geometrical optics limit, the polarization vector maintains a constant angle with respect to the scattering plane formed by the electron density gradient Δn_e and the wave vector $\vec{k}$ of the incident plane wave, while in the metal limit the tangential electric fields of the incident and reflected waves must cancel at the boundary. Therefore, both the vertical and the horizontal components of the polarization vector are reversed upon reflection, leading to a polarization vector that projects below the scattering plane by Ψ . In both limits the reflected wave is linearly polarized, but in directions that differ by 2Ψ . For a density profile with a finite slope, the reflected wave will, in general, be elliptically polarized with major and minor axes unaligned with the scattering plane. Maxwell's equations have been solved numerically, as a function of the density scale length, for a variety of incidence angles and density profiles. These results and the experimental data show that for 1.06- μ m irradiation of glass microspheres at an intensity $I_L \approx 10^{16}$ W/cm², the density profile has a scale length of no greater than 1.5 μ m.

Numerous other experiments support these results. Our measurements agree with an estimate of the scale length made by Eidman and Siegel,¹³⁷ who established an upper limit of 1 μ m from observations of the angular distribution of the second harmonic (SH) light. The light was generated by a CH₂ plasma irradiated by a 5 ns, 1.06- μ m pulse focused by an aspheric lens ($\Omega = 1$ steradian) to a 30- μ m-diam spot ($I_L = 10^{14}$ W/cm²). SH emission maximized at the lens edge ($\theta = 25^\circ$) and conversion efficiency was small ($\sim 10^{-5}$). Both imply a scale length $L \gtrsim \lambda$. Profile steepening has been directly observed in microwave experiments at 1.2 GHz, in which a

Fig. 5-151. Polarization state of the reflected light for linearly polarized light incident upon a plane-stratified plasma. The plasma's electric field polarization vector $\hat{e}$ is at an angle Ψ to the scattering plane. (a) In the geometrical optics limit of a large density scale length, $\hat{e}$ will always remain at a constant angle to the scattering plane, while, (b), in the limit of an infinitely steep density profile, with n_e jumping from 0 to ∞ , $\hat{e}$ will be inverted upon reflection so that it projects below the scattering plane by an angle Ψ .

TE_{10} rectangular waveguide mode was normally incident upon an inhomogeneous plasma.¹³⁸ The steepening was also observed in interferometry experiments carried out by Fedosejevs, Tomov, and Richardson,¹³⁹ in which an aluminum slab was irradiated by a 1.5-ns CO_2 laser pulse and probed at various times by a 200-ps, 5320-Å pulse. They placed an upper limit of 40 μm upon the scale length at critical density.

Short scale lengths may also be inferred from studying the time-integrated angular distribution of scattered light at the laser wavelength (1.064 μm) on the premise that any azimuthal asymmetry about the beam axis is due to resonance absorption. For the reflection to be specular, the amount of light sidescattered by the Brillouin instability must be small, and the critical density surface must be fairly smooth. Scattered light distributions from experi-

ments on single-beam-irradiated tungsten-glass and parylene disks and two-beam-irradiated DT-filled glass microspheres are discussed elsewhere in this report. For intensities between $2 \times 10^{13} \text{ W/cm}^2$ and $2 \times 10^{16} \text{ W/cm}^2$, we find that the scattered light is azimuthally asymmetric at large angles away from the beam axis. This implies a steep density profile since resonance absorption can be efficient over a wide range of incidence angles only if the profile near critical density has a scale length on the order of a few vacuum wavelengths or less. Simulations carried out by Estabrook, Valeo, and Krueer¹⁴⁰ using a two-dimensional, relativistic particle and electromagnetic field simulation code have shown that light pressure rapidly steepens the density profile scale length around critical density to a few tens of electron Debye lengths on a time scale of a few hundred optical cycles.

Polarimetry Measurements on Scattered Light

The electromagnetic field equations describing a monochromatic plane wave obliquely incident upon a plane-stratified plasma with the electron density varying along the z axis may be divided into two uncoupled groups of equations. For $\vec{k}$ lying in the yz plane, the TE or s-polarized wave has field components E_x , H_y , H_z , while the TM or p-polarized wave has field components E_y , E_z , H_x . The cold plasma wave equations in cgs units are:

$$\frac{\partial^2 H_x}{\partial z^2} - 1/\epsilon \frac{\partial \epsilon}{\partial z} \frac{\partial H_x}{\partial z} + \frac{\omega^2}{c^2} (\epsilon - \sin^2 \theta_0) H_x = 0$$

p-polarization

$$\frac{\partial^2 E_x}{\partial z^2} + \frac{\omega^2}{c^2} (\epsilon - \sin^2 \theta_0) E_x = 0$$

s-polarization (17)

where c is light speed, ω is the circular optical frequency, θ_0 is the incidence angle in vacuum, and ϵ is the dielectric constant. Since the two polarization components obey different wave equations, they undergo different phase shifts and attenuations upon reflection. By measuring the polarization state of the reflected wave and assuming a shape for the plasma density profile, we can deduce a characteristic density scale length.

The two extreme limiting cases are shown in Fig. 5-151. In the geometric optics limit of a large density scale length, the electric vector $\vec{E}$ makes a constant angle with the scattering plane. This may be seen from the equation for the unit vector $\hat{u}$, which may be expressed in terms of the eikonal ζ and the refractive index n as ⁽¹⁴⁾:

$$n \frac{d\hat{u}}{ds} = - (\hat{u} \cdot \text{grad } \ln n) \text{ grad } \zeta, \quad (18)$$

where ds is the differential distance along the ray trajectory. Since $\text{grad } \zeta$ always lies in the scattering plane, we find that by taking the dot product of Eq. (18) with the normal vector to this plane that $\hat{u}$ will remain at a constant angle to the plane. In the metal limit, the density discontinuously jumps from vacuum to infinite density. At the discontinuity, the tangential electric field must be zero. Upon reflection,

$\hat{u}$ will thus be inverted so that it projects below the scattering plane. The disparity between the limits is maximum when Ψ equals 45° and the incident wave is an equal-amplitude superposition of TE and TM waves.

The polarimeter, described elsewhere in this report, measured only the degree of linear polarization along an axis. This axis was at an angle of 45° to the scattering plane, as was the incident laser electric field (Fig. 5-152). If the plasma behaved as a perfect metal ($\sigma = \infty$), the measured degree of linear polarization along the axis would be $p = +1$. The polarimeter looked at light backscattered at an angle of 45° to the incident beam axis.

If the radius R of the microsphere greatly exceeds both the characteristic height ΔR of the underdense plasma and the vacuum wavelength λ_0 , then a one-dimensional model of the plasma should give good results. Let α be the factor by which the p-polarized component is attenuated in amplitude relative to the s-polarized component and let δ be the relative phase difference $\delta_{TM} - \delta_{TE}$. We identify $\alpha = 1$, $\delta = 180^\circ$ as the metal limit and $\alpha = 1$, $\delta = 0^\circ$ as the geometrical optics limit. The polarimeter analyzes the reflected wave into the components:

$$I_{||} = 0.25 |1 - \alpha e^{i\delta}|^2 \quad \text{and} \quad I_{\perp} = 0.25 |1 + \alpha e^{i\delta}|^2, \quad (19)$$

giving for the degree of linear polarization:

$$p = \left(\frac{2\alpha}{1 + \alpha^2} \right) (-\cos \delta). \quad (20)$$

Setting the first factor equal to one in Eq. (19) is a good approximation since even if the TM wave undergoes 50% resonant absorption, this factor is only reduced to 0.94.

Before the measurement of p can be translated into a density scale length L , a specific density profile must be assumed. We assume the electron density increases linearly with distance from a subcritical density n_L to a supercritical density n_H with a slope $L^{-1} = d(n/n_{crit})/dz$. The electron density decreases from n_L to vacuum density with vanishingly small slope on the one side and remains constant at n_H on the other.

Fig. 6-162. Polarimetry of the light backscattered at an angle of 45° to the incident beam for a one-sided ball-on-stalk shot. The transmission axis of the Brewster window points below the scattering plane at an angle of 45° , while the laser electric field points above the plane by $\Psi = 45^\circ$. The density contours are unrealistic, since they were generated by a computer model which ignores light pressure.

Equation (17) was integrated numerically between the limits n_L and n_H , starting from the high density boundary, where the tangential electric and magnetic field components were matched to an evanescent wave on the constant density side. The incident and reflected wave amplitudes were obtained by again matching tangential field components at the low density boundary. The step size was computed at each step by solving for the characteristic spatial frequencies of the second order difference equation (we assumed that the equation's coefficients did not vary rapidly). The second order equation replaced the wave equation in the numerical integration. The step size was made equal to a small number η ($\eta \leq 0.01$) divided by the greater of the two moduli of the characteristic fre-

quencies. This stratagem ensured that the fractional change in the wave function in each iteration would be of order η . This was necessary because of the singularity at critical density in the TM wave equation. This singularity was shifted off the real frequency axis by assuming a phenomenological electron-ion collision frequency ν :

$$\frac{\nu}{\omega} = 10^{-3} \frac{n}{n_c} \quad (21)$$

The complex dielectric constant is then

$$\epsilon(z) = 1 - \frac{\omega_p^2(z)}{\omega(\omega - i\nu)} \quad (22)$$

At the end of this article, we present an analytical solution for a particular density profile which asymptotically approaches critical density with increasing distance. This model, which was used to test the numerical integration scheme has value when the turning point, $n_c = n_c \cos^2 \theta_0$, is far from critical density.

The modulus and phase of the ratio of the amplitude reflection coefficients for the two polarization components are given in Fig. 5-153. Each point represents the results of numerically integrating the wave equations (17) for both polarization states. Their phase difference is plotted against the scale length for two combinations of (n_L, n_H) ; namely,

Fig. 5-153. Determination of the density scale length at critical density by polarimetry. Each point represents a numerical integration of the wave equations. (a) Phase shift δ is plotted against the density scale length $L = |\partial(n/n_c)/\partial z|^{-1}$ for several incidence angles and density profiles. The degree of linear polarization $p = \cos \delta$ is that measured by a polarimeter looking at the light scattered in a plane at 45° to the laser electric field and oriented so that $p = -1$ in the geometrical optics limit. Curves identified by open symbols are for the density profile $(n_L, n_H) = (0.75n_c, 1.25n_c)$, while solid symbols are for $(n_L, n_H) = (0.5n_c, 2.0n_c)$. (b) Azimuthal asymmetry is plotted against the scale length, assuming $n_L = 0.5n_c$ and $n_H = 2.0n_c$. The azimuthal asymmetry $I_{\text{in-plane}}/I_{\text{out-of-plane}}$ equals $|r_{TM}/r_{TE}|^2$, where r_{TM} and r_{TE} are the amplitude reflection coefficients.

(0.5n_c, 2.0n_c) and (0.75n_c, 1.25n_c). The angle of incidence θ₀ is shown as a parameter in Fig. 5-153(a). The angles denoted θ₀ are measured from the normal in vacuum, and the densities are in units of the critical density n_c. The phase difference and relative attenuation are insensitive to ν, provided ν/ω << 1.

To demonstrate this, we have listed in Table 5-19 several combinations of ν/ω and δ for the conditions n_L = 0.5 n_c, n_H = 2.0 n_c, L = 1.5 λ₀, and θ₀ = 22.5°. The phase difference δ does not approach 180° in the limit of a discontinuous jump since the magnitude of the jump is finite. Within this limit, δ can be found from the Fresnel formula¹⁴²

$$\tan \frac{\delta}{2} = \frac{\cos \theta_1 \sqrt{\sin^2 \theta_1 - \left(\frac{n_2}{n_1}\right)^2}}{\sin^2 \theta_1}, \quad (23)$$

where n₁, n₂ are the indices of refraction on the low and high density sides of discontinuity, respectively, and θ₁ is obtained from the incidence angle θ₀ by Snell's law:

$$\theta_1 = \sin^{-1} \left(\frac{\sin \theta_0}{n_1} \right). \quad (24)$$

The periods of the oscillations in the curves are consistent with interference between reflections from the turning point at n_c = n_c cos²θ₀ and from the discontinuity in the slope at z = 0.

Table 5-19. Combinations of damping and phase difference

Damping at critical density (ν _{cr} /ω)	Phase difference (δ)
10 ⁻⁵	96.67°
10 ⁻³	96.64°
10 ⁻¹	96.21°

Both resonance absorption and inverse bremsstrahlung are correctly treated. The fraction resonantly absorbed is represented by the fraction 1-I_{in-plane}/I_{out-of-plane}. For each incidence angle θ₀, this fraction is found to be maximum for that scale length L that satisfies the equation

$$\tau \equiv (k_0 L)^{1/3} \sin \theta_0 \approx 0.67, \quad (25)$$

where k₀ = 2π/λ₀, and τ is the dimensionless parameter in terms of which Ginzberg expresses the resonance function Φ(τ). The fraction absorbed should be about |Φ(τ)|²/2, and, when the curves in Fig. 5-153(b) are expressed in terms of τ, this behavior is indeed, found. Inverse bremsstrahlung absorption in the geometrical optics limit is given by¹⁴³

$$I_{\text{refl}}/I_{\text{incident}} = 1 - \exp \left(\frac{-32}{15} \frac{\nu_{\text{cr}} L}{c} \cos^5 \theta_0 \right), \quad (26)$$

for light incident at an angle θ₀ upon a linear density ramp of scale length L. For values of ν, L, and θ₀ consistent with the geometrical optics approximation, the numerical simulation verifies this result.

We have measured the polarization of the light scattered by laser fusion targets irradiated at the two-beam Argus facility. The beams had a laser pulse duration ≈40 ps FWHM. A potential problem with such measurements is that there is a possibility of not knowing from which beam the scattered light originated. However, this was not a problem during our experiment because the energy imbalance between the laser arms (north/south beam energies = 6/41 J) made it almost seem as though the target had only been irradiated by a single beam. Thus, after we had irradiated an 84-μm-diam microsphere, we were able to measure a polarization of 0.77. When we irradiated a microsphere with just one beam (48 J incident at the target, 44-ps FWHM oscillator pulse, 89-μm-diam target), we measured a polarization of 0.80. The beams were focused onto the target so that 90% of the energy was contained in a 19° half-angle cone.

The beams were made nearly circular by removing the astigmatism with an adjustable corrector. The range of incidence angles in Fig. 5-153(a) is intended to indicate the measurement uncertainties associated with the finite angular width of the incident beam. If the polarimeters saw light originally incident on-axis, the density scale height must have been less than $1\text{ }\mu\text{m}$ and the magnitude of the density jump must have exceeded n_c .

Single-beam irradiation experiments on $10\text{-}\mu\text{m}$ -thick tungsten-glass and parylene disks were carried out on the Cyclops facility for intensities ranging from $1.2 \cdot 10^{13}\text{ W/cm}^2$ to $5.7 \cdot 10^{14}\text{ W/cm}^2$ and for oscillator pulse widths of $220 \pm 40\text{ ps}$ FWHM. The polarimeters looked at light backscattered at an angle of 16° to the beam axis (the marginal ray angle of the $f/2.5$ lens was 11.3°), as shown in Fig. 5-154. The polarimeter for which $\psi = 0^\circ$ looked at light that, assuming specular reflection, was originally incident upon the plasma as a p-polarized wave, while the polarimeter for which $\psi = 45^\circ$ looked at light that was incident as an equal-amplitude superposition of TE and TM waves. According to the linear optics model already described (in which the finite angular extent of the incident beam, Faraday rotation, Brillouin scattering, and

rippling or cavitation of the critical density surface are ignored), the measured degree of linear polarization p ($\psi = 0^\circ$) should be $+1$. If we assume only a part of the scattered light is polarized, then p ($\psi = 0^\circ$) gives that fraction, and it is the ratio p ($\psi = 45^\circ$)/ p ($\psi = 0^\circ$) that should be set equal to the right hand side of Eq. (20). From the average value for this ratio of 0.92 (Table 5-20), a scale length of about $4\text{ }\mu\text{m}$ is calculated. However, the large angular extent of the beam makes the uncertainty great (Fig. 5-155).

Spatial Distribution of Scattered Light

To study the spatial distributions of the scattered light and particle blowoff from the laser-produced plasma, it is essential to understand the stimulated scattering and collective absorption processes. These processes determine both the fraction of light absorbed and where and how it is deposited in the plasma. Large azimuthal asymmetries in the scattered light have always been observed in LLL experiments with Janus, Cyclops, and Argus. But azimuthal asymmetries in the energy of the particle

Fig. 5-154. Experimental geometry for the single-beam irradiation experiments on $10\text{-}\mu\text{m}$ -thick glass and parylene slabs. The polarimeters look at light backscattered at an angle of 45° to the incident beam axis and are at azimuths $\psi = 0^\circ$ and $\psi = 45^\circ$ relative to the laser electric field.

blowoff have only been observed in experiments on DT-filled glass microsphere targets and not in experiments on disk targets. For the microsphere targets and for a given polar angle (angle made by the detector line-of-sight with the beam axis), light preferentially scatters in a plane which is perpendicular to the laser electric field (out-of-plane scattering), while the most energetic particle blowoff usually occurs in the plane of polarization formed by the electric field and propagation directions of the incident beams (in-plane scattering). If we assume that the particle blowoff is more or less directed radially outward, then the ion calorimetry results imply that those sectors of the ball where the light was incident as a p-polarized wave were preferentially heated. Figure 5-156 shows the in- and out-of-plane polar distributions of both the scattered light and particle blowoff energies for a DT-filled glass microsphere target irradiated on the Argus facility.

Stimulated Brillouin sidescatter (SBS) can easily explain the asymmetric light distribution, since it preferentially scatters light normal to the electric field of the incident light. The coupling coefficient is proportional both to the dot product of the electric polarization vectors of the incident and scattered

Fig. 5-155. Dependence of the phase difference $\delta_{TM} - \delta_{TE}$ upon the scale length L for several small angles of incidence.

light waves and to $\sqrt{|\vec{k}_a|}$, where k_a is the ion acoustic wave vector. Thus, the coupling coefficient may be found from¹⁴⁴

$$\gamma(\theta) = \begin{cases} \gamma(\pi) \sqrt{\sin(\theta/2)}, & \text{s-polarization} \\ \gamma(\pi) \cos \theta \sqrt{\sin(\theta/2)}, & \text{p-polarization} \end{cases} \quad (27)$$

where $\gamma(\pi)$ is the coupling coefficient for direct backscatter and θ is the scattering angle before refraction. Thresholds for Brillouin back- and sidescatter and for the growth of Brillouin quasimodes in an inhomogeneous plasma (where the density, electron temperature, and flow velocity vary in one direction) are given by Liu, Rosenbluth, and White.¹⁴⁵ At low intensities, the amplitude of the acoustic wave is limited by pump depletion, but at higher intensities, ion wave-breaking and density profile modification limit the wave's amplitude. Biskamp and Welter¹⁴⁶ have numerically simulated the problem of either s- or p-polarized light obliquely incident upon a plane-stratified plasma with a piecewise-linear density profile. The reflected light is analyzed into its Fourier components to determine the specularly-reflected and Brillouin backscattered components. Experimentally, we do not know quantitatively how important Brillouin

Table 5-20. Polarimetry data on Tungsten-glass and Parylene disks

Shot No.	Degrees of linear polarization		Intensity, W/cm ²
	p($\psi = 45^\circ$)	p($\psi \approx 0^\circ$)	
<u>Tungsten-glass</u>			
56032202	0.78	—	$1.2 \cdot 10^{13}$
56031902	0.73	—	$4.5 \cdot 10^{13}$
56032301	0.77	0.83	$7.2 \cdot 10^{13}$
56032204	0.70	0.74	$4.4 \cdot 10^{14}$
56031802	0.72	0.61	$5.7 \cdot 10^{14}$
<u>Parylene</u>			
56032201	0.75	0.80	$1.4 \cdot 10^{14}$
56031901	0.76	0.84	$4.4 \cdot 10^{14}$
56032203	0.76	0.88	$5.3 \cdot 10^{14}$

scattering is, particularly at high intensities, although much work in the intensity range $10^{12} \rightarrow 4 \times 10^{14}$ W/cm² has been done at Garching¹⁴⁷ and at NRL.¹⁴⁸ Note that any explanation of asymmetric heating in terms of SBS, rather than resonance absorption, must assume SBS to be more efficient in the out-of-plane sectors where the incident light is s-polarized.

In conclusion, experimental evidence based on measurements of the spatial distribution and polarization of the time-integrated, scattered 1.06- μ m light indicates the density profile near critical density is steepened to ϕ (1 μ m).

Analytic Solution of Wave Equations for Density Profile

The wave equations (17) can be solved analytically for at least one nontrivial density profile, given by

$$n/n_c = [1 + \exp(mk_0 z)]^{-1}. \quad (28)$$

where $k_0 = 2\pi/\lambda_0$. The wave equations may be expressed in terms of the vector potential A by

$$\frac{d^2 A_y}{dz^2} + \frac{\omega^2}{c^2} (\epsilon - \sin^2 \theta_0) A_y = 0$$

s-polarization

$$\frac{d^2 \psi}{dz^2} + \left[k^2 - k \frac{d^2}{dz^2} \left(\frac{1}{k} \right) - \frac{\omega^2}{c^2} \sin^2 \theta_0 \right] \psi = 0$$

p-polarization

(29)

where $\psi = A_x/k$ and $k \approx \sqrt{\epsilon} \omega/c$. For this profile, we obtain the equations

$$\frac{d^2 \psi_{\parallel,1}}{dz^2} + \frac{\omega^2}{c^2} \epsilon_{\parallel,1} \psi_{\parallel,1} = 0,$$

$$\epsilon_{\parallel} = \cos^2 \theta_0 - \left(1 + \frac{m^2}{4} \right) \frac{e^{mk_0 z}}{1 + e^{mk_0 z}} - \frac{m^2}{4} \frac{e^{mk_0 z}}{(1 + e^{mk_0 z})^2},$$

$$\epsilon_{\perp} = \cos^2 \theta_0 - \frac{e^{mk_0 z}}{1 + e^{mk_0 z}},$$

$$\psi_{\parallel} = A_z/k, \quad \psi_{\perp} = A_y. \quad (30)$$

Equation (30) can be put into the form of a hypergeometric differential equation by a change of both the independent and dependent variables, as described by Brekhovskikh.¹⁴⁹ The difference in the phase retardations that the two polarization states undergo upon reflection is

$$\delta = \delta_{TM} - \delta_{TE} = 4 \left[\arg \Gamma(\alpha_s) - \arg \Gamma(\alpha_p) \right] - 2 \arg(\alpha_s - 1),$$

where

$$\alpha_s = 1 + \frac{i}{m} e^{-i\theta_0}$$

and

$$\alpha_p = \frac{1}{2} + \frac{i}{m} \left[\cos \theta_0 - i \sqrt{\left(1 + \frac{m^2}{4} \right) - \cos^2 \theta_0} \right] \quad (31)$$

Here Γ is the complex gamma function¹⁵⁰ and $-180^\circ \leq \arg \Gamma < 180^\circ$ is its phase.

References

137. K. Eidman and R. Siegel, *Phys. Rev. Lett.* **34**, 799 (1975).
138. K. Mizuno and J. S. DeGroot, *Bull. Am. Phys. Soc.* **21**, 1042 (1976).
139. R. Fedosejevs, I. V. Tomov, and M. C. Richardson, *Bull. Am. Phys. Soc.* **21**, 1047 (1976).
140. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975).
141. M. Born and E. Wolf, *Principles of Optics* (Pergamon Press, Oxford, 1970), 4th ed., p. 119.
142. J. A. Stratton, *Electromagnetic Theory* (McGraw-Hill Book Co., New York, 1941), p. 500.
143. J. W. Shearer, *Effect of Oblique Incidence on Optical Absorption of Laser Light by a Plasma*, Lawrence Livermore Laboratory, Rept. UCRL-72400 (1976).
144. J. M. Dawson and A. T. Lin, *Parametric Instabilities in Plasma*, University of California at Los Angeles, Rept. PPG-191 (1974).
145. C. S. Liu, M. N. Rosenbluth, and R. B. White, *Phys. Fluids* **17**, 1211 (1974).
146. D. Biskamp and H. Welter, to be published.
147. K. Eidman and R. Siegel, "Backscatter Experiments," in *Laser Interaction and Related Plasma Phenomena*, H. J. Schwarz and H. Hora, Eds. (Plenum Press, New York, 1974), Vol. 3B, pp. 667-690.
148. B. H. Ripin, J. M. McMahon, E. A. McClean, W. M. Manheimer, and J. A. Stamper, *Phys. Rev. Lett.* **33**, 634 (1974).
149. L. Brekhovskikh, *Waves in Layered Media* (Academic Press, New York, 1964), p. 174.
150. M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions* (Dover Publications, Inc., New York, 1964), p. 253.

Author

D. Phillion

Section 6

ADVANCED LASERS

Contents

Section 6 — ADVANCED LASERS	6-3	Other Problems	6-46
6-1 Overview	6-3	Front End	6-47
Laser Fusion Activities	6-3	A Near-Resonant Atomic-Scatterer—	
Laser Isotope Separation Activities	6-6	Kr-F-Pumped Calcium	6-47
6-2 Group VI-A Photolytic Lasers	6-6	6-7 Rare Gas Halide (RGH) Lasers	6-49
Efficient Rare-Gas-Excimer		Kinetics of RGH Molecules	6-50
Photolytic Sources	6-8	Electron Beam Excitation Studies	6-52
Photolytic Production of O(¹ S) from		Discharge Excitation Studies	6-55
CO ² Using NeF Emission	6-15	RGH Laser Tuning Studies	6-59
Electronic States of CO ₂	6-18	Theoretical Studies	6-60
Polarizability of Atomic Oxygen	6-18	Summary	6-63
6-3 Rare Earth Vapor (REV) Lasers	6-19	6-8 Developments in Theoretical and	
Experimental Studies	6-21	Computational Models	6-64
Theoretical Aspects	6-24	Atomic and Molecular Structure	6-64
6-4 Metal Vapor Lasers	6-27	Heavy Particle Dynamics Codes	6-65
6-5 Rare Gas Oxide (RGO) Lasers	6-29	Electron-Molecule Scattering Codes	6-66
Kinetic Studies	6-31	Laser-Kinetic Modeling	6-66
Amplifier Development	6-34	Photon Dynamics	6-67
Future Plans	6-37	6-9 Photoionization	6-67
6-6 Raman Pulse Compression of Rare		Theory: Stieltjes Imaging	6-68
Gas Fluoride Lasers	6-40	Examples	6-71
Pulse Compression in a Backward-Wave		6-10 New Infrared Lasers	6-72
Raman Amplifier	6-40	6-11 Electron Beam Physics	6-77
Design of a Nominal KrF-		System Components	6-77
Methane Amplifier	6-42	Electron Beam Source	6-78
Second Stokes Stimulated Scattering in a		Beam Pinch	6-78
Saturated Amplifier	6-45	Vacuum Breakdown	6-78
Staged Compression for Short-Pulse		Other Considerations	6-80
Generation Without Higher Order		Energy Deposition	6-80
Stokes Parasitics	6-45		

Section 6

ADVANCED LASERS

6-1 Overview

Our Laser Fusion and Laser Isotope Separation Programs are both in the early phases of defining applications and attendant laser requirements. As these programs mature and the requirements harden, we must anticipate laser problems and ensure that conceptual and technological solutions have been identified. For this purpose the Advanced Quantum Electronics (AQE) element of the LLL Laser Program was organized in 1975 as a broadly based, cohesive activity, divided into two groups: the Advanced Lasers Group, and the Theoretical Atomic and Molecular Physics Group. Through a balanced application of theoretical, analytical, computational, and experimental skills, the AQE effort serves two primary programmatic functions: (1) to identify, demonstrate, and pursue the technological development of new laser devices and systems in support of the Laser Fusion and Laser Isotope Separation Programs, and (2) to provide theoretical, analytical, and computational expertise in areas of atomic and molecular physics and chemistry relevant to laser isotope separation and laser photochemical processes. The broad multidisciplinary character of the AQE effort reflects our recognition that both laser fusion and laser isotope separation applications require the development of concepts and quantum electronic devices which are at or beyond the frontiers of our present knowledge.

Laser Fusion Activities

We anticipate achievement of early *scientific* milestones of ERDA's Inertial Confinement Fusion (ICF) Program on a single-pulse basis using laser facilities now in construction (Shiva, HEGLF) or proposed (Nova). But the major ICF *applications* milestones cannot be achieved with these laser facilities. Advanced drivers must be developed which are capable of delivering high average powers to fusion targets and meeting other stringent

technical and cost/performance objectives. Three types of drivers are being considered to implement ICF applications: lasers, electron-beam accelerators, and ion-beam accelerators. In the National ICF Program Plan, the first applications facility is the Experimental Power Reactor (EPR-1), which requires a megawatt-class driver with pulse parameters capable of producing pellet gains of 10. All AQE efforts in the Laser Fusion Program are directed toward the achievement of the EPR-1 milestone.

It has long been recognized at LLL that laser-induced fusion can be approached using many different target concepts which, in terms of projected applications, dictate a range of laser system performance requirements. During the next few years, the viability of the various target concepts will be evaluated through fusion experiments (using the Janus, Argus, and Shiva laser systems) and target design iteration. On the basis of experiments conducted to date, we have been able to establish preliminary laser-system performance requirements for various laser-fusion applications. The nominal laser performance requirements are as follows:

Wavelength	300-2000 nm
Pulse length	~1 ns
Pulse energy	100-1000 kJ
Average power	1-10 MW
On-target efficiency	≥1%

Laser concepts and media that can reasonably be related to these performance requirements may be grouped into three distinct types: (1) stimulated emission occurring on electric-dipole allowed electronic transitions, (2) stimulated emission occurring on electric-dipole forbidden electronic transitions (electric quadrupoles, magnetic dipole, forced electric dipole), and (3) stimulated emission occurring on optically induced transitions (Raman scattering, tripling, etc.). Laser media of the first type, such as the rare-gas and rare-gas-halogen excimers, exhibit stimulated-emission cross sections in the range 10^{-16} - 10^{-17} cm², upper-laser-level radiative lifetimes of

tens of nanoseconds, and instantaneous stored energy densities of less than 1 J/liter under efficient excitation conditions. In contrast, laser media of the second type, such as iodine, Group VI-A atoms, and rare-earth molecular vapors, exhibit stimulated-emission cross sections in the range 10^{-18} - 10^{-20} cm², upper-laser-level radiative lifetimes of hundreds of microseconds, and instantaneous stored energy densities of tens of joules/liter under useful pumping conditions. The radically different physical and kinetic properties of types 1 and 2 laser media dictate distinctly different laser-system concepts and technologies. During the past few years, advanced laser research at LLL has centered almost exclusively on type 2 energy-storing laser media (Group VI atoms, rare-gas Group VI excimers, rare-earth vapors). With the recent invention of efficient rare-gas-halogen excimer lasers (type 1 media), widespread interest has been generated in finding conceptual and technological approaches for using these laser media in fusion lasers (as opposed to using them as pump sources for energy-storage laser media). During the last several months of 1976 we identified at least one method with potential for exploiting the rare-gas-halogen lasers for fusion: compression of 100-ns rare-gas-halogen laser pulses into the nanosecond range using backward-wave Raman scattering processes.

The main thrust of the LLL program continues to emphasize the two energy-storage-type lasers already identified at LLL. First priority is assigned to an assessment of the scalability of the photolytic Group VI atom lasers, oxygen, sulfur and selenium. This effort is in direct support of the ERDA goal of demonstrating a 1-TW/kJ, scalable short-wavelength laser in 1981. Second priority is placed on the determination of critical structural, spectral, kinetic, and thermodynamic properties of the rare-earth vapors.

In the following, we briefly describe AQE activities in support of the Laser Fusion Program, which are divided into five areas:

- Laser development.
- Candidate laser evaluation.
- New laser media and concepts.
- Laser systems design analysis.
- Supporting research and technology.

Laser Development. The Group VI-A atoms (oxygen, sulfur, selenium), excited to the metastable ¹S states, have been identified as a class of laser storage media with properties satisfying many of the re-

quirements for fusion lasers. Efforts at LLL have proceeded in two directions: (1) direct electronic excitation of rare-gas-oxide excimers, and (2) photolytic dissociation of simple polyatomic molecules into the atomic systems.

Activities in the rare-gas-oxide lasers (§ 6-5) have involved determination of the kinetics of ¹S production and design of rare-gas-oxide amplifiers. The production and subsequent quenching of O(¹S) has been studied as a function of a number of oxygen additives with various rare gases and over a wide range of pressures. These experiments have provided a great deal of understanding about relevant microscopic collisional processes in these systems, but not all production channels of O(¹S) in electron-beam-excited gas mixtures have been completely determined. From a device point of view, utilizing one of our large electron-beam machines, we have evaluated the properties of a multipass, master-oscillator/power-amplifier (MOPA) laser system with XeO as the active medium. Measured fluorescence intensities were in very good agreement with computer code predictions. Gain and saturation measurements were made using both cw and pulsed dye lasers as the master oscillator. Peak energy storage was 5 J/liter, and medium efficiency was 0.3-0.6%, depending on the rare gas.

Our studies of the photolytic systems (see § 6-2) are divided into those involving the laser transition and those pertaining to the photolytic transition. Efforts at LLL have emphasized the latter. An evaluation of the rare-gas-excimer photolytic pump sources both as fluorescers and lasers has been undertaken. We have developed theoretical estimates of the practicality of rare-gas-halide photolytic pumps. In addition, supporting systems analyses and scaling analyses of the photolytically driven lasers have been initiated to define key future experiments. On the basis of our present understanding of the relevant kinetics and spectroscopy of the Group VI-A atoms, we are shifting our emphasis to the photolytic option.

Candidate Laser Evaluation. In the area of candidate laser evaluation, only one class of laser media is currently under consideration: rare-earth-vapor systems. Rare-earth ions embedded in solid matrices (e.g., Nd³⁺ in glass) are the active medium of current solid-state lasers used routinely in fusion research. However, the average-power capabilities of these flashlamp-pumped Nd³⁺ lasers may be too limited to meet our future requirements. A number

of vapor-phase complexes of rare-earth ions (see § 6-3) have been identified that have the potential of scalability to high peak and average powers as well as high efficiency. Experimental gain measurements in complexes of NdCl_3 with AlCl_3 have been performed. Upper-laser-level kinetic storage times of several microseconds (with stored energy densities of hundreds of joules per liter) were observed, and gain signals were in fair agreement with predictions. Theoretical analyses of the rare-earth trihalides have been completed, including the systematics of electronic states and evaluation of pumping scenarios. Research into volatile rare-earth compounds, such as organometallic chelates, was pursued as an alternate approach in view of serious materials problems encountered with AlCl_3 at high temperatures.

New Laser Media and Concepts. Our search for new lasers includes studies of storage media, studies of possible fluorescers/lasers for pumps, and development of alternative methods for energy extraction. The new class of high-efficiency uv lasers operating on rare-gas-monohalide molecules cannot be used in their standard configuration as fusion lasers because of their low energy storage density. A number of novel schemes utilizing these species were analyzed in 1976 for potential application to fusion. One very promising approach involves using backward-wave Raman-effect pulse compression (see § 6-6) to shorten a high-energy 100-ns KrF pulse to a few nanoseconds. Methane has been identified as a likely compressor candidate. Overall efficiencies of several percent appear attainable.

The development of our understanding of optical pumps for potential storage systems has continued. Laser action on KrCl at 222 nm and Br_2 at 282 nm was first demonstrated, and experimental studies of other high-power, high-efficiency rare-gas-halide systems were continued. Research on rare-gas-excimer lasers concentrated on validating computer code predictions of laser performance under conditions of efficient excitation. The metal-vapor systems (Hg and Cd) have been of interest as another class of pump laser. Although the Hg-Hg₂ system will probably not show net gain, recent experiments of others revived interest at LLL in the Cd-Hg system (see § 6-4). Preliminary experiments on Cd-Hg conducted at LLL have not reproduced net gain as reported in the literature.

Laser Systems Design Analysis. A recent addition to AQE fusion program activities is laser systems

design analysis, which develops analytical and computational models that couple the important features of microscopic collisional processes of a laser medium with macroscopic technological parameters of the pump and optical-transport subsystems. These models are then exercised to define optimized device and system configurations and to identify critical parameters of highest performance leverage. Such endeavors have been associated with the LLL glass-laser program since its inception and have led to very successful, sophisticated laser-systems models permitting the identification of design solutions giving optimum cost/performance. Our initial activities in this area have been directed toward candidate-laser evaluation studies and assessment of new laser architectures for utilizing existing laser media.

Supporting Research and Technology. The AQE program includes many supporting research and technology efforts; in this annual report we have chosen to highlight only a few: electron-beam physics, calculation of photoionization cross sections, and development of new theoretical and computational methods.

The usefulness of relativistic electron beams (see § 6-11) for pumping gas-laser media derives from their ability to rapidly deposit large amounts of energy in large volumes with high efficiency and reasonable spatial uniformity. We have undertaken a basic study of electron-beam generation, transport, and deposition processes covering a wide variety of voltages, currents, and pulse lengths.

Our most recent theoretical accomplishment (and potentially the most significant) was developing an *ab initio* technique for determining photoionization cross sections for small polyatomic molecules (see § 6-8). To demonstrate the accuracy of the method, we have determined the photoionization cross section of N_2 for three channels. These calculations indicate that the method is capable of determining cross sections to within 10%. The method involves the use of discrete-basis-set techniques, which means that traditional quantum-chemical computational methods can be utilized. The method is general and can also be applied to excited states and ions.

Finally, the need for models describing collisional phenomena in laser systems has led to the establishment of a broad-based modeling capability which is used to develop not only computer codes but also

underlying theories that in the future will support the overall AQE program.

Laser Isotope Separation Activities

AQE activities in support of the Laser Isotope Separation Program are focused on five areas:

- Copper-vapor lasers.
- Rare-gas-halide lasers.
- Dye amplifiers.
- Infrared lasers.
- Photon dynamics.

Recent experiments involving copper-vapor lasers (see Section 8) have demonstrated that this system is efficient and is a moderately high power source of visible radiation. Their ultimate utility in applications such as dye-laser pumping depends upon the ability to achieve mode control and to develop oscillator/amplifier staging techniques. We have performed experiments with unstable-resonator oscillators and oscillator/amplifier configurations which have demonstrated nearly diffraction-limited beams and efficient extraction of amplifier power.

The rare-gas halogens are of particular importance because of a potential for efficient excitation through a wide range of techniques. The basic mechanisms responsible for laser action in the rare-gas halides are now reasonably well documented. However, many of the details that may affect scaling and device performance remain to be resolved. Work this year on the rare-gas halides has concentrated on investigation of the mechanisms responsible for excitation and laser emission in these molecules. Measurements of fluorescence spectra of the various rare-gas-halide molecules have been made using a high-current-density electron beam system as a pumping source. This work, in conjunction with theoretical calculations, has led to an improved understanding of the energy level structure of rare-gas-halide molecules and to the identification of the major emission features of their spectrum.

Copper-vapor lasers are an attractive pump source for dye oscillator/amplifier systems (see Section 8). We have conducted an extensive study directed toward development of efficient, high-average-power, coherently pumped dye oscillators and amplifiers. The study involved considerable experimental and analytical characterization of dye amplifiers pumped by copper-vapor lasers.

With our CO₂ laser and spectroscopy facility we

have done experiments that demonstrated several new and potentially efficient infrared laser transitions (see § 6-10) discretely spanning the wavelengths 6-35 μm , using a two-photon excitation technique. The applications of these new lasers will be in isotope separation and laser photochemistry.

Theoretical efforts aimed toward applying laser-induced excitation and ionization have focused mainly on modeling atomic vapor excitation by lasers (see § 6-8). Significant progress has been made in three areas. A simplified mathematical model describing the atomic vapor excitation has been studied analytically and numerically, the relationship between physical parameters and dynamical behavior has been developed, and conditions for maximum ionization as related to the physical parameters have been studied.

Authors

W. F. Krupke
C. F. Bender
E. V. George

6-2 Group VI-A Photolytic Lasers

The Group VI-A atoms, excited to the ¹S metastable level, have been identified as promising candidates for energy storage lasers for fusion.^{1,2} Efforts to date have been directed toward (1) high-pressure, directly excited rare-gas-oxide lasers, as first demonstrated at LLL^{3,4} (described in a later article in this section), and (2) the lower pressure, photolytically driven atomic systems² described in this article. The 1976 effort in photolytic Group VI lasers centered on two main issues: developing our understanding of rare-gas-excimer photolytic pump sources both as fluorescers and lasers, and developing theoretical estimates of the practicality of a rare-gas-halide photolytic Group VI laser with emphasis on NeF photolysis of CO₂. These two prime efforts are reported here. Supporting systems and scaling analyses of these potential fusion lasers were also initiated to define key research experiments for 1977.

The properties of the photolytic lasers can be divided into two parts for convenience of tabulation: those pertaining to the lasing transition itself, and those pertaining to the photolyzing transition. Table 6-1 lists the wavelengths, cross sections, and

saturation fluences of these free atomic transitions. The properties of the collision-induced rare-gas-“oxide” molecules form a spectrum of cross sections and wavelengths near the values given here and naturally depend on the number density and nature of the perturber.

The atomic lines of primary interest are the 558-nm oxygen line, 772-nm sulfur line, and either of the selenium lines, with preferential interest in the shorter wavelength 489-nm line. The wavelengths, typical absorption coefficients, photolytic saturation fluxes, and possible combinations of pump molecules and precursor molecules are given in Table 6-2, along with the rate constants for quenching of the excited 1S state by the precursor.

An important point to note in comparing Tables 6-1 and 6-2 is that the cross section for photodissociation (σ_p) is several orders of magnitude larger than the cross section for lasing on the atomic lines (σ_L). For large lasers built with a transverse g_{eff} of order one for the atomic transition, the medium being photolyzed will be optically thick by more than two orders of magnitude. Thus, the photolyzing source must bleach through the medium, possibly producing medium inhomogeneities in the wake of a bleaching wave front. The time for the pump flux to bleach through the medium clearly sets a minimum time that the inversion must be sustained. Note also that N_2O and OCS both quench excited 1S states rapidly and

Table 6-1. Photolytic Group VI-A atoms: laser parameters

Atom	Transition	λ_L (nm)	σ_L (10^{-20} cm)	E_s (J/cm 2)
O	$^1S_0 \rightarrow ^1D_2$	558	8.0	4.0
	$\rightarrow ^3P_1$	297	0.05	1300.0
S	$^1S_0 \rightarrow ^1D_2$	772	45.0	0.6
	$\rightarrow ^3P_1$	459	3.0	14.0
Se	$^1S_0 \rightarrow ^1D_2$	777	48.0	0.5
	$\rightarrow ^3P_1$	489	40.0	1.0

Table 6-2. Photolytic Group VI-A atoms: pump parameters^a

Atom	Pump/precursor	λ_p (nm)	σ_p (10^{-16} cm 2)	k_Q (10^{-10} cm 3 /s)	E_s (mJ/cm 2)
O(1S)	Ar $_2^*/N_2O$	128	0.8	0.1	18
	NeF $^*/CO_2$	107	0.5	0.004	35
	Ne $_2F^*/N_2O$	130	0.8	0.1	18
S(1S)	Kr $_2^*/OCS$	147	1	0.004	13
Se(1S)	Xe $_2^*/OCS$	172	4	2	3
	ArF $^*/OCS$	193	0.4	2	25

^aAll photolytic quantum yields unity, except ArF/OCS assumed to be 33%.

thus must be removed by complete photodissociation to have storage times of order 1-10 μ s at initial densities of 10^{16} - 10^{17} cm^{-3} .

One sees from Table 6-2 that each of the three prime candidates can be photolyzed with rare-gas-excimer radiation. Previous work showed that the intrinsic fluorescence efficiencies of these species were very high, about 50%. Our 1976 effort dealt with the possibility of making a high-efficiency rare-gas-excimer laser or amplifier. Long-pulse (1- μ s) e-beam excited laser action by xenon excimers was demonstrated; further refinement, improvement, and validation of the LLL rare-gas-excimer computer code was accomplished; and optimized computer designs of rare-gas-excimer lasers can now be performed.

The theoretical effort on the NeF/CO₂ system shows that the B $^2\Sigma_{1/2}$ excited state of NeF has a short radiative lifetime. Because of this, one could design an *in situ*-radiatively-coupled Group VI laser. Previous experience with rare gas oxides showed that for the Ar₂/N₂O *in situ* case, collisional energy transfer was the primary excitation mode, because of the long effective lifetime of the rare gas excimers. The *in situ* radiative coupling mechanism offers the possibility of high specificity and efficiency of energy transfer. The possible competing pathways for collisional losses in this system are discussed below.

Efficient Rare-Gas-Excimer Photolytic Sources

There are two basic e-beam-pumped photolytic driver options, the incoherent fluorescer and the coherent laser. Optimum system design requires a knowledge of the intrinsic fluorescence and laser efficiencies in order to evaluate trade-offs associated with optical coupling, materials' limits, complexity, etc. Some qualitative discussions of efficient generation of excimer radiation and general statements on potentially limiting processes were made in the 1975 annual report (§ 9.2.1 and 9.3.1).⁵ In addition, experimental measurements of absolute fluorescence efficiencies of about 50% for argon and krypton at near atmospheric pressure, excited state densities of 10^{13} to 10^{14} cm^{-3} , and energy deposition density of 10 mJ/cm³ were reported there and published elsewhere.⁶ Since then, our understanding of the efficiency limitations has advanced considerably and

our theoretical tools have been subjected to a more rigorous experimental laser test.

Excited-State Mixing Model. Our experimental work related to efficient production of rare-gas-excimer radiation has been guided by a comprehensive kinetics-laser model which has successfully predicted certain fluorescence and laser characteristics in high-pressure xenon and krypton⁷ and fluorescence efficiencies at low pressure.^{5,6}

The model is basically a two-temperature (gas, electrons) Maxwellian treatment which conserves charge and energy. The simplified kinetic model is outlined in the potential energy diagram of Fig. 6-1 where X can be Ar, Kr, or Xe. The 3P_1 and 3P_2 atomic states are lumped into a single species X^{*}.

Fig. 6-1. Simplified model and potential energy diagram for rare-gas excimers. Not shown are excitations by thermal electron impact; Penning ionization of X^{*}, X^{**}; trimer ion (X₃⁺) level and processes.

due to lack of detailed information on the populating mechanisms and the fact that an equilibrium mixture should occur for the typical electron temperature near 1 eV since the $^3P_{1,2}$ level separation is only 0.12 eV. The levels between X^* and the atomic ion level (X^+) are lumped into a single level X^* , a considerable simplification which has been justified elsewhere along with a detailed discussion of the many processes and rates considered.^{7,8} For our purpose it is sufficient to note that e-beam pump energy is channeled rapidly at pressures greater than 1 atm to the X^* level where rapid formation of the $^3\Sigma_u^+$ and $^1\Sigma_u^+$ excimer states occurs by means of the three-body association in a three-to-one ratio determined by the statistical weights (degeneracies) of the levels. These states can radiate through spontaneous fluorescence or stimulated emission to the repulsive $^1\Sigma_g^+$ level. They can suffer other loss processes whose importance depends on operating parameters such as pressure, beam intensity, pulse width, presence or absence of a laser cavity, and cavity parameters. Some of the treated loss processes are: Penning ionization (excited-state/excited-state collisions) producing $X_2^+ + 2X$ from two excimers, dissociative superelastic collisions of an excimer and electron producing $2X$, thermal dissociation of an excimer to $X^* + X$, and ionization producing X_2^+ from an excimer and a VUV photon or electron. Other very important processes are mixing of the excimer levels in collisions with electrons and atoms,

where M can be e , X , or other buffer gas atoms. For laser performance optimization, it is important to note that the $^3\Sigma$ state represents a loss channel since its stimulated emission cross section for Ar, Kr, or Xe appears to be lower than the photoionization cross section by at least a factor of 2, and the triplet-to-singlet ratio can be no lower than 3 at equilibrium. Thus, as will be noted later, conditions that reduce k_d or increase k_{-u} , in addition to minimizing other losses, have the greatest potential for producing optimum laser efficiency.

The gas kinetic processes which produce an inversion on the bound-free excimer transitions have been incorporated into an interactive model which

can treat the temporal and spectral evolution of the laser cavity field. The spectral gain calculation as a function of gas temperature follows the method of Mies.⁹ The spectral field evolution is numerically accomplished via a relatively small number (25) of noninteracting "supermodes." The approximations involved, details of the numerical procedures used, and limitations of the approach appear elsewhere.⁸

Rare-Gas-Excimer Fluorescence at Low Pressure.

As noted previously, theoretical upper limits of about 50% were placed on fluorescence efficiency by invoking energy balance constraints,¹⁰ and some measurements at very low excitation density approached this limit.¹¹⁻¹³ These results were in conflict with low fluorescence efficiencies (about 10%) determined at the high excitation densities, pressures, and pump rates prevailing in early rare-gas-laser experiments.^{14,15} The model attributed those low efficiencies to excimer Penning ionization.

An example of model calculations in a parameter region expected to minimize the Penning process is shown in Fig. 6-2. Here a fluorescence efficiency near 50% is predicted for xenon at 1.5 atm for energy deposition density up to 0.5 J/cm^3 in a $1\text{-}\mu\text{s}$ pulse. This represents a narrowband fluorescence source at 172 nm having a power density of 250

Fig. 6-2. Calculated 172-nm VUV fluorescence efficiency for 1.5 atm of xenon as a function of energy deposition rate, for e-beam pumping with a fixed $1\text{-}\mu\text{s}$ pump pulse or a fixed 600-mJ/cm^3 energy deposition density. Calculation is based on the simplified kinetic model of Fig. 1.

MW/liter and total radiated energy density of 250 J/liter. Figure 6-2 also shows that reasonably good efficiency can be maintained at somewhat higher pump rates if the total energy deposited and, consequently, the gas temperature rise are restricted by shortening the pump pulse. At near atmospheric pressure the loss in fluorescence efficiency observed at high energy deposition is the result of excessive gas heating.

As was mentioned earlier, our nearly 50% absolute fluorescence efficiency measurements at the $10\text{-mJ}/\text{cm}^3 \cdot \mu\text{s}$ level in 1 to 2 atm of argon at 127 nm and krypton at 147 nm gave excellent agreement with computer predictions.^{5,6}

Rare-Gas-Excimer Lasers at Low Pressure. Model calculations of Xe_2 laser performance at 172 nm in low pressure xenon under conditions

corresponding to predicted high fluorescence efficiency are shown in Fig. 6-3. The parameters and energy deposition limit shown correspond to an expected experimental capability on the EB-300 facility and *not* optimum system predictions or fundamental limitations. The potentially accessible predicted laser efficiency near 1% is over an order of magnitude higher than predictions for prior high-pressure, high-current-density, short-pulse experiments. These favorable predictions motivated us to seek experimental verification.

Table 6-3 contrasts the parameter regimes of previous "typical" laser experiments with those undertaken here. Clearly, we have greatly reduced the gas pressure, pump rate, and energy deposition density while substantially increasing the pump pulse and plasma lengths.

Fig. 6-3. Calculated 172-nm xenon laser efficiency, fluence, and peak flux as a function of energy deposition density for the parameters shown. Based on Fig. 6-1 model.

The experimental layout is shown schematically in Fig. 6-4. The electron beam source was essentially the same as used in previous fluorescence^{5,6} and laser^{5,16,17} studies except for differences in cathode

Table 6-3. Parameters of previous "typical" laser experiments compared with those of our present experiments

	Previous	Present
Pressure (atm)	~10	1.5
Current density (A/cm ²)	~1000	≤10
Energy deposition (J/cm ³)	>10	~0.2
Pump pulse (μs)	~0.1	1
Plasma length (cm)	~10	100

geometry, anode-cathode spacing (5 cm here), and pulse duration.

Figure 6-5 shows the temporal behavior of the laser axis emission, the transverse fluorescence, and the approximate pump rate in the gas. The spectral width of the laser emission was measured to be 1.8 nm (FWHM), and the emission peaked at 172 nm. The weak dashed trace in Fig. 6-5(a) came from a nonlasing shot on the same gas fill for the same pump conditions and clearly lacks the distinctive time dependence of the first shot which indicated oscillation. The laser is near threshold and oscillation is sensitive to gas impurities often generated in gas mixtures excited more than once. In order to compare these experimental results with the model predictions, limits on both the laser intracavity power density and energy deposition density were determined from SANDYL code¹⁸ estimates and mirror geometry considerations.

Fig. 6-4. Schematic diagram of the experimental configuration used for the 1.5-atm-xenon laser demonstration. The Marx output voltage was 260 kV. An anode-to-cathode distance of 5 cm was used. The filter peaked at 172 nm with FWHM = 20 nm.

The e-beam current was determined as $J_{eb} = 6.8 \pm 2.4 \text{ A/cm}^2$, and the resulting energy deposition density was $E_d = 1.7 \pm 0.65 \text{ mJ/cm}^2$. The main source of uncertainty was lack of information about the e-beam's vertical profile for our present operating parameters.

Fig. 6-5. Time dependence of (a) laser axis emission (172-nm), (b) transverse VUV fluorescence, and (c) pump rate in the gas, for the 1.5-atm-xenon laser demonstration. Clear aperture is $< 2.5 \text{ cm}^2$, most probable beam diameter is 1 to 2 mm. P_1 and P_2 are the peak powers of the first and second shots on the same gas fill. Power is in arbitrary units for (b) and (c).

Good agreement between our experimental peak power density result and model predictions is shown in Fig. 6-6. The shaded window corresponds to a beam diameter between 1 and 2 mm, which is considered to be most probable. The extreme limits of the shown experimental window are determined by the Gaussian fundamental mode size (average diameter about 0.5 mm) and the calculated decay of energy deposition (about 50% per cm) across the clear aperture. Near threshold oscillation could not occur over a diameter greater than 4 mm and is very unlikely for a diameter greater than 2 mm. Unobserved mirror damage would have been probable for a diameter less than about 1 mm.

A more stringent test of the model calculations is provided by a comparison of the experimental laser pulse shape and FWHM given in Fig. 6-5 with the calculated pulses shown in Fig. 6-7. Calculationally, a 200-ns FWHM corresponds to energy deposition densities in the range of 140-160 mJ/cm^2 or 180-200 mJ/cm^2 . The calculated laser flux in the former case is inconsistent with the extreme lower limit on the experimental laser flux. The laser fluxes for the latter case correspond to experimental beam diameters between 2.3 and 0.9 mm. A 200-ns FWHM would require a less likely diameter closer to 1 mm and a peak two-way flux of about 10 MW/cm^2 . At the corresponding incident mirror fluence of 1 J/cm^2 , we would have expected to see dielectric coating damage, which was not observed.

The probable explanation for the FWHM differences between theory and experiment in the most likely experimental window is that the calculated FWHM (but not peak flux) is expected to be rather sensitive to the spontaneous emission noise emitted into the laser cavity modes. For the "supermode" approximation used in the numerical cavity modeling, this noise term is difficult to treat with high accuracy. Hence, slight discrepancies in near-threshold oscillation buildup time or laser FWHM are not surprising. For stronger pumping the results are insensitive to the noise term.

A comparison between calculated fluorescence and laser intensities for corresponding energy deposition densities, E_d (mJ/cm^2), during laser operation is also shown in Fig. 6-7. Even for the case of the highest laser efficiency shown ($E_d = 400$), the fluorescence accounts for 25% of the energy deposited while only 3.3% comes out as laser emission. The high fluorescence yield is due to failure to maintain a saturating field for the entire

Fig. 6-6. Comparison of the calculated dependence of peak laser flux on energy deposition density with the limits deduced for the experimental xenon laser demonstration for the same parameters; $\phi_{\min}$ and $\phi_{\max}$ are the deduced minimum and maximum beam diameters, respectively.

pulse length. Clearly, laser efficiency should be significantly higher in a master oscillator, power amplified (MOPA) system, or where an injected pulse rather than spontaneous noise is used to drive the cavity field into oscillation faster. The pure fluorescence efficiency obtained from Fig. 6-2 for $E_d = 400 \text{ mJ/cm}^3$ is about 50%. Thus, about 20% of the energy during oscillation is lost due to photoionization-induced processes.

It appears unlikely that large changes in predicted laser efficiency will occur for Xe_2^+ oscillators operated in pure xenon. This conclusion is based on the fact that the high-pressure threshold laser behavior is sensitive to the important photoionization and atomic-mixing cross sections employed; 10% changes in either cross section shift the predicted pressure threshold by a factor of 2 (Ref. 7).

Also, the laser results are little affected by similar changes in other estimated rates. Furthermore, the model has been very successful at predicting a variety of laser and fluorescence characteristics at both high and low pressure.

Within the model framework, the laser efficiency could be improved if the electronic mixing, which favors the $^1\Sigma_u^+$ state at $kT_e \approx 1 \text{ eV}$, could be increased, or if the atomic mixing, which predominantly quenches the $^1\Sigma_u^+$ to the $^3\Sigma_u^+$ state, could be reduced. Increasing the electron density can increase the triplet-to-singlet mixing but is limited by other electronic loss processes. Reduction of the atomic density could reduce the rate of atomic mixing to the $^3\Sigma_u^+$ state but requires a corresponding increase in beam current to achieve equivalent energy deposition. Moreover, the pressure must be kept

high enough to maintain the desired rapid three-body excimer association rates. For pure xenon we expect an optimum pressure near 1 atm, and a potential intrinsic laser efficiency of 10% is quite conceivable.

Though less amenable to rapid calculational verification, the most promising approach is likely to be utilization of argon buffer gas doped with about 100 Torr of xenon to reduce atomic mixing. About 2.5 atm of argon would be required to

Fig. 6-7. Calculated temporal dependences of the 172-nm xenon laser flux and intracavity fluorescence power density for several energy deposition densities E_d (mJ/cm²). The parameters used are 1.5 atm, 1-μs flat pump pulse, 1-m plasma, 1.5-m cavity, and 95%-reflectivity mirrors. I_p (W/cm²) is the peak laser flux, P_p (W/cm²) is the peak fluorescence power density, ϵ_l and ϵ_f are the respective intrinsic laser and fluorescence efficiencies.

produce energy deposition comparable to that in pure xenon at 1 atm. The rapid energy channeling from excited argon to xenon excimers is well known.¹⁹ Improved laser performance in Ar/Xe mixtures at high pressure has been observed^{20,21} and may be at least partially due to the fact that atomic mixing rates of xenon excimers in collisions with argon should be appreciably slower.

Summary and Conclusions. Observation of laser oscillation at 172 nm in low pressure xenon and the good agreement between measured near-threshold behavior and the predictions of our excited-state mixing model have considerably enhanced the predictive utility of this model as a theoretical tool. Unoptimized calculations of oscillator performance have produced attractive efficiencies of about 4% at an output fluence of 2 J/cm² and output flux of 3.5 MW/cm². Cavity, laser configuration, and/or kinetics optimization techniques indicated above can probably produce intrinsic laser efficiencies exceeding 10%. We expect to continue to examine these possibilities and their systems utility in the coming year. Fluorescence efficiencies approaching 50% seem likely for useful excitation densities, pump rates, and pulse lengths.

Photolytic Production of O(¹S) from CO₂ Using NeF Emission

The photolysis of CO₂ in the deep VUV, $\lambda \approx 110$ nm, is known to produce O(¹S) in high yields, 75 $\pm$ 25%.²² No efficient fluorescer or laser has yet been demonstrated experimentally in this region. However, the rare-gas monohalide NeF has been predicted to emit at 107 nm,^{23,24} near the peak of the yield curve for O(¹S) production. Also, it has recently been recognized that di-rare-gas monohalides, such as Ne₂F⁺, can emit with high efficiency. The estimated emission band of Ne₂F⁺ at about 130 nm is in good coincidence with the band of N₂O which produces O(¹S) with high yield.²² Our studies suggest that spontaneous or stimulated emission from the neon fluorides could be high-efficiency sources capable of producing O(¹S) and having notable advantages over rare-gas-excimer pumping, including the demonstrated ability to run a long-pulse, electron-beam-stabilized discharge in rare-gas/halogen mixtures. Large energy storages and reasonable storage times (1 μ s) can be anticipated.

The kinetics and spectroscopy of the CO₂/O(¹S) system are detailed in the papers of Murray and Rhodes.^{1,2} For the case of CO₂ photolysis, the absorption coefficient at 107 nm is about 500 cm⁻¹·atm⁻¹, and both CO₂ and CO quench O(¹S) slowly. In He at 1 atm pressure with 1 Torr of CO₂, 100- μ s storage times and stored energies of 15 J/liter can be achieved. If the collection of pump photons is efficient, one can imagine overall system efficiencies for the O(¹S) $\rightarrow$ O(¹D) laser as high as 1-3% if the primary NeF⁺ radiation can be generated at efficiencies in the range 10-30%. This is the range of efficiency predicted for electron-beam-stabilized KrF lasers.

During 1976 we have investigated the NeF-pumped CO₂/O(¹S) system to identify quantitatively the advantages this combination offers and to determine some of the key unknowns. In order to obtain an understanding of the fundamental physical and optical properties of the system, we have made theoretical studies of several areas of interest discussed in some detail below:

1. Spectroscopy of NeF.
2. Kinetics of forming the NeF⁺ excited states.
3. Various schemes for coupling the pump radiation to CO₂.
4. Spectroscopy of CO₂.
5. Dielectric properties of atomic oxygen, the lasing species.

To provide an accurate prediction of the NeF⁺ fluorescence, we have carried out extensive configuration-interaction calculations²⁵ on the covalent and ionic ² Σ and ² Π states. The covalent states arise from the ground state atoms Ne(¹S) and F(²P). The ionic states correlate to the ions Ne⁺(²P) and F(¹S). The calculations were carried out to an accuracy sufficient to predict the transition energies to within 0.1 to 0.2 eV.

The potential curves were first determined without spin-orbit coupling. The spin-orbit states were generated by assuming that the spin-orbit interaction, V_{so} , was independent of internuclear distance and fixed at the atomic values (Ne⁺, 782 cm⁻¹, for the ionic curves; and F, 404 cm⁻¹, for the covalent curves). The total Hamiltonian

$$H(R) = H_0(R) + V_{so} \quad (2)$$

was then diagonalized at each internuclear distance. The calculated points were least-squares-fitted to a Rittner potential,

$$V(R) = A + B/R + C/R^4 + De^{-\alpha R} \quad (3)$$

For the ionic states and a simple exponential potential for the covalent states,

$$V(R) = A + Be^{-\alpha R} \quad (4)$$

The fits for the ground and ion-pair states predict the energy separation between the $\text{Ne}(^1\text{S}) + \text{F}(^2\text{P})$ and $\text{Ne}^+(^2\text{P}) + \text{F}^-(^1\text{S})$ limits to be 17.7 eV compared to the experimental value of 18.1 eV. Since the error of 0.4 eV is essentially constant at each internuclear distance, the potential curves for the excited states were adjusted accordingly. The spin-orbit potential curves are plotted in Fig. 6-8.

The transition moments were determined for the states without spin-orbit interaction and used to calculate the transition moments and lifetimes for the eigenvectors of the Hamiltonian given by Eq. (2). The transition moments, lifetimes, and wavelengths for these transitions are summarized in Table 6-4. The transition moments were evaluated at an internuclear distance of 3.8 a.u. The results are given for both the calculated and adjusted potential curves.

The strongest transition, $B \rightarrow X$, has a short lifetime, about 2 ns, and a transition energy which overlaps the CO_2 band, about 11.5 eV. The other strong transition which falls close to the CO_2 band is the $D \rightarrow X$ at about 11.6 eV. In the heavier rare gas halides, the $D \rightarrow X$ band is the second strongest transition due to the strong Σ - Π mixing induced by the spin-orbit coupling. Because this effect is much

Fig. 6-8. Calculated potential-energy curves for the ground and excited states of NeF .

smaller in NeF , the Π - Π transitions near 11.3 eV are about as strong. These transitions terminate on the repulsive $A^2\Pi_{1/2,3/2}$ curves, which leads to broad emission bands overlapping the $B \rightarrow X$ and $D \rightarrow X$ transitions.

Table 6-4. Einstein A-coefficients and spontaneous lifetimes for the states of NeF . Calculated values are given first, followed by predicted values (in parentheses)

Transition	μ_z (a.u.)	λ (nm)	A (10^8 s^{-1})	τ (ns)
$B^2\Sigma_{1/2} \rightarrow X^2\Sigma_{1/2}$	0.525	113.1 (108.1)	3.9 (4.4)	2.6 (2.3)
$D^2\Pi_{1/2} \rightarrow X^2\Sigma_{1/2}$	0.137	111.1 (106.5)	0.28 (0.32)	35.6 (31.4)
$C^2\Pi_{3/2} \rightarrow A^2\Pi_{3/2}$	0.135	115.1 (110.2)	0.25 (0.28)	40.5 (35.6)
$D^2\Pi_{1/2} \rightarrow A^2\Pi_{1/2}$	0.121	114.3 (109.5)	0.20 (0.23)	49.6 (43.6)

Because all these transitions overlap, the fluorescence spectrum in the range 100 to 115 nm is a complicated superposition of the emissions from each of the vibrational levels from each electronic state. The predicted fluorescence from the main band at 108 nm was obtained by assuming a Boltzmann distribution for the upper-state vibrational levels. The results for two temperatures are shown in Fig. 6-9. The effects of rotation were not included. The predicted NeF* emission overlaps the peak in the O(¹S) production from CO₂ very well. On the basis of these calculations, one can be optimistic about the use of NeF* as a photolytic source for O(¹S).

The most important kinetic difference one predicts for NeF in comparison to the heavier rare-gas monofluorides is that F* and higher excited F states can be accessed by reactions of Ne* + F₂. In analogy to Ar* + Cl₂ and Ar* + Br₂, a large yield of F* and higher states should result.²⁶ Also, Ne* is sufficiently energetic to Penning-ionize F₂ into F₂⁺ + e. The yield of the ArCl*, Cl*, and Cl₂⁺ products in the Ar* + Cl₂ system is 50% ArCl*, 15% Cl*, and 35% Cl₂⁺. Since the principal difference between Ne* + F₂ and Ar* + Cl₂ is the lower dissociation energy of NeF* into Ne + F* relative to ArCl* → Ar + Cl*, one should expect a lower yield of NeF*, say ≥20%. A similar yield from Ne⁺ + F⁻ ion recombination should apply.

Since Ne* + F₂ will yield predominantly F*, efficient production of NeF* requires that the three-body recombination of F* with Ne into NeF* be faster than F* + F₂ reactions. Symbolizing the three-body rate constant for the Ne + F* + M recombination by k₃, and the two-body rate constant for the F* + F₂ reaction by k₂, one obtains the density requirement

$$k_3(\text{Ne})(\text{M}) \geq k_2(\text{F}_2) \quad (5)$$

This forces one to work at high Ne/F₂ fractions. At higher Ne pressures, reactions favoring the formation of Ne₂F* could become important as well.

The very-short-wavelength output from a NeF laser or fluorescence source could be coupled to a He/CO₂ mixture without the use of a solid window by utilizing a gas window of ultrapure He, either flowing or static, to separate a He/CO₂ mixture from a He/Ne/F₂ mixture, the most likely mixture

Fig. 6-9. Calculated fluorescence spectra for NeF based on the theoretical potential-energy curves and transition moments.

for the NeF source. Since the storage time kinetics of the He/CO₂O(¹S) system are not especially sensitive to the pressure, the total pressure of the He/CO₂ system can be set equal to that required for efficient operation of the He/Ne/F₂ mixture of the pump source.

An alternative pumping scheme involves the *in situ* photolysis of CO₂ utilizing the short-lifetime NeF fluorescence. The optimum densities used would differ from the externally photolyzed case since the O(¹S) excited state can be quenched by electrons and probably by F₂. If one assumes that O(¹S) quenching by F₂ proceeds with a rate constant of 10⁻¹⁰ cm³/s, and that the NeF fluorescence will optimize at F₂ densities of about 10¹⁶ cm⁻³, then storage times of order 1 μs are expected. Clearly F₂ quenching of O(¹S) would be detrimental to an *in situ* system. Moreover, CO₂ quenching of He* or Ne* will limit the efficiency of producing NeF* which radiatively couples to the CO₂. Simple kinetic analogies to measured rates for F₂ reacting with inert gas metastables and CO₂ quenching Ne* and He* (Refs. 27 and 28) suggest that for an *in situ* excited NeF*/CO₂ mixture, optimum densities of F₂ ≈ CO₂ ≈ 10¹⁶ cm⁻³ are expected, with He/Ne mixture buffers at higher pressure. Gain coefficients of ≥1/4% cm⁻¹ or lower at energy storage densities of about 5 J/liter are expected. The *in situ* scenario

offers a large collection efficiency for the NeF* emission, but at the risk of possible kinetic branching losses not present in the externally photolyzed case.

Electronic States of CO₂

Potential energy surfaces for the ground and excited states of CO₂ have been calculated using the generalized valence bond (GVB) method.²⁹ The bending curves for the states correlating to CO(¹Σ⁺) + O(³P) and O(¹D) are shown in Fig. 6-10 for an internuclear separation close to the equilibrium value for the excited states. The ¹B₂ (¹Δ_g) state has been well characterized by Dixon.³⁰ The experimental bond length is 1.246 Å, the bond angle 122°; the calculated bond length is 1.269 Å, the bond angle 120°. Emission from the CO + O(³P) recombination reaction has placed the ¹B₂

Fig. 6-10. Calculated potential-energy curves for CO₂ at internuclear separation of 2.355 a.u.

state at 5.6 eV above the ground state when all nuclei are at their respective equilibrium positions. The GVB calculations predict an energy separation of 6.0 eV. Previous mechanisms for the CO + O(³P) recombination have not taken into account both the ³B₂ and ³A₂ states.³¹ The presence of two low-lying excited triplet states, one intersecting the ground state and the other crossing the ¹B₂ state, may explain the pressure dependence of the recombination reaction observed by DeMore.³² Calculations on other excited states of CO₂ are in progress.

Polarizability of Atomic Oxygen

Lasers involving atomic oxygen operate on the auroral (¹S → ¹D) and transauroral (¹S → ³P) transitions. A question was recently raised as to the differences in the polarizabilities of these atomic states and the possible limitations such differences could place on the amount of usable laser energy that could be extracted from a high-pressure medium in a short pulse. A sudden large change in the polarizability of the medium could lead to large nonlinear effects and consequent degradation of beam quality.

The atomic polarizability can be expressed as

$$\alpha = \sum_j \frac{f_{0j}}{(E_0 - E_j)^2}, \quad (6)$$

where f_{0j} is the oscillator strength connecting the state of interest, 0, and another state j , E_0 , and E_j are the energies of these states, and j runs over all bound and continuum optically allowed levels. The ¹D and ¹S excited states of oxygen, which lie 2.0 and 4.2 eV, respectively, above the ground state, both have the same configuration, 2s² 2p⁴. Since there is only one other bound atomic state, 2s² 2p³ ¹D, at 12.7 eV, to which these states are optically connected by a dipole matrix element, the polarizabilities of ¹S and ¹D oxygen only contain one bound-to-bound component, the rest coming from continuum contributions. One might then expect the polarizabilities of ¹S and ¹D oxygen to be small, based on typical bound-free oscillator strength values and the large energy denominators that will appear in Eq. (6).

In order to settle this question quantitatively, the static polarizabilities of the 2p⁴ ¹S, ¹D, and ³P

states of oxygen were calculated with configuration-interaction wave functions.³³ The continuum contributions to Eq. (6) were approximated by a sum over square-integrable pseudostates which form a discrete representation of the ionization continuum. The calculated values of the polarizabilities are $0.837 \text{ \AA}^3$, $0.804 \text{ \AA}^3$, and $0.778 \text{ \AA}^3$ for the ^1S , ^1D , and ^3P states, respectively. These values indicate that nonlinear optical effects mentioned above will not be a significant problem in atomic oxygen lasers.

References

- J. R. Murray and C. K. Rhodes, *The Possibility of a High Energy Storage Laser on the Auroral line of Atomic Oxygen*, Lawrence Livermore Laboratory, Rept. UCRL-51455 (1973).
- J. R. Murray and C. K. Rhodes, *J. Appl. Phys.* **47**, 5041 (1976).
- H. T. Powell, J. R. Murray, and C. K. Rhodes, *Appl. Phys. Lett.* **25**, 730 (1974).
- Laser Program Annual Report — 1975*, pp. 505-511.
- Laser Program Annual Report — 1975*, Ch. 9.
- C. E. Turner, Jr., P. W. Hoff, and J. Taska, *Electron Beam Energy Deposition and VUV Efficiency Measurements in Rare Gases*, Lawrence Livermore Laboratory, Rept. UCRL-77202 Preprint (Nov. 1975). See also Proceedings of the International Topical Conference on Electron Beam Research and Technology, Albuquerque, New Mexico, Nov. 3-6, 1975, SAND-76-5122, Vol. II, p. 224.
- C. W. Werner, E. V. George, P. W. Hoff, and C. K. Rhodes, *Appl. Phys. Lett.* **25**, 235 (1974), and Lawrence Livermore Laboratory, Rept. UCRL-77412 Preprint (1975) (to be published *IEEE J. Quant. Electron.*, Sept., 1977).
- C. W. Werner, Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, Mass. (August 1975).
- F. Mies, *Mol. Phys.* **26**, 1233 (1973).
- D. C. Lorents, *Physica* **82 B + C**, 19 (1976).
- J. Jortner, L. Meyer, S. A. Rice, and E. G. Wilson, *J. Chem. Phys.* **42**, 4250 (1965).
- E. E. Huber, Jr., D. A. Emmons, and R. B. Lerner, *Opt. Commun.* **11**, 155 (1974).
- G. S. Hurst, T. E. Stewart, and J. E. Parks, *Phys. Rev. A* **2**, 768 (1974).
- H. A. Koehler, L. J. Ferderber, D. L. Redhead, and P. J. Ebert, *Phys. Rev. A* **9**, 768 (1974).
- H. A. Koehler, L. J. Ferderber, D. L. Redhead, and P. J. Ebert, *Phys. Rev. A* **12**, 968 (1975).
- J. C. Swingle, C. E. Turner, Jr., J. R. Murray, E. V. George, and W. F. Krupke, *Appl. Phys. Lett.* **28**, 387 (1976).
- J. R. Murray, J. C. Swingle, and C. E. Turner, Jr., *Appl. Phys. Lett.* **28**, 530 (1976).
- H. M. Colbert, *SANDYL*, Sandia Laboratories, Livermore, Calif., Rept. SCL-DR-720109 (1973).
- A. Gedanken, J. Jortner, B. Raz, and A. Szoke, *J. Chem. Phys.* **57**, 3456 (1972).
- P. W. Hoff, J. C. Swingle, and C. K. Rhodes, *Appl. Phys. Lett.* **23**, 245 (1973).
- A. W. Johnson and J. B. Gerardo, *J. Appl. Phys.* **45**, 867 (1974).
- See, for example, Figs. 9 and 10 of UCRL-78196 Preprint, *The Possibility of High Energy Storage Lasers Using the Auroral and Transauroral Transitions of Column VI Elements*, by J. R. Murray and C. K. Rhodes; G. M. Lawrence, *J. Chem. Phys.* **57**, 5616 (1972); I. Kayano, T. S. Wauchop, and K. H. Welge, *J. Chem. Phys.* **63**, 110 (1975).
- J. J. Ewing and C. A. Brau, *Phys. Rev. A* **12**, 129 (1975).
- J. J. Ewing, Lawrence Livermore Laboratory Internal Document AL-76-1023 (1976).
- N. W. Winter, C. F. Bender, and T. N. Rescigno, Lawrence Livermore Laboratory, Rept. UCRL-79046 Preprint (1977).
- L. A. Gundel et al., *J. Chem. Phys.* **64**, 4390 (1976).
- J. E. Velazco, J. H. Kolts, and D. W. Setser, "Quenching Rate Constants for $\text{Ar}(^3\text{P}_2)$, $\text{Kr}(^3\text{P}_2)$, and $\text{Xe}(^3\text{P}_2)$ by Halogen Molecules, and Branching Ratios for XeF and KrF Formation," to be published.
- A. L. Schmeltekopf and F. C. Fehsenfeld, *J. Chem. Phys.* **53**, 3173 (1970).
- W. J. Hunt, P. J. Hay, and W. A. Goddard, *J. Chem. Phys.* **57**, 738 (1972).
- R. N. Dixon, *Proc. Roy. Soc. A275*, 430 (1963).
- M. A. A. Clyne and B. A. Thrush, *Proc. Roy. Soc. (London)* **269**, 404 (1962).
- W. B. DeMore, *J. Phys. Chem.* **76**, 3527 (1973).
- R. K. Nesbet and T. N. Rescigno, Lawrence Livermore Laboratory Internal Document TAMP-76-539 (1976); R. K. Nesbet, *Phys. Rev. A*, to be published.

Authors

J. J. Ewing
A. U. Hazi
C. E. Turner
N. W. Winter

6-3 Rare Earth Vapor (REV) Lasers

In last year's annual report we suggested the use, as a fusion laser medium, of trivalent rare earth ions (RE^{3+}) in the vapor phase. We identified three potentially viable rare-earth vapor carriers: RE^{3+} -trihalogenes, RE^{3+} -transition metal trihalides, and RE^{3+} -chelates. We also estimated their radiative and nonradiative properties. It was shown, using Nd^{3+} and Tb^{3+} as examples, that the vapor phase could preserve many of the desirable attributes of the four-level RE^{3+} energy level structure exploited in glass lasers. At the same time, two significant liabilities might be overcome because of the liberation of these active centers from their traditional solid state environment. First, use of the gas phase

could reduce self-focusing problems since the non-linear index, n_2 , can reasonably be assumed to be markedly reduced. Second, high average power operation could be anticipated via gas flow of the active medium.

After the initial analysis on the feasibility of REV lasers, we investigated the fluorescence properties of rare-earth vapors for the specific case of the

Tb(thd)₃ chelate vapor.³⁴ (This is the first time that the fluorescence properties of any trivalent rare-earth vapor had been investigated.) Self-quenching of the Tb³⁺, ⁵D₄ state by the carrier chelate was observed; the magnitude of the measured quenching rates confirmed our earlier expectations. At a temperature of 230°C and a corresponding vapor pressure of 10 Torr (representing the possibility of

Fig. 6-11. Fluorescence decay curves for Nd-Al-Cl vapor complexes under weak (Cases I and II) and strong (Case III) excitation intensities. In all cases, the pump pulse duration was $< 1 \mu s$. Case III indicates the effects of excited state/excited state collisional deactivation.

Fig. 6-12. Observed nonradiative decay rate (τ_{NR}^{-1}) in Nd-Al-Cl vapor complexes as a function of the inverse cell temperature (T^{-1}). Clearly, this behavior is well described by $Ae^{-B/T}$, where A and B are phenomenological parameters. These data were taken under conditions of weak excitation (i.e., low excited state densities) corresponding to Cases I and II of Fig. 6-11.

≤ 10 J/liter stored for the $0.55 \mu\text{m}$ transition for excitation of half the ground state molecules), the measured lifetime was $\geq 1 \mu\text{s}$. With the recent development of efficient rare gas halogen lasers that emit in the UV spectral region (XeF - 353 nm, KrF - 249 nm, and ArF - 193 nm), the possibility arose of using them to optically excite rare-earth chelate vapors. In operation as a gain medium, the stored energy would have to be extracted before the intramolecular deactivation of the excited states density. For example, the stored energy would have to be extracted in $< 1 \mu\text{s}$ for the $\text{Tb}(\text{thd})_3$ -chelate. We are presently evaluating this vapor as a fusion gain medium.

Experimental Studies

In addition to chelate vapor investigations we have also been studying Nd and Tb metal complexes. LLL-funded research at Argonne National Laboratory (ANL) indicated that fluorescence lifetimes in Tb-Al-Cl vapor complexes are equal to the calculated radiative lifetimes under conditions of low excited state densities. LLL studies on Nd-Al-Cl complexes addressed the following issues:

Fig. 6-13. Absorption spectrum of Nd-Al-Cl vapor complexes (64 Torr pressure) at 489°C . The spectra were taken when solid NdCl_3 and gaseous AlCl_3 reached equilibrium. The vapor pressure of the complexing agent Al_2Cl_6 is ≈ 7 atm. A tentative background curve is indicated. These conditions were typical of those used in attempts to demonstrate laser action/gain at $1.06 \mu\text{m}$.

- Excited state lifetimes at operating laser temperatures of $\approx 500^\circ\text{C}$
 - Excited state/excited state deactivations under conditions of intense optical excitation (at $5872 \text{ \AA}$). A flashlamp-pumped dye laser was used to optically excite the vapor
 - Fluorescence spectrum at $1.06 \mu\text{m}$. The spectrum was used to calculate a stimulated emission cross section value ($\approx 2 \times 10^{-20} \text{ cm}^2$). Details of these studies have been reported.^{35,36}
- Some of the results of these investigations are shown in Figs. 6-11 and 6-12. Figure 6-13 shows the absorption spectrum in Nd-Al-Cl vapor complexes. Because of the pronounced absorption at $17,030 \text{ cm}^{-1}$, we selected a flashlamp-pumped dye laser emitting at $5872 \text{ \AA}$ to promote lasing in this representative rare-earth vapor. The measured fluorescence spectrum at $1.06 \mu\text{m}$ yielded an effective emission linewidth which, in conjunction with the Judd-Ofelt theory^{37,38} for ligand-field-induced electric-dipole transitions, determines the stimulated emission cross section at $1.06 \mu\text{m}$. In Fig. 6-11 the fluorescent decay curves for Nd-Al-Cl vapors are shown under weak and strong excitation intensities. In the latter instance (Case III, Fig. 6-11) the importance of near resonant excited state/excited state collisional deactivation is demonstrated

(compare with Case II). Figure 6-12 displays the dependence of the nonradiative decay rate vs the inverse of the vapor temperature. The data in Fig. 6-12 correspond to the type given in Cases I and II of Fig. 6-11.

These investigations showed that lasing at $1.06\ \mu\text{m}$ in Nd-Al-Cl vapor complexes was kinetically feasible under suitable optical excitation conditions and laser cavity arrangement.³⁶ The experimental approach is depicted in Fig. 6-14. Unfortunately, severe impurity problems exist for these vapors, so the anticipated gain ($\approx 15\%$ /pass) could not be exploited to yield a laser demonstration. Such a demonstration would have given us an opportunity to study lasing dynamics. After such impurity-dominated lasing attempts, we measured the gain (Fig. 6-15). The traces indicate signals consistent with gains of a few percent/pass. This is less than anticipated, possibly because of the lack of unit quantum efficiency between an absorbed pump photon and the generated upper laser level Nd^{3+} , $^4\text{F}_{3/2}$. Definitive conclusions on the presence of gain require the elimination of impurities that can contribute to such signals either by bleaching effects at the windows or through beam walk in the gain "direction." Although the latter effect was searched for — using other probe wavelengths — it was not observed.

There are several ways to solve impurity problems in the proposed Nd-Al-Cl laser:

- Sapphire coating the interior faces of the quartz Brewster windows to minimize or eliminate the etching process:

- Providing an optimal cell pressure of SiCl_4 to minimize the forward yield of this reaction. At the same time guarding against the unfavorable deactivation of excited Nd-Al-Cl molecules

- Using Nd-Al-Br complexes (instead of Nd-Al-Cl) to reduce (empirically observed) impurity effects

- Using water-free quartz to guarantee the elimination of the pernicious deactivation and reaction agent — H_2O

- Scrupulous attention to the purity of the starting materials; i.e., NdCl_3 and AlCl_3

- Handling the ingredient chemicals so as to prohibit the introduction of ambient impurities. The latter procedure will be implemented when a high-purity chemical handling/filling facility becomes operational in the summer of 1977.

These various approaches to reduce impurity effects in the Nd-Al-Cl vapor experiments are straightforward but also time consuming and expensive. Accordingly, we decided not to pursue these circumventions for the Nd-Al-Cl case since this system is not scalable for fusion laser use due to scaling limitations of the flashlamp-pumped dye laser excitation source. An exception to this limitation involves using barium vapors to Raman shift the XeF laser output from 353 nm to the 560-nm region ($\approx 17\,000\ \text{cm}^{-1}$, see Fig. 6-13). The overall excitation source efficiency of this approach could be as high as several percent.³⁹

In spite of the inability to "quickly" demonstrate laser action in Nd-Al-Cl vapor complexes, several important collisional features have been investigated which have critical bearing on any rare-earth vapor fusion amplifier:

- Collisional deactivation by Al_2Cl_6 of metastable levels in Nd^{3+} (gap to next lowest level

Fig. 6-14. Experimental arrangement for laser demonstration attempts at $1.06\ \mu\text{m}$ in Nd-Al-Cl vapor complexes. The flashlamp-pumped dye laser produces $\approx 2\ \text{J}$ at $5872\ \text{\AA}$ in pulse lengths $\approx 1\ \mu\text{s}$. The REV laser confocal cavity consists of two dielectric-coated, dichroic mirrors separated by a distance equal to the mirror radius of curvature (60 cm). Note the 20-cm-long vapor cell within the temperature-controlled oven.

Fig. 6-15. Representative gain probe. The indicated portion of the C and ambient Al_2Cl_6 pressure ≈ 7 atm for two dye laser excitation intensities. The upper trace represents the dye laser pump evolution in time and the lower one the $1.06 \mu\text{m}$ gain probe. The indicated portion of the lower trace is consistent with gain, while the longer time behavior represents a probe beam decrease caused by thermally induced medium inhomogeneities initiated by the excitation laser.

$\approx 5000 \text{ cm}^{-1}$) and Tb^{3+} (gap $\approx 14000 \text{ cm}^{-1}$) is unimportant for pressures up to 7 atm.

- The limitation on storage times in the Nd vapors is set by excited state/excited state, near-resonant deactivations involving other Nd^{3+} levels (Case III, Fig. 6-11). The importance of such deactivations in other vapors (e.g., Tb-Al-Cl) must be decided on a case-by-case basis. For the Tb-Al-Cl example, collisional access from the metastable 4f level ($^5\text{D}_4$) to the (highly allowed) 5d states depends on the precise energy location of the latter; consequently, this collisional deactivation mechanism may or may not be a problem. In this context comprehensive computer programs involving all the trivalent rare earths were developed — based on the Judd-Ofelt theory to evaluate the matrix elements for transitions between any pair of 4f, RE^{3+} levels. With such information, we can determine the importance of either near-resonant collisional deactivation(s), or excited state absorptions of pump light/fluorescence involving the 4f states.

- The basic thrust of the earlier analyses^{40,41} has been verified for the Nd-Al-Cl example. Namely, the molecular system dynamics (E-V, V-T, R-T transfer times) are such that energy storage densities ($\approx 50 \text{ J/liter}$) can be sustained for the acceptably long time of several μs .

A REV candidate using scalable and efficient rare gas halogen pump lasers as excitation sources involves the Tb^{3+} -ion carried by either trihalogens (TbCl_3 or TbBr_3) or transition metal trihalide complexes (Tb-Al-Cl or Tb-Al-Br), or the chelates dis-

cussed previously. In LLL-funded work at ANL the fluorescence spectra from Tb-Al-Cl and Tb-Al-Br vapors were studied and the fluorescence lifetime was measured at low excited state densities. The work paralleled the earlier work at LLL on the Nd-Al-Cl vapors. The temperature-dependent lifetimes under such conditions of low excited state densities were observed to be greater than $400 \mu\text{s}$. These Tb^{3+} vapor data were taken with a mechanically chopped 4-kW H_2 lamp emitting over a range ≈ 240 to 400 nm . The laser fusion device attraction lies in the possibility of using the efficient and scalable KrF laser as a driver at 249 nm . Equally attractive is that with this excitation wavelength, one accesses the allowed 4f-5d pump bands in Tb^{3+} rather than the much less allowed 4f-4f bands as in the Nd^{3+} case.

The major issues at present for the Tb^{3+} vapor are:

- The value of the absorption coefficient at 249 nm for the various vapor carriers
- The number density of Tb-Al-Cl molecules as a function of temperature
- The quantum efficiency for creating the excited Tb^{3+} , $^5\text{D}_4$ state for each absorbed pump photon
- The importance of excited state processes such as excited state/excited state collisional deactivations and excited state absorption at the pump/lasing wavelengths
- Medium homogeneity at high temperatures; i.e., to produce 1 Torr of TbCl_3 vapor requires a temperature of 967°C .

These issues for the Tb^{3+} -vapors will be addressed in 1977.

Rare-earth vapor chelates were previously mentioned in studies³⁴ on $\text{Tb}(\text{thd})_3$. Recently, kinetics studies have begun on the $\text{Nd}(\text{thd})_3$ chelate vapor in which 1- μs -long pulses from the flashlamp-pumped dye laser have been used to optically excite the carried Nd^{3+} ion. Preliminary results indicate that the Nd^{3+} , $^4\text{F}_{3/2}$ level lifetimes are $\approx 1 \mu\text{s}$ long for high excited-state densities and are approximately independent of number density (bimolecular deactivation) and vapor temperature for a fixed number density (unimolecular). This latter feature differs from the deactivation behavior observed in the $\text{Td}(\text{thd})_3$ study. Work on unraveling the relevant quenching mechanism(s) in the $\text{Nd}(\text{thd})_3$ case is in progress. In comparison with the Nd-Al-Cl vapor, the chelate is $\approx 70\%$ more absorptive at 5872 Å and has an estimated laser cross section $\approx 25\%$ less. More important, however, is that the debilitating impurity problems have been largely eliminated — at least visually. Furthermore, since we can now obtain a chelate vapor pressure ≈ 10 Torr at 250°C, medium homogeneity problems will be significantly reduced.

Another attractive research path for rare-earth vapor lasers involves carrier ligand excitation with a suitable gas laser pump, followed by ligand-to-rare

earth energy transfer. This mechanism is operative in the $\text{Tb}(\text{thd})_3$ chelate vapor case.³⁴ Such an excitation pathway for other molecular species (e.g., RE^{3+} -trihalogen), coupled with the possibility of working on "hypersensitive" RE^{3+} transitions (which have laser cross sections approximately ten times those for typical $4f \rightarrow 4f$ transitions that are $\approx 10^{-20} \text{ cm}^2$), can reduce the operating temperature. For such transitions, we can reduce the energy storage to $\approx 10 \text{ J/liter}$ instead of 50 to 100 J/liter while maintaining the same overall gain. Correspondingly, the storage times will increase as the square of the number density ratio for the two temperatures when excited state/excited state collisional deactivation is important.

Theoretical Aspects

The simplest class of rare-earth gas lasers — the rare-earth trihalides (ReX_3) — have many of the molecular features of the more complicated compounds described above and yet can be theoretically studied in considerable detail. During 1976, we undertook a quantitative study of this class of compounds (14 rare earths $\times$ 4 halogens = 56 possible compounds).⁴² The study involved:

Fig. 6-16. Rare-earth trihalide molecular geometry.

- Predicting geometries and electric configurations

- Calculating emission characteristics
- Evaluating energy pumping scenarios

Bonding characteristics, descriptive chemistry, and intuition were used to determine the molecular configuration and geometry of these compounds. Only three electrons from the rare earths are involved in the bonds with the halogens; hence, the electronic configuration describing the valence (interacting) electrons takes the form

$$f_m^N b^6 s^6 \ell^{12} d_m^0 p_m^0 s_m^0 \quad (8)$$

The occupied f_m and unoccupied d_m , p_m , and s_m are atomic-like orbitals on the rare earth; b denotes the three bonds (two electrons per bond) between the halogens and rare earth. The s and ℓ orbitals are localized on the halogen atom, s denoting the s -like atomic orbitals and ℓ denoting the lone pair electrons (linear combinations of the p orbitals). For compounds with only one type of halogen, a C_{3v} or D_{3h} symmetry is expected. The halogens are positioned at the vertices of an equilateral triangle. We have assumed the rare-earth atom lies in the plane of the triangle, arguing that the nonbonding electrons (core and f) form a spherically symmetric charge distribution and were, therefore, not displaced from the plane via some asymmetry. Thus, we predicted (and later computationally verified) that the ReX_3 compound would have D_{3h} symmetry and the geometric structure shown in Fig. 6-16. The positions of the bonds (b) and lone pairs (ℓ) are also shown. The atomic-like orbitals are centered on the atom. The bond distances were taken as the sum of the "covalent radii" available on any chart of the periodic properties of the elements. The accuracy of this approximation has been checked by comparing it with experimental (x-ray) data obtained in the solid state. We found errors of $\pm 2\%$ in the bond distances.

Having determined the electronic configuration, group theoretical methods were used to determine allowed and forbidden transitions. The transitions for a D_{3h} molecule have the following selection rules:

	Occupied orbitals					
	a_1'	a_2'	e'	a_1''	a_2''	e''
a_1'	0	0	0	0	N	0
a_2'	0	0	N	N	0	0
e'	N	N	N	0	0	N
a_1''	0	N	0	0	0	N
a_2''	N	0	0	0	0	N
e''	0	0	N	N	N	N

Thus, only excitations taking an occupied orbital of certain symmetry to an unoccupied orbital of another will be allowed (possibly) if the appropriate transition moment is nonzero (N). The orbitals described above contain the following symmetries:

$$\begin{aligned} s &\rightarrow a_1', e' \\ b &\rightarrow a_1', e' \\ \ell &\rightarrow a_2'', e'', a_2', e' \\ f_m &\rightarrow a_1', a_2'', a_2', e', e'' \\ d_m &\rightarrow a_1', e'', e' \\ p_m &\rightarrow a_2'', e' \\ s_m &\rightarrow a_1' \end{aligned}$$

Although the localized picture is convenient for intuitive purposes, for analysis of the spectra, the group theoretical orbitals are more useful.

The emission-absorption characteristics were determined in two steps. Our recently developed code (IONPAK) for determining radiative and non-radiative transition probabilities was used to predict the atomic-like f - f transitions. The code also calculates line strength products for determining possible resonant dipole-dipole interactions. An approximate semiempirical molecular orbital technique was used to predict the positions of the other

atomic and molecular states. These Wolfsberg-Helmholtz Extended Hückel⁴³ calculations were used to study the effects of the different ligands and the systematics of the rare-earth ions. The effect of changing the bond characteristics has been studied by observing the changes that occurred in the spectra when the halogens changed. Thus, the spectral behavior in more complex compounds can be inferred. The most important finding of the systematics study was the strong dependence of atomic $f \rightarrow d$ transitions on the effective charge of the rare-earth ion. Having determined approximate energy levels, we used group theory and overlap arguments to estimate relative transition strengths. For example, $f \rightarrow d_m$ transitions are expected to have small transition strengths since they are localized in different parts of space. As experimental data are collected, parameters that were used in predicting emission characteristics will be refined. We have also studied the spectra of fragments of the rare-earth trihalides. Such fragments are expected because of the low vapor pressure and high operating temperature of the proposed laser. For the positively charged ions — ReX_3^+ and ReX_2^+ — we find that the atomic-like transitions

$$f_m \rightarrow d_m$$

$$f_m \rightarrow p_m$$

$$f_m \rightarrow s_m$$

are shifted to a shorter wavelength; hence, spurious absorptions, if occurring, would be shifted to the blue. In a similar fashion, the negatively charged ions, ReX_3^- , ReX_2^- , etc., have transitions that are red shifted.

Calculations similar to those described above have been used to evaluate laser pumping scenarios. Pumping via the $f \rightarrow d$ transition is one possible optical pumping technique which is particularly attractive because of the atomic nature of the transition. One question addressed theoretically was whether molecular transitions may also lie in the same energy regime. Of particular interest were those states which may lead to dissociated products ($\text{ReX}_2 + \text{X}$ or $\text{ReX} + \text{X}_2$). For three systems,

NdCl_3 , EuCl_3 , and ErCl_3 , the positions of the excited states have been computed as a function of small variations ($\pm 1.0\%$) in the molecular geometry (corresponding to the products mentioned above). We did indeed find some expected dissociative states. The systematics of these dissociative states (varying Re and X) were studied to select candidate laser compounds. Two rare earths were finally selected, Ce and Tb. Unfortunately, Ce must be ruled out as a possible candidate laser system because of the scarcity of $f \rightarrow f$ transitions. Therefore, from our theoretical analysis, the two compounds, TbCl_3 and TbBr_3 and their complexed analogues, appear to be most attractive.

During 1977, similar types of semi-empirical molecular modeling calculations will be performed for the RE^{3+} -chelates and RE^{3+} -transition metal trihalides.

References

34. R. R. Jacobs, M. J. Weber, and R. K. Pearson, *Chem. Phys. Lett.* **34**, 80 (1975).
35. R. R. Jacobs, W. F. Krupke, J. P. Hessler, and W. T. Carnall, *Deactivation of the $\text{Nd}^{3+} \text{F}_{3/2}$ Level in Neodymium Chloride-Aluminum Chloride Vapor Complexes*, Lawrence Livermore Laboratory, Rept. UCRL-78733 (1976), to be published in *Opt. Commun.*
36. R. R. Jacobs and W. F. Krupke, "Trivalent Rare Earth Molecular Vapor Laser Systems," *Proc. 3rd Summer Colloquium on Electronic Transition Lasers*, (MIT Press, Cambridge, MA, 1977).
37. B. R. Judd, *Phys. Rev.* **127**, 750 (1962).
38. G. S. Ofelt, *J. Chem. Phys.* **37**, 511 (1962).
39. N. Djeu, Naval Research Laboratory; J. Goldhar and A. Szoke, Lawrence Livermore Laboratory, private communication (1977).
40. W. F. Krupke, *Prospects for Trivalent Rare Earth Vapor Lasers*, Lawrence Livermore Laboratory, Rept. UCRL-77033 (1975).
41. W. F. Krupke, *Dynamics of Trivalent Rare Earth Molecular Vapor Lasers*, Lawrence Livermore Laboratory, Rept. UCRL-16933 (1976).
42. C. F. Bender and E. R. Davidson, Lawrence Livermore Laboratory, to be published.
43. S. P. McAllynn, et al., *Introduction to Applied Quantum Chemistry* (Holt, Rinehart, and Winston, Inc., 1972).

Authors

C. F. Bender
R. R. Jacobs
W. F. Krupke

Major Contributor

R. E. Wilder

6-4 Metal Vapor Lasers

The high electrical excitation efficiency and relatively long radiative lifetime of the resonance levels of mercury have stimulated a continuing interest over the years in the possibilities of exploiting this energy reservoir to pump lasers for fusion applications.

One possibility is to shift the emission band to the wings of the resonance line through formation and emission on transitions of weakly bound molecules such as (HgXe). Experiments directed towards this approach have been described previously.⁴⁴ No further experiments on (HgXe)* have been conducted this year. A second possibility is to convert the energy in the atomic transition to a diatomic molecule emitting at longer wavelengths. Mercury, for example, forms Hg₂ dimers. These molecules have strongly bound electronic states and weakly bound ground states. The combination of long radiative lifetime and wide emission bandwidth in such molecules results in the low stimulated emission cross sections needed for energy storage. The Hg dimers can be readily formed from the excited Hg(³P) states by three body collisions. The Hg-Hg₂ system has been studied extensively over the years with little success. A consensus seems to be emerging that the Hg-Hg₂ system will not show net gain because of excited state absorption, but the evidence is not yet conclusive.

Recently, interest in metal vapor excimer systems for fusion applications has been revived by the

report of gain in the Cd-HgCd system by Fournier and McGeoch.⁴⁵ Lifetimes of a few microseconds were measured for an emission band near 4700 Å which was attributed to the HgCd excimer. While these measurements have not yet been confirmed by duplication, this report has stimulated renewed interest of the potential of the metal vapor excimer systems.

The primary processes which are expected to lead to laser action in HgCd are illustrated in Fig. 6-17. The cadmium is excited to its resonance levels, the ³P manifold, by electron impact:

The excited Cd is then converted to the HgCd excimer by three body collisions:

where M is the third body, which may be Hg or a buffer gas. The HgCd* then radiates in a broadband around 4700 Å to a dissociative ground state:

Fig. 6-17. Primary processes in an HgCd* excimer laser.

The cross sections and rates for these primary processes have been measured or can be estimated. The rates for electrical excitation of the triplet states of Hg are relatively well known. The corresponding cross sections for excitation of Cd(³P) should be of similar magnitude but with a threshold at the lower energy of the cadmium resonance levels. In electrical discharges, the lowest energy inelastic process is usually excited more efficiently than higher levels. Thus, selective excitation of Cd should be possible, provided the Hg density is not too high. This selective effect has been observed in the emission spectrum of a Hg lamp with additions of small amounts of cadmium.⁴⁶ Addition of 1% by density is sufficient to divert half the emission in the visible range to Cd lines. The three-body formation rate, k_3 , has been estimated to be $\sim 10^{-31}$ cm⁶/s by McGeoch, Fournier, and Ewart.⁴⁷ Pressures of a few hundred torr of buffer gas or Hg would be sufficient to insure that the CdHg* formation rate is faster than the Cd(³P) radiative lifetime. These numbers are consistent with energy storage of a few joules per liter for a mixture of Hg and Cd at temperatures between 400 and 600°C.

An experiment was assembled to duplicate the conditions under which gain had been reported. Figure 6-18 shows a schematic of the experimental apparatus used in these studies. A quartz tube 4 mm i.d., 20 cm long, and filled with Hg and Cd, was pumped with four flashlamps surrounding the tube. The energy input to the flashlamps was approximately 1000 J over a pulse duration of 10 μ s. The HgCd cell was surrounded by a Pyrex sleeve to reduce the pumping of the Hg resonance levels. The entire assembly was surrounded by an oven and heated to temperatures up to 600°C. Gain was monitored at 4880 Å, using an argon ion laser as a

source. Extensive efforts were made to reduce the background of the flashlamps and the electrical noise from the detection system. The probe laser was chopped to minimize heating effects in the photodiodes. The flashlamps were triggered when the probe signal amplitude had reached the flat portion of the chopped signal. Sensitivity was sufficient enough that gain or absorption of $\pm 1\%$ should have been observed.

The several tubes used in the experiments contained an excess of Cd with varying densities of Hg. The tubes were initially cleaned and then were baked at 200°C to a base pressure of 1×10^{-7} Torr. Cadmium of 99.999% purity was placed in the tubes and outgassed at 250°C to the same base pressure. The Hg was either distilled into the tube in excess or inserted in measured amounts in an atmosphere of inert gas. Cell tubes were sealed after filling.

Neither gain nor absorption was observed under any of the conditions investigated. The cells were operated at temperatures from 30 to 600°C. The flashlamp energy input was varied up to 1000 J input energy. No change in the transmitted signal was observed during the 10 to 30 μ s duration of the flashlamp pulse. Large amplitude fluctuations ($\pm 10\%$) began approximately 100 μ s after the flashlamp pulse. Their amplitude decayed with a time constant of tens of milliseconds. These fluctuations were attributed either to acoustic waves in the gas in the cell or to mechanical vibration of the cell itself.

It has not been determined why gain was not observed. Conditions were similar but not identical with those of Fournier.⁴⁵ The flashlamp pulse length in these experiments was longer. Peak pumping power was lower, although the absorbed energies should be similar. Impurities introduced in

Fig. 6-18. Experimental apparatus used for gain measurements in the flashlamp-pumped HgCd laser.

the filling process may be deactivating the excited state. The optical absorption cross section of the $\text{Cd}(^3\text{P}_1)$ resource level has been measured in mixtures of Hg and Cd at 420°C . The integrated absorption was found to be $0.1/\text{cm}$ over a bandwidth of $\sim 1 \text{ \AA}$. This absorption is insufficient to allow optical pumping by excitation of the Cd resonance level as has been hypothesized. Broadband absorptions at other wavelengths may be responsible for the reported gain.

Besides HgCd and Hg_2 , there are several other potential metal excimer systems which may prove of interest for fusion or LIS laser applications. Figure 6-19 shows the energy of the ^3P resonance levels of the Group II metals. Bound metastable excimers, in principle, could be formed by combinations of any of these metals. Emission wavelengths of the various excimers should fall over a range from the middle visible to the near infrared.

The characteristics of the metal excimers is also of theoretical interest. Spin-orbit effects will be important in determining the radiative lifetimes of these molecules particularly for the heavier metals. A program has begun in this area. Calculations have already been initiated on the potential energy curves of Be_2 and Mg_2 .⁴⁸ Because the IIA and IIB group of atoms have closed-shell (s^2) ground electronic configurations, and because the lowest excited states of interest in these systems arise from excitations out of the s-shell, these diatomics to first order can be accurately treated as four electron systems. Accurate (LS) curves will first be constructed for the diatomics of Be, Mg, and Zn in an effort to understand the nature of the bonding in these systems. Potential curves for the heavier atoms (Cd and Hg) will then be obtained by freezing out the core electrons and treating the bonding electrons in the same fashion as was done for the lighter systems. Electronic transition dipoles will also be obtained from these wavefunctions, and a theoretical modeling of the emission characteristics of several systems will be carried out.

In summary, a broadbased program of experimental and theoretical studies of the metal excimer systems has begun. Experiments to confirm reported gain in HgCd have not yet been successful. Further work is expected to resolve this discrepancy and lead to development of a new group of lasers suitable for LIS or fusion application

Fig. 6-19. Energy of the resonance levels of the Group II metals.

References

44. 1975 *Laser Program Annual Report*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75, M6 518.
45. G. R. Fournier and M. W. McGeoch, Proc. 1Xth International Quantum Electronics Conference, Amsterdam, June 1976.
46. W. Elenbass, *The High Pressure Mercury Vapor Discharge* (North Holland, Amsterdam, 1951).
47. M. W. McGeoch, G. R. Fournier and P. Ewart, *J. Phys. B* 9, L121 (1976).
48. C. F. Bender, work in progress; W. J. Stevens and M. Krauss, "The Electronic Structure of the Ground and Excited States of Mg_2^+ and Mg_2 ," to be published.

Authors

L. D. Pleasance
T. N. Rescigno

6-5 Rare Gas Oxide (RGO) Lasers

Rare gas oxides (RGO's) have been investigated as possible gain media for scalable fusion lasers. The primary energy carriers in these lasers are metastable oxygen atoms excited to the ^3P state. Typical mixtures using electron-beam excitation are 12 atm Xe or 25 atm Kr plus a few Torr of O_2 . A

small fraction of the excited $O(^1S)$ atoms form rare-gas-oxygen excimers for which the $^1S \rightarrow ^1D$ atomic quadrupole transition becomes an electric dipole $^1\Sigma \rightarrow ^1\Sigma$ or $^1\Sigma \rightarrow ^1\pi$ molecular transition. The emitting excimers may be either bound molecules as in the case of $XeO(^1S)$ or free molecules like $ArO(^1S)$. Because of their greater radiation rate, the excimers provide useful gain while the free $O(^1S)$ atoms act as an energy reservoir. Useful energy extraction from an RGO amplifier requires depleting the $O(^1S)$ atoms via cross-relaxation to rare-gas- $O(^1S)$ excimers.

The radiative properties and laser characteristics of RGO excimers have been discussed in the 1974 and 1975 Annual Reports.^{49,50} The optical gain has been shown to be proportional to the produce of rare gas and $O(^1S)$ densities. The gain cross sections referenced to the $O(^1S)$ density have been computed to be $1.8 \times 10^{-19} P_{Xe} \text{ cm}^2$ and $1.1 \times 10^{-20} P_{Kr} \text{ cm}^2$, where the rare gas pressure P is given in atmospheres. Hence, assuming the optical field does not affect the chemical equilibrium between the rare-gas-oxide molecules and $O(^1S)$ atoms, a saturation flux of 1 J/cm^2 occurs at approximately 2 atm in Xe and 30 atm in Kr.

The formulations of the gain cross section and saturation flux for collision-induced emission have been investigated under contract by Julianne at NBS.⁵¹ The formulas relating the gain and saturation flux to the spectral intensity of spontaneous emission for a homogeneously broadened line have been shown to be appropriate for a free-free or free-bound (upper state-lower state) molecular emitter such as ArO or KrO . Cross-relaxation via three-body association and vibrational/rotational relaxation must be considered to describe the short-pulse saturation of a bound-bound emitter such as XeO .

A fundamental question in using XeO to amplify short pulses is whether the energy stored in $O(^1S)$ can be extracted via cross-relaxation. A rate-equation analysis has been used to model this problem, assuming three-body formation to be the rate-limiting step in production of $XeO(^1S)$, $v' = 0$. Full extraction from $O(^1S)$ occurs provided the extraction pulse is longer than the formation time, a result analogous to that found in the rotational reservoir model of single-line CO_2 extraction.⁵² Measurements of three-body formation of $XeO(^1S)$ by Xe have produced rates^{53,54} of $1.0 \times 10^{-32} \text{ cm}^6/\text{s}$ and $1.1 \times 10^{-31} \text{ cm}^6/\text{s}$ which yield extraction times of 1.2 and 0.1 ns at 12 atm Xe.

The requirement of high Xe pressure to achieve short-pulse extraction severely limits high-average-power XeO amplifiers because of the large index of refraction of the optical medium ($n = 1.0 + 7 \times 10^{-4} P_{Xe}$). Acoustical waves in the medium must be strongly damped between pulses to reduce phase distortion of the amplified beam. Furthermore, if gas flow is used it must be carefully contoured to reduce steady-state inhomogeneities. Because the laser medium is reusable, single-shot or very-low-repetition-rate ($< 0.1\text{-Hz}$) applications can be considered in the absence of flow.

The XeO system may prove useful for amplifying frequency-doubled Nd:YAG pulses at 532 nm. Fluorescence spectra (Fig. 6-20) suggest that the XeO gain at this wavelength, provided mostly by the $v' = 0 \rightarrow v'' = 4$ vibrational transition,⁵⁵ is 80% of the peak gain found in the band. Gain measurements using the cw dye laser confirm this ratio. An exact coincidence with the doubled Nd frequency is not required since the XeO lines are merged to a continuum at high pressure.

Fig. 6-20. Fluorescence spectrum for XeO . The intensity contours were determined with a neutral-density step wedge. Vertical bar indicates the 532-nm wavelength of frequency-doubled Nd:YAG.

Kinetic Studies

The production of $O(^1S)$ in electron-beam-excited Xe and Xe/Ar mixtures was studied as a function of oxygen additive (O_2 , CO_2 , N_2O , O_3), rare-gas pressure, and current density using the MEG I electron-beam facility. The XeO fluorescence from a region adjacent to the input foil was viewed through a double-pinhole arrangement using a photomultiplier tube shielded in a lead container and suitably attenuated by calibrated neutral-density filters. A carbon screen technique was used to vary the beam current at constant voltage (600 keV), pulse length (50 ns), and geometric cross section ($2.5 \times 10 \text{ cm}^2$). Portions of the electron beam passed through holes in a perforated carbon plate inserted in a 10-cm-long drift region for the beam before it entered the laser cell. The individual beamlets thus formed were found to homogenize in the remainder of the drift region and uniformly illuminate the entrance foil. A carbon calorimeter was placed in the laser cell to calibrate the energy and hence current (constant voltage and area) for a given carbon screen. The current density can be varied from 1 to 1000 A/cm² by this technique.

The variation of peak XeO fluorescence intensity with Xe pressure at constant current using either O_2 or N_2O as an additive is shown in Fig. 6-21. The optical gain after the 50-ns pump period is proportional to the fluorescence signal and has a peak value of about $1\% \text{ cm}^{-1}$ for a Xe/ O_2 mixture at 8000 Torr. If one assumes constant $O(^1S)$ production efficiency, the XeO(1S) fluorescence intensity should scale as $(P_{\text{Xe}})^2$ at constant current since both the energy deposition and the collision-induced emission are proportional to Xe pressure. Hence, in Fig. 6-21 the Xe/ N_2O mixture exhibits constant $O(^1S)$ efficiency while the Xe/ O_2 case has an efficiency which increases linearly with Xe pressure up to 8000 Torr.

The time dependence of the XeO fluorescence shows a 50-ns growth period of $O(^1S)$ during the e-beam pumping, a rapid increase at the end of the pumping, and then a slower decay. The $O(^1S)$ decay in the N_2O mixture is caused by N_2O , $O(^3P)$, and Xe, while the decay in the Xe/ O_2 case is dominated by $O(^3P)$ quenching.⁵⁶ The O_2 quenching rate is quite small. Relevant decay rates for various donors and fragments of the donors are shown in Table 6-5. Note that if all the O_2 were dissociated, $O(^1S)$ quenching time by $O(^3P)$ would be about 150 ns.

Table 6-5. Quenching of $O(^1S)$ by various donors and their fragmented products at 300°K (from Ref. 57)

Donor or fragment	$O(^1S)$ quenching rate (cm ³ /s)
Xe	2.7×10^{-15}
O_2	3.6×10^{-13}
CO_2	3.6×10^{-13}
N_2O	1.1×10^{-11}
O_3	6.0×10^{-10}
O	2.0×10^{-11}
NO	8.0×10^{-11}
N	1.8×10^{-11}
CO	$\leq 1.6 \times 10^{-16}$

The Xe/ O_2 decay times approach that value at high Xe pressure, indicating nearly total dissociation of O_2 and a relatively low percentage of $O(^1S)$. The XeO dependence in Xe/ CO_2 mixtures resembles the Xe/ O_2 case, having a somewhat smaller $O(^1S)$ yield and longer decay time.

The peak XeO fluorescence signal is plotted versus current density in Fig. 6-22, again for O_2 and N_2O mixtures. A peak fluorescence proportional to current implies a constant $O(^1S)$ production efficiency as observed for N_2O at low currents. The saturation in XeO fluorescence above 100 A/cm² is partially caused by a temperature change in the medium, which reduces the XeO(1S)/ $O(^1S)$ chemical equilibrium; but it also indicates a decrease in $O(^1S)$ production efficiency, which had increased markedly with current at lower current values. The current dependence at low current values becomes asymptotic to an I^2 dependence, possibly indicating a two-step $O(^1S)$ production mechanism, with the optimum efficiency occurring near 30 A/cm². Note also the different dependence on additive pressure as a function of current in the O_2 and N_2O cases. Again, the CO_2 mixture is analogous to the O_3 case. An O_3 current dependence like that of N_2O was inferred by noting the large increase in $O(^1S)$ yield with repeated shots on

Fig. 6-21. Peak fluorescence of XeO vs Xe pressure. Mixtures were excited by a 50-ns electron beam at a fixed current density of 38 A/cm^2 .

Xe/O₂ mixtures at low currents. This increase is believed to result from ozone formation via the reaction $O + O_2 + M \rightarrow O_3 + M$.

The production of O(¹S) in Xe, Kr, and Ar has been studied under contract at SRI by Huestis, Zamir, Nakano, and Lorents.⁵⁸ By using a calibrated photomultiplier and a 3-ns excitation pulse then infer an extractable O(¹S) energy storage efficiency of 2% in Xe/O₂, 2.2% in Kr/O₂, and 1.6% in Ar/N₂O. The general trends with rare-gas and additive pressures agree with those shown here.

The O(¹S) production mechanism in electron-beam-excited gas mixtures has not been solidly determined. The Xe/N₂O or O₃ case could be described by a single-step process,

However, for Xe₂^{*} in collision with either O₂ or CO₂, there is insufficient energy to produce O(¹S) in a single step. Huestis has suggested a two-step mechanism⁵⁹ where the O₂ is dissociated to O(³P) by one excimer collision and then excited to O(¹S) by the exothermic process, $Xe_2^* + O(^3P) \rightarrow O(^1S) + 2Xe$. This mechanism does not appear to be consistent with finding a constant O(¹S) yield at low current, independent of the O₂ additive pressure. The experimental result suggests that the O(¹S) production via a second step does not involve an Xe₂^{*} excimer. In all cases the O(¹S) production efficiency is strongly limited by superelastic electron

Fig. 6-22. Peak fluorescence of XeO vs current density for Xe/O₂ and Xe/N₂O mixtures.

quenching, $O(^1S) + e \rightarrow O(^1D) + e$, having a rate of $10^{-9} \text{ cm}^3/\text{s}$ at 1 eV plasma temperature.⁶⁰

Amplifier Development

A slab amplifier was designed to optimize the e-beam coupling efficiency to a gas at 100 A/cm^2 with operating pressures up to 500 psi. A Maxwell POCO Beam machine (MEG II), which normally produces a 50-cm beam containing 4 kJ of 1-MeV electrons in a 50-ns pulse, was modified for this purpose. Carbon cathodes consisting of either two blades or a smooth rectangular block of general dimensions $3 \times 43 \text{ cm}$ were found to pump the entire anode area ($7.5 \times 50 \text{ cm}$) and produce a 10- Ω impedance at a 2.5-cm anode-cathode spacing. For efficient injection into the gas, a single foil was used, with the foil support defining the anode surface (Fig. 6-23). This structure employs 1.3-cm-wide slots separated by 0.5-cm-wide ribs to support a 0.13-mm-thick Ti foil. The overall transport efficiency to the gas is greater than 20%, as summarized in Table 6-6. For typical conditions the 1-MeV beam penetrates about 3 cm into the gas and scatters to a width of about 10 cm. The cross section

Fig. 6-23. Schematic cross section of multipass amplifier cell and e-beam diode.

Table 6-6. Energy transport in the e-beam-pumped RGO amplifier (modified MEG 11 e-beam)

	Energy (kJ)	Net efficiency (%)
Stored in Marx	7.2	—
Transferred to line	4.6	65
Delivered to anode	4.4	61
Transmitted into cell	2.3	32
Deposited in Kr	1.7	24
Deposited in Xe	1.5	21

of the gas volume ($3 \times 15 \text{ cm}$) is ample to accommodate this deposition region.

A photograph of the KrO fluorescence from this cell operating at 375 psi Kr and 10 Torr O_2 is shown in Fig. 6-24. The excited volume exhibits an apparent cross section of $2.5 \times 8 \text{ cm}$, giving an excitation volume of approximately 1 liter for a 50-cm length. Black-and-white negatives of the RGO fluorescence were taken at a distance of 5 m using a long-focal-length lens to reduce parallax. An isodensitometer scan of such a negative is also shown in Fig. 6-24; note that the x dimension has been expanded by a factor of two relative to the y dimension for ease of reading. Optical density plots were converted to plots of relative intensity versus position by using a neutral-density step wedge to calibrate the film response.

In Fig. 6-25 the fluorescence intensity is compared with relative energy deposition calculated by the three-dimensional electron trajectory code SANDYL.⁶¹ An input beam at 1 MeV was assumed with a transverse current distribution as measured by 4-chlorostyrene film exposure. The close agreement of the calculated deposition with fluorescence intensity suggests an $O(^1S)$ yield proportional to input energy at 25 atm Kr. Similar data for the XeO fluorescence show a saturation near the foil caused by overdriving the medium.

The distribution of small-signal gain over the aperture was determined with a cw dye laser. Time-dependent single-pass gain profiles measured at various positions in the aperture for a mixture of 180 psi Xe/7 Torr O_2 are shown in Fig. 6-26. The cw level of the dye laser beam is observed at the left

of each trace. Essentially 100% absorption occurs during the e-beam excitation, followed by a recovery to net gain which then decays like the XeO fluorescence. Note that the deposition near the foil at position 4 is somewhat too intense for optimum efficiency; the gain is actually larger at position 5 although the energy deposition is less.

The peak small-signal gains were used to calculate an extractable energy storage via the optical cross-section data and to calculate medium efficiency values using the SANDYL deposition data. Peak energy storage of 5 J/liter and optimum

medium efficiency figures of 0.6% and 0.3% were found for the Kr and Xe cases respectively. These values, considerably smaller than the SRI findings, are believed conservative in the sense that they represent a gas mixture contaminated by many repeated shots. Also, the optical cross-section values used for Xe are extrapolations from low pressure data and may be too large as suggested by earlier collision-induced-emission experiments. Given these qualifications, a medium efficiency of 0.5% with an energy storage of 5 J/liter appears realizable.

Fig. 6-24. Photograph and corresponding isodensity plot of the KrO fluorescence excited at 375 psi Kr/10 Torr O_2 . Contour spacing on plot is 0.1 density unit.

The large medium absorption during the e-beam excitation has been investigated by Zamir at SRI under ERDA contract support.⁵⁸ These absorptions have been found to be broad band, extending throughout the visible, and are believed to be caused by contributions from several atomic and molecular rare-gas excited states. A sample of the absorption spectrum found for e-beam-excited Kr is shown in Fig. 6-27.

Rectangular mirrors of cross section 3×7.5 cm were placed inside the slab amplifier to provide multipass gain. A picture of the beam path for nine passes (4.5 in gain length), obtained by removing the entrance foil support and rolling back the e-beam generator, is shown in Fig. 6-28. It was found

necessary to design feedthrough mirror gimbals to adjust the internal mirrors while under high pressure to compensate for slight deformations of the cell upon pressurization.

Small-signal gains obtained for the standard Xe and Kr mixtures with the nine-pass configuration are shown in Fig. 6-29. Peak multipass gains of $8\times$ for KrO and $20\times$ for XeO were observed for this path length. Note that the effective decay time of the gain is obviously shortened because of the large exponentiation. Notice also in the XeO data that the dye laser signal recovers to a smaller value than before the pulse. This residual absorption has been correlated with the presence of suspended particles in the amplifier gas present after repeated shots.

Fig. 6-25. Measured fluorescence intensity profiles for KrO in the multipass amplifier cell compared with SANDYL calculations of energy deposition.

Such particles were removed either by refilling the amplifier with new gas or by condensing the old gas with liquid N₂ and then warming it to refill the amplifier.

High-power gain measurements were taken using a coaxial flashlamp-pumped dye laser (Phasar Model 2100 B) operating in synchronism with the e-beam machine. Unfortunately, the beam divergence of this device was so large (~5 mrad) as to make the multipass configuration impractical. The experiment was further limited by the lack of efficient flashlamp-pumped dyes in the 540-to-560-nm region. Fluorinated Coumarin 6 dye provided the best performance, yielding an output power of approximately 1 MW. Focusing geometries were used to maximize the peak power density of the dye laser

beam passing through the cell. Under optimum conditions we have extracted about 2 J/liter from the medium without producing obvious gain saturation (Fig. 6-30). We also tried a regenerative amplifier configuration, injecting about 1% of the dye laser power into a high-Q XeO laser cavity. Enhancement of the XeO laser output by tenfold was observed, again without medium saturation.

Future Plans

Our efforts to develop RGO amplifiers that are directly pumped by an electron beam are being substantially reduced in 1977 in favor of the related Group VI atom lasers that are photolytically pumped. The RGO system has a low medium efficiency

Fig. 6-26. Single-pass gain vs time for XeO at six different locations in the multipass cell. Peak small-signal gains are indicated at each location. Gas mixture 1/180 psi Xe/7 Torr O₂.

Fig. 6-27. Atomic, molecular, and background absorption by e-beam-excited Kr (Stanford Research Institute data^{58,59}).

Fig. 6-28. Beam path for nine-pass amplification in the multipass amplifier.

Fig. 6-29 Nine-pass gain (4.5 gain length) observed for Xe/O₂ and Kr/O₂ mixtures in the multipass amplifier.

and a high operating-medium index which makes it difficult to scale to high average power. A small effort is anticipated to address the general issue of short-pulse energy extraction from XeO using a frequency-doubled Nd:YAG laser.

References

49. *Laser Program Annual Report—1974*, UCRL-50021-74 (1975), pp. 451-56.
50. *Laser Program Annual Report—1975*, UCRL-50021-75 (1976), pp. 505-511.
51. P. S. Julienne, to be published in *J. Appl. Phys.*.
52. G. T. Shappert, *Appl. Phys. Lett.* **23**, 319 (1973).
53. H. T. Powell and J. R. Murray, LLL, private communication.
54. G. Black, R. L. Sharpless, and T. G. Slinger, *J. Chem. Phys.* **63**, 4546 (1975).
55. C. D. Cooper, G. C. Cobb, and E. L. Tolnas, *J. Mol. Spectrosc.* **7**, 223 (1961).
56. T. G. Slinger and G. Black, *J. Chem. Phys.* **64** 3763 (1976).
57. Numerous deactivation rates for Group VI's atoms are collected in J. R. Murray and C. K. Rhodes, *J. Appl. Phys.* **47**, 5041 (1976).
58. D. L. Huestis, E. Zamir, H. H. Nakano, R. H. Hill, and D. C. Lorents, *Final Report Contract E(04-3)-115* (1977).
59. D. L. Huestis, R. A. Gutcheck, R. M. Hill, M. V. McCusker, and D. C. Lorents, Stanford Research Institute Report No. MP 75-18 (1975).

Gain length = 50 cm
 Input pulse energy = 200 mJ
 Peak power = 4.3 MW/cm²
 Beam area = 0.12 cm²
 Extracted energy = 2 J/liter

50 ns/div

Fig. 6-30. High-power gain profile for XeO. The dye-laser probe has a smoothly varying time dependence. Extracted energy is calculated from the area of the amplification region.

60. L. D. Thomas and R. K. Nesbet, *Phys. Rev. A* **11**, 170 (1975).
61. H. M. Colbert, Sandia Laboratories Report No. SCL-DR-720109 (1973).

Authors

H. T. Powell
 J. R. Murray
 L. G. Schlitt
 J. Taska

6-6 Raman Pulse Compression of Rare Gas Fluoride Lasers

For some years it has been recognized that pulse compression in a backward Raman amplifier might be used to generate short, high-energy laser pulses such as those required for fusion. As early as 1967, A. J. Glass⁶², discussed in detail the potential

properties of such systems. "...In the design of Raman lasers, beam trapping dictates the use of a gaseous medium for high power densities. The most flexible configuration consists of a mode-controlled oscillator followed by an amplifier which brings the beam up to the saturation level and then by a backward-traveling amplifier to shorten and intensify the output pulse. Intensities of the order of 10^{10} W/cm² seem possible..."

The 10 years since have not changed this perception, although research during the decade has greatly improved our understanding of the sometimes rather complex behavior of Raman amplifiers. Research studies at LLL have included detailed experimental investigations and computer modelings of gas-phase Raman oscillators and amplifiers by Kachen and Lowdermilk⁶³ as well as theoretical and experimental studies on stored-energy extraction by Raman and other two-photon processes by Carman and Lowdermilk.^{64,65} However, it has not been possible to identify an appropriate process for practical application of Raman pulse compression using the pump lasers which were available.

During the past year, we have recognized that the recent development of efficient, rare-gas-fluoride ultraviolet lasers may be the critical development required to change the Raman pulse compressor from merely a good idea to a practical one.⁶⁶ As a result, we have initiated a program to evaluate these devices.

If we consider the simplest conceptual design for such a compressor using vibrational Raman scattering far from resonance, a KrF-pumped Raman amplifier operating at gas pressures of a few atmospheres appears to be able to achieve saturation energies near 1 J/cm². These energies are appropriate for a fusion amplifier. There are also a number of near-resonant Raman processes in atoms or molecules that are accessible with rare-gas fluorides⁶⁷ and these may exhibit superior properties for Raman pulse compression.

Pulse Compression in a Backward-Wave Raman Amplifier

Figure 6-31 illustrates the principle involved in pulse compression using a backward-wave Raman amplifier. A long laser pulse, which we call the pump pulse, propagates from right to left into a Raman-active interaction zone, producing gain at a

frequency given by $\nu_P - \nu_R = \nu_S$, where ν_R is the frequency of the excited Raman transition. A Stokes input pulse at ν_S is injected into the interaction zone precisely when the pump pulse just reaches the exit window of the interaction zone. As the Stokes pulse propagates from left to right and the pump pulse propagates from right to left, the Stokes pulse at ν_S is amplified at the expense of the pump pulse. After a time $\tau_P/2$, the Stokes pulse emerges as an amplified pulse traveling in the backward direction with respect to the pump pulse. The Stokes pulse can be much shorter in time than the pump pulse (see Fig. 6-31). The net result is to compress a long laser pulse at ν_P into a short pulse at ν_S . A net loss of energy results because ν_S is less than ν_P .

The backward Raman amplifier is really an energy-storage laser in which energy is stored in the form of a photon density in the collimated pump beam rather than in an actual inversion in the medium. The properties of such an amplifier may be expressed in a conventional-amplifier form using an energy storage density, Δn (photon/cm³), and an effective stimulated emission cross section, σ_{er} , for conversion of a pump photon to a Stokes photon. A saturation energy fluence, $E_s = (h\nu_S/\sigma_{er})$, may be defined as the energy fluence required in the Stokes

wave to reduce the pump-wave intensity (photon density) to $(1/e)$ of its initial value.

The simplest Raman process considered for this application is vibrational Raman scattering from a molecule far from resonance with the electronic intermediate state. For this case, the gain at the first Stokes frequency, ν_S , may be expressed⁶⁸ as

$$\left(\lambda_S^2 c g(\nu_S) \frac{\partial \sigma}{\partial \Omega} N \right) \left(\frac{I_P}{h\nu_P c} \right) \ell$$

$$= (\sigma_{er} \Delta n) \ell \quad (13)$$

We have rearranged the expression somewhat from the usual formulation to display explicitly the effective cross section, σ_{er} , and the pump photon density, Δn . In this expression, the S subscript denotes Stokes, the P subscript denotes the pump, $g(\nu)$ is the lineshape of the transition, $(\partial \sigma / \partial \Omega)$ is the phenomenological differential Raman-scattering cross section, N is the density of scatterers, and ℓ is the length of the amplifier.

Fig. 6-31. Pulse compression by backward Raman scattering.

The effective Raman-stimulated emission cross section, σ_{er} , can now be estimated for excitation by an efficient rare-gas-halide source such as KrF at 249 nm. The amplifier is evaluated for KrF pumping because a KrF laser avoids the optical material problems found at the shorter ArF wavelength and in measurements to date, KrF laser has shown higher efficiency than XeF. The differential scattering cross section ($\partial\sigma/\partial\Omega$) has not been measured at this wavelength. However, it may be inferred from measurements at other wavelengths with any of several models that have been developed for the frequency dependence of ($\partial\sigma/\partial\Omega$). The simplest of these is Placzek's model^{69,70} which gives a frequency dependence of the form

$$\frac{\nu_s^4}{(\nu_e - \nu_p)^2}, \quad (14)$$

where ν_e is the frequency of the electronic intermediate state through which the Raman transition is induced. More complex models can sometimes give a better fit to the data,⁷⁰ but we will use Placzek's model here as a good first approximation.

A preliminary analysis of the various molecules for which sufficient data are available suggests that the Q branch of the ν_1 vibration of spherical top molecules (e.g., methane) is probably the most promising transition for a Raman amplifier. Thus, we shall limit our discussion to this transition although several other candidates are discussed elsewhere.⁶⁶ The Q branch of the ν_1 vibration of methane (stationary carbon with four hydrogens moving radially in phase with equal amplitude) has a large Raman cross section, permitting operation at a lower gas pressure than is possible for other common gases. Cross sections for other vibrational modes are significantly less and can be ignored.

Like all spherical top molecules, methane has no rotational Raman cross section, eliminating one potential class of parasitic oscillations. The ν_1 Q branch consists of numerous rotational lines which are so closely spaced that, at pressures of interest (~ 1 to 20 atm), the branch probably can be treated as an envelope of overlapped lines with a resulting pressure-independent linewidth of approximately 0.3 cm^{-1} (see Ref. 71). Although detailed high-resolution data on methane are not available, this model is in reasonable agreement with experimental data.⁶³

Table 6-7 gives the important parameters for Raman scattering of KrF radiation from methane. The 249-nm input beam is used as a pump to amplify a pulse at 268 nm shifted by 2917 cm^{-1} . The lineshape of the amplifier is given by a convolution of the lineshape of the ν_1 Q branch of methane and the lineshape of the pump laser. Saturation energies given in Table 6-7 are for the linewidth of the KrF pump laser negligible when compared with the approximate 0.3-cm^{-1} methane ν_1 Q width and a KrF linewidth of 1 cm^{-1} . Our analysis predicts that a KrF-pumped Raman amplifier saturating at 1 J/cm^2 will operate at a methane-gas pressure between about 0.5 and 3 atm.

A comparison of σ_{er} at 249 nm and σ_{er} at 1060 nm illustrates why the availability of efficient ultraviolet-laser sources makes a Raman pulse compressor more attractive than it might be for excitation with a common, reasonably efficient, rare-earth laser such as neodymium in glass or YAG. When all other conditions are held constant, the saturation energy fluence, E_s , varies as $(h\nu_s/\sigma_{er})$ or $E_s \propto [(\nu_e - \nu_p)^2/\nu_s N]$.

For a 2900-cm^{-1} Raman scatterer, a 1060-nm pumped amplifier must operate at 12 times the pressure of a 249-nm pumped amplifier to achieve the same saturation energy. Because pressures of approximately 2 to 5 atm are required for reasonable saturation energies at 249 nm, the very high pressures required at 1060 nm are a significant disadvantage. Problems with stimulated Brillouin scattering are also more serious at 1060 nm.

Design of a Nominal KrF-Methane Amplifier

We must now consider the size and design of a nominal KrF-methane Raman amplifier to visualize the layout and potential problems of such a device. Parasitic oscillation problems such as first Stokes superfluorescence will be neglected for the moment and will be discussed below. Assume a KrF pump source operating with a 100-ns pulse and a linewidth of 1 cm^{-1} . A pump laser with a larger linewidth necessitates the use of a higher methane pressure. The 100-ns KrF pump requires a compressor cell with a 50-ns transit time (i.e., 15 m in length).

Table 6-7. Properties of KrF Raman scattering by methane

Property	Methane, Q_{01} branch
Shift, cm^{-1}	2,917
Linewidth, cm^{-1}	~ 0.3
Assumed intermediate state, cm^{-1}	Diffuse, 70,000
$\frac{\partial \sigma}{\partial \Omega}$ measured 488 nm	1.98×10^{-30}
$\frac{\partial \sigma}{\partial \Omega}$ calculated 249 nm	7.5×10^{-29}
ν_s , cm^{-1}	37,247
λ_s , nm	268
σ_{er} , cm^2	$1.4 \times 10^{-18} \text{P}^a$ $3.2 \times 10^{-19} \text{P}^b$
E_{sat} , J/cm^2	$0.5/\text{P}^a$ $2.2/\text{P}^b$

^aFor 249-nm excitation with P = pressure (atm) and $\Delta\nu_{\text{laser}} \ll 0.3 \text{ cm}^{-1}$.

^bFor 249-nm excitation with P = pressure (atm) and $\Delta\nu_{\text{laser}} = 1.0 \text{ cm}^{-1}$.

Figure 6-32 shows a possible layout for such a Raman amplifier. A dichroic mirror reflects the KrF radiation into the compressor cell, where it amplifies an injected Stokes pulse at 268 nm. The Stokes pulse passes through the dichroic mirror and

Fig. 6-32. Nominal KrF-methane compressor.

continues on its way. The output of the amplifier is determined mainly by the damage threshold of window B and the dichroic mirror because these components are exposed to an energy flux equal to the sum of the 249-nm and the 268-nm energy fluxes. We model a conservative case with a $2 \text{ J}/\text{cm}^2$ peak flux. *Though undemonstrated, $2 \text{ J}/\text{cm}^2$ is probably a very safe projection based on results at other wavelengths.* The power density in a 1-ns Stokes pulse is about $10^9 \text{ W}/\text{cm}^2$ and may be approaching an intensity at which two-photon absorption in the windows could be a problem. We also assume that the amplifier will stand off a gain of e^5 , a conservative value for a 100-ns pulse and a $0.3\% \text{ cm}^{-1}$ gain.

The resulting amplifier parameters are shown in Table 6-8. The parameters are chosen to give an amplifier with an energy gain of about 5 and an efficiency for extraction with a pulse of uniform intensity (i.e., $E_{\text{out}}/E_{\text{in}} + E_{\text{pump}}$) of approximately 80%.

A shaped pulse will probably reduce the extraction twofold to yield a stage efficiency of about 40% for conversion of a 249-nm, 100-ns pulse to a compressed 268-nm pulse. If a KrF 100-ns pump can be built with an efficiency of approximately 5%, this compressor permits a 2% efficient laser to be constructed at 268 nm. Some projections of ultimate KrF efficiency considerably exceed 5% but there will be little argument that a few percent efficiency should be achievable.

The spatial coherence required for the KrF pump beam is an important parameter by which to evaluate Raman compressors since it may be very difficult to preserve high-beam quality in a flowing gas, repetitively pulsed KrF laser. The intensity of the KrF beam in the Raman cell is to first order simply an energy storage density. Thus, the question of spatial coherence reduces to an analysis of the

maximum gain-nonuniformity that can be tolerated when higher order effects such as self-focusing and self-phase modulation are absent. We might propagate even a very highly divergent beam by grazing incidence reflection from highly reflective cell walls. This method of propagation results in interference fringes in the pump beam which create severe local variations in Raman gain at different positions in the amplifier aperture for any short section of the amplifier. However, because these interference patterns vary rapidly with position along the axis of the cell, integrating the gain for the entire amplifier along a line parallel to the cell axis will average out these fluctuations. Careful modeling and experimental analysis of Raman amplifier performance with collimated and multiple reflected pump beams is required to establish criteria for the minimum acceptable pump-beam quality.

Table 6-8. Performance of a nominal KrF-methane compressor

Property	Performance
<u>KrF Pump</u>	
Pulselength, ns	100
Fluence, J/cm ²	1
Intensity, J/cm ²	10 ⁷
Linewidth, cm ⁻¹	1
<u>Methane Compressor</u>	
Gas pressure, atm	10
Effective bandwidth, cm ⁻¹	1.3
Saturation fluence, J/cm ²	0.2
Small signal gain in a 15-m amplifier	~e ^{4.4}
<u>Performance as 268-nm First Stokes Amplifier</u>	
Input fluence, J/cm ²	0.2
Output fluence, J/cm ²	0.98
Stage efficiency, $\left(\frac{\text{energy extracted}}{\text{energy in pump}} \right)$, %	~80 (~40 for 50% extraction of stored energy)

Second Stokes Stimulated Scattering in a Saturated Amplifier

The Raman parasitic process of lowest order (and highest gain) in an amplifier design such as that discussed above is the generation of a second Stokes pulse that propagates coincident with the 268-nm first Stokes pulse. The 268-nm pulse is injected at the left-hand side of the amplifier in Fig. 6-32 and produces gain and some fluorescence at 291 nm, corresponding to a shift of 2917 cm^{-1} from 268 nm. The portion of the fluorescence of parametrically generated 291-nm radiation that propagates coincident with the 268-nm pulse sees gain for the entire 50-ns transit time of the amplifier. Radiation propagating in other directions sees gain for less than the 268-nm pulse length and can be ignored.

The small-signal gain at the second Stokes frequency is $\exp(\sigma_2 \Delta n_1 \ell)$, where σ_2 is the Raman σ_{eff} for scattering a first Stokes photon into the second Stokes, Δn_1 is the density of photons in the Stokes wave, and ℓ is the gain length. For a saturating amplifier such as that discussed above, where $E_{\text{in}} = E_{\text{sat}}$, the small signal gain for the second Stokes is expressed by

$$\exp \frac{\sigma_2}{\sigma_1} \frac{\tau_p}{\tau_1} \frac{1+G}{4}, \quad (15)$$

where G is the energy gain of the amplifier ($E_{\text{out}}/E_{\text{in}}$). The high compression ratio, τ_p/τ_1 , desired here aggravates the situation considerably if second Stokes is to be suppressed.

The effective stimulated emission cross section, σ_2 , for conversion of first Stokes to second Stokes may be evaluated for methane pumped by KrF with the model presented above. For $\Delta\nu_p = 0$, the resulting σ_2 is $2 \times 10^{-19} \text{ cm}^2$ or $\sigma_1/\sigma_2 = 0.79$.

We consider an amplifier (Fig. 6-32) that operates at a large compression ratio; e.g., a compression of 100 from a 100-ns pump pulse to 1-ns first Stokes pulse with an energy gain of 5. The small signal gain for the second Stokes is approximately e^{120} under these circumstances and suppression of the second and higher Stokes orders is obviously essential if a pure first Stokes output is required. This might be accomplished by inserting 10 to 15 dichroic mirrors or etalons in the methane gas that pass 249 and 268 nm but reject 291 nm. (Note that this is formally equivalent to a series of short amplifiers pumped by

a single KrF pump source.) This solution is rather clumsy, however, and a more refined approach may be to stage the pulse compression at smaller compression ratios, as discussed below.

Also, it may not be necessary to restrict the final amplifier to first Stokes output for coupling to laser fusion targets. The output at the second and higher Stokes frequencies is coincident in time with the first Stokes pulse as it leaves the final amplifier. If the spatial coherence of the higher Stokes orders is good enough to permit them to be focused on the target, then the shift of pulse energy to higher Stokes orders is of secondary significance. One vibrational quantum is subtracted from the energy of the photon with each higher order so that the efficiency of the final amplifier is reduced in higher order operation. However, this loss is probably minor when compared to other losses in the system. To maintain spatial coherence and focusability, it may be necessary to inject pulses at the higher Stokes frequencies to prevent superfluorescent amplification of highly divergent Raman fluorescence, although, parametrically generated higher order Stokes waves may have sufficient spatial coherence to serve as input waves for the higher orders. It will require very careful analysis and experimentation to determine the distribution of intensity and spatial coherence in various Stokes orders and to predict the behavior of an amplifier with this degree of complexity.

The second Stokes instability is minimized for large Stokes shifts and for resonance enhancement of the first Stokes cross section. The differences are not large, however, unless the shift is very large or unless a close resonance is present for the first Stokes (this is discussed in a later section for atomic near resonant scattering).

Staged Compression for Short-Pulse Generation Without Higher Order Stokes Parasitics

The second Stokes gain in a backward Raman compressor is proportional to the compression ratio, τ_p/τ_1 . The amplifier of Fig. 6-32 has approximately e^{120} gain for compression from 100 to 1 ns and only e^{12} gain for compression from 100 to 10 ns; this second gain is probably too low to cause problems. We might envision, therefore, a stage pulse compression chain similar to the one shown in

Fig. 6-33. A 100-ns, 249-nm KrF pump pulse is converged to a 10-ns, 268-nm first Stokes pulse in a 15-m methane cell by serving as a Raman amplifier for a 10-ns, 268-nm pulse that is injected at $E_1 \approx E_{st1}$ for the cell. This 10-ns, 268-nm pulse is then used as a pump pulse in a 1.5-m cell to produce a 1-ns, 291-nm pulse by amplifying an injected 1-ns, 291-nm pulse in similar fashion. The efficiency of a staged compressor will always be less than that of a single compressor, although, under conditions that do not permit the construction of a single-stage compressor, the multistaged compressor may be the best available solution. The increased complexity is also an undesirable feature.

Other Problems

Stimulated Brillouin Scattering. Under certain conditions, stimulated Brillouin scattering can compete with stimulated Raman scattering in gases and may increase the bandwidth of the Raman pulse

beyond the bandwidth of the amplifier. Experimental gain cross sections for Raman and Brillouin scattering in methane at 694 nm as a function of gas pressure reveal that the crossover point at which Brillouin gain exceeds Raman gain is approximately 15 atm.⁷²

The ratio of Brillouin to Raman scattering for other pump frequencies may be calculated from theoretical models for the frequency dependence of the two effects.¹¹ The stimulated Brillouin effective cross-section, σ_{eb} , varies as $\sigma_{eb} \propto \rho^2 (\partial\epsilon/\partial\rho)^2 \nu_{sb}$, where ρ is the gas density, $(\partial\epsilon/\partial\rho)$ is the change in dielectric constant with respect to density, and ν_{sb} is the Brillouin Stokes frequency and is very close to ν pump. The Raman cross section varies as $\rho\nu_{st}^2$, neglecting the energy denominators that involve the intermediate state, ν , (i.e., $\nu_e \rightarrow \infty$). For a small Raman shift, we may set $\nu_{sb} \approx \nu_p \approx \nu_{st}$ and find $\sigma_{st}/\sigma_{eb} \propto \nu/\rho$. For 249-nm excitation, σ_{st}/σ_{eb} is less than 1 for pressures approximately less than 40 atm. Thus, amplifiers at pressures less than 40 atm

Fig. 6-33. Two-stage compressor to suppress higher order Stokes waves.

and saturating at energies above about 0.02 J/cm^2 will have no serious competition from Brillouin scattering.

Brillouin competition is much worse for 1060-nm excitation, where $\sigma_{\text{sc}}/\sigma_{\text{sb}}$ equals one at approximately 9 atm. A 1060-nm pumped Raman amplifier will therefore have significant Brillouin competition for any Raman saturation energy below about 0.6 J/cm^2 corresponding to the saturation energy at 9 atm.

Anti-Stokes Generation. Direct production of stimulated anti-Stokes scattering from an excitation of the vibrational population is negligible for the devices discussed here because particle densities of 10^{20} to 10^{21} cm^{-3} are implied. The vibrational excitation densities might reach as high as approximately 10^{17} cm^{-3} for a 10- to 1-ns compressor, but this involves only a very small fraction of the population in the ground state. However, this might not be the case for a scatterer very near resonance and hence operating at a much lower particle density for the equivalent saturation energy. We have not specifically evaluated parametric generation of anti-Stokes and it no doubt requires further study. Qualitatively, it can probably be ignored under any conditions that avoid the second Stokes problems discussed earlier.

Front End

The preceding discussion has focused almost exclusively on a saturated final amplifier for a Raman compressor. The input pulses at 268 nm, 291 nm, etc., for such an amplifier stage must also be generated, however. We only present a superficial discussion here, following the argument that several potential schemes for generating the necessary pulses are available and probably are not too difficult to implement, assuming that efficiency is not a principal concern. An efficient, saturated final amplifier, on the other hand, is crucial to the success of this type of laser.

A train of short, first Stokes pulses may be generated by superfluorescent backward scattering of an intense pump source. One of these pulses may be switched out by conventional optical technology and amplified through linear amplifiers to an energy level appropriate for injection into a final amplifier. Higher order Stokes pulses may be generated as required in a very vigorously pumped superfluorescent source. Alternately, they may be generated as

first-order waves from a first or second Stokes pulse generated previously. Longer pulses (10 to 100 ns) may be generated using conventional switchout technology or by proper choice of the cell length and pump intensity of a superfluorescent Raman oscillator. In the latter case, the forward first Stokes pulse, which is typically much longer than a backward oscillator pulse, is switched out.

The behavior of superfluorescent Raman oscillators under conditions appropriate for this application is discussed in considerable detail in Ref. 63. Implementation of these sources requires careful pulse timing, especially for staged compression. Because beams split off from the pump are used to pump all amplifiers and the oscillator, pulses may be timed with optical delays synchronized off the firing of a master KrF pump. Timing by optical delays is jitter-free and comparatively straightforward. However, we shall not expend extensive effort on a detailed design until a useful final amplifier is available.

A Near-Resonant Atomic Scatterer—KrF-Pumped Calcium

Resonant Raman scattering in atomic vapors may be applicable to backward Raman pulse compression but it involves different characteristic problems than those encountered for the systems far from resonance as discussed previously.⁶⁷ Here, we consider a resonant electronic Raman process in calcium vapor which appears to be highly suitable for pulse compression.

Figure 6-34 shows an energy-level diagram with relevant parameters for KrF Raman scattering in calcium. The transition of highest quantum efficiency converts a 249-nm pump photon to Raman-scattered photon at 544 nm. There are several other possible infrared Raman transitions shown in the figure which may give rise to parasitic oscillations. The small energy defect for the Raman process implies a very large $(\partial\sigma/\partial\Omega)$ and consequently very low particle densities but still requires fairly high temperatures to produce an adequate concentration of atomic metal vapor. The low particle density permitted by the very high Raman cross sections near resonance allows a low index of refraction, compared to the high particle density required for systems far from resonance, and obviates the usual problems of medium homogeneity in a high-pressure system. On the other hand, the low particle

density implies that saturation phenomena can become much more complex because the amplifier may saturate by depletion of the atomic ground state as well as by depletion of the pump beam. For the 10^{16} density of Fig. 6-34, the saturation energy is comparable to the methane compressor discussed above and only 10 to 15% of the population is used with a 1-J/cm^2 pump. However, operation of a calcium compressor at fluences much higher than this may be very difficult.

The near resonance for the first Stokes, together with the large Stokes shift in electronic transitions, reduces the gain for higher order Stokes parasitic processes and avoids the need for staged pulse compression at compression ratios of approximately 100. This substantially simplifies the design of a compressor. However, atoms very near resonance suffer from two other characteristic problems. A close resonance for the Raman effect also implies a close resonance for multiquantum ionization, a

two-photon process in this system. If the energy defect between the pump laser and the intermediate state is so small as to be comparable to kT , the mean thermal energy, there is also a high probability of collisional transfer into the intermediate state as well as dephasing of the Stokes radiation, adding serious complexities. The calcium system is probably sufficiently far off resonance to avoid these problems,⁶⁷ but experimental results are needed to resolve these issues.

Near-resonant scattering in molecular gases may permit operation at low density and low temperature and is therefore an attractive candidate for a compressor. However, there is very little useful data available on the appropriate systems. A near-resonant system would also minimize the competition from the higher order Stokes processes discussed for methane. Multiquantum dissociation may pose a serious limitation at the high intensities found in a compressor.

Fig. 6-34. Raman scattering of KrF by atomic calcium. Here, the energy defect, $\nu_s - \nu_p$ is only $\approx 1500\text{ cm}^{-1}$.

References

62. A. J. Glass, *IEEE J. Quant. Elect.* QE3, 516 (1967).
63. G. I. Kachen, *Spatial and Temporal Characteristics of Collimated and Focused Traveling-Wave Raman Amplifiers*, Lawrence Livermore Laboratory, Rept. UCRL-51753 (1975).
64. R. L. Carman, *Phys. Rev. A* 12, 1048 (1975).
65. W. H. Lowdermilk and R. L. Carman, *Phys. Rev. Lett.* 33, 190 (1974).
66. J. R. Murray, Internal Memo AL 76-1121 (1976).
67. A. Szoke, Internal Memo AL-77-107 (1977).
68. P. Lallemand, in *The Raman Effect*, A. Anderson, Ed. (Marcel Dekker, New York, 1971), vol. I, ch. 5.
69. G. Placzek, *Rayleigh and Raman Effect*, Lawrence Livermore Laboratory, English Translation, Rept. UCRL-Trans-526(L) (1959).
70. J. Behringer and H. Brandmüller, *Zeits. Fur Elektrochem.* 60, 643 (1956).
71. W. R. L. Clements and B. P. Stoicheff, *J. Molec. Spectry.* 33, 183 (1970).
72. R. W. Minck, E. E. Hugenlocker, and W. G. Rado, *J. Appl. Phys.* 38, 2254 (1967).

Authors

J. R. Murray
A. Szoke

Major Contributor
J. Goldhar

6-7 Rare Gas Halide (RGH) Lasers

Over the past few years, several new lasers that emit in the visible and near ultraviolet region of the spectrum have been discovered. These include the rare gas excimers,⁷³ the dihalogens,⁷⁴ and most recently, the rare gas halides.⁷⁵ In Fig. 6-35, the emission spectra of these molecules illustrate the wide range of wavelengths that have been observed in fluorescence and laser emission. The rare gas halogens are of particular importance because of their potential for efficient excitation by a wide range of techniques. The basic mechanisms responsible for laser action in the rare gas halides are now reasonably well documented; however, many details affecting scaling and device performance remain to be resolved.

This year, we have investigated the mechanisms responsible for excitation and laser emission in these rare gas halide (RGH) molecules. We have measured the fluorescence spectra of these molecules using a high-current-density electron beam system (MEG I) as the pumping source. In

Fig. 6-35. Fluorescence spectra of the rare gas excimers and rare gas halides. The circles denote those systems and transitions for which stimulated emission has been observed.

conjunction with theoretical calculations, this work has led to the identification of the major emission features of their spectra as well as to an improved understanding of the energy-level structure of RGH molecules.

The MEG I pumping source was also used to study the parametric variation of laser output in ArF and KrF with buffer gas and total pressure. Efficiencies of 5 to 7% were observed under optimal conditions. In addition, we were able to demonstrate laser action in KrCl for the first time.

We constructed a small pulsed electron beam source to study electron-beam sustainer pumping of RGH lasers. This source was also used to measure the gain and electrical discharge characteristics in the KrF laser. Gains up to 12%/cm were observed at input power densities of 1.5 MW/cm² to the discharge. Studies of the electrical characteristics of the discharge revealed that the primary variation of laser output with gas mixture arises from changes in the impedance matching of the discharge to the external circuit.

We also built several UV preionized discharge lasers that were used as probe lasers and as sources

for investigating the tunability of RGH lasers. With intercavity etalons, tuning across the 20-cm^{-1} wide, 353-nm XeF band was demonstrated with a resolution of approximately 2 cm^{-1} .

In addition to this experimental program, we have addressed a wide range of theoretical issues. *Ab initio* calculations were carried out for KrF, KrCl, ArF, ArCl, and other RGH molecules. A computer model was also constructed to compare the theoretical and experimental data. Comparisons of the calculated emission spectrum and radiative lifetimes have enabled us to delineate differences among the various laser molecules.

Kinetics of RGH Molecules

The excited states of the rare gas halides are predominately ionic in character and show a strong similarity to the excited states of the alkali halides. A potential energy diagram for XeF, typical of all RGH molecules, is shown in Fig. 6-36. The lowest lying excited states can be correlated at infinite internuclear separation with $\text{Xe}^+ + \text{F}^-$. As these particles approach one another they attract along a

very long range coulomb curve that crosses curves associated with the excited states of both xenon and fluorine. These curve crossings provide an efficient collisional channeling of the energy residing in the excited-state manifolds into the lowest-lying molecular excited states (i.e., the $^2\Sigma^+_{1/2}$ state).

The ground states are split into Σ and Π branches. The $^2\Pi_{1/2,3/2}$ is repulsive in character (unbound) whereas the $^2\Sigma_{1/2}$ exhibits a binding, the magnitude of which depends on the species under consideration. For example, the $^2\Sigma_{1/2}$ ground state is unbound or only slightly bound in XeI but more strongly bound in XeF. The radiation emitted, therefore, may have a bound-bound as well as a bound-free spectral character. In the xenon halides, laser emission occurs predominantly between bound states. The emission spectra consist of a multitude of lines from various rotational-vibrational transitions. In contrast, the laser emission spectra in the krypton and argon halides are predominantly bound-free and continuous.

The excited states of the rare gas halides can be formed by several different processes. For example, in XeF, one important process is three-body recombination,

Fig. 6-36. Estimated potential energy curves for xenon fluoride.

where M is a buffer gas molecule. The effective two-body rates for this reaction can be as large as $1 \times 10^{-6} \text{ cm}^3/\text{s}$ at gas pressures between 0.5 and 2 atm. Under suitable conditions, two-body recombination,

may also contribute.

A second excitation process is the reaction,

This reaction proceeds rapidly with a high yield of excited rare-gas halides. In cases where a rare gas halide is excited in a gas mixture with rare gas buffers, the transfer reaction,

is a possible production mechanism. The ArF^* is formed by the primary reactions outlined above. In any particular situation, all of these reactions may be contributing to the buildup of the excited-state population of the RGHS.

The primary loss processes for the RGH upper states are radiative decay and collisional deactivation. The radiative lifetimes are short, ranging from 10 nsec in XeF to a few nanoseconds in ArF. At pressures around 1 atm, collisional deactivation by the rare gases is not particularly effective on this time scale. Fluorine, however, can deactivate the excited states in the pressure range of a few tens of Torr.⁷⁶ Collisions between excited-state molecules have been hypothesized as another loss mechanism but have not yet been observed.

Two collisional loss processes for Xe^* are especially important: the excited-state/excited-state collisions

and the two-step ionization

Reaction (16) is a Penning ionization process and cross sections of approximately 10^{-14} cm^2 are probable. Reaction (17) involves the ionization (or excitation) of the excited state as a result of interactions with the cold background plasma. This is a well-known phenomenon in gaseous discharges and cross sections as large as about 10^{-15} cm^2 are possible.

This two-step ionization is of utmost importance in determining the performance characteristics of electron-beam sustainers and simple electrical discharge excitation schemes. It has been both experimentally and theoretically demonstrated that this reaction substantially limits the effective use of a sustainer discharge to augment the electron-beam pumped xenon excimer system. Roughly speaking, these two reactions indicate that to produce Xe^* at high efficiencies, Xe^* will have to be approximately less than 10^{15} cm^{-3} . In addition, these processes will be important for producing XeF^* and will probably have similarly large cross section values.

The rare gas halide lasers can be excited by a wide range of electrical techniques. The laser is often pumped by direct electron-beam excitation. Excited states are produced predominantly by ion recombination. The secondary electrons produced by the high-energy electron beam are rapidly converted to negative ions by dissociative attachment,

This process proceeds at a rate approximately greater than $10^{-9} \text{ cm}^3/\text{s}$ for low-energy electrons. Additional energy can be added to the discharge if the electrons are heated to the volume excited by the electron beam by application of either a drift-electric field or by a "sustainer" field. At sufficiently low electron-beam-power inputs, the sustainer power input can dominate. The RGH laser can also be excited by short-pulse discharge techniques. In this case, the ionization is produced by volume processes that are driven by the drift field itself.

Electron Beam Excitation Studies

High-energy electron beams are an effective pump source for exciting a wide variety of laser processes, particularly those involving ion channels. Thus, we have carried out a wide range of studies of RGH excitation and lasing processes this year, using the MEG I electron-beam pumping facility.

The electron-beam gun of this facility supplies approximately 750 J of energy in electrons at 600 keV through a stainless steel foil (2 by 10 cm) in 50 ns. The electron-beam energy that is incident on the gas can be decreased by inserting attenuators into a beam drift chamber located between the electron-beam source and the foil. These attenuators are carbon plates that have been drilled with hole patterns to transmit a fraction of the electron-beam current without changing the beam voltage.

This source has been used for fluorescence and laser performance studies of KrF, KrCl, and ArF. We were able to demonstrate laser emission in KrCl for the first time with this system. In addition, the ArF laser output was used for studies of an optically pumped iodine laser.

A spectrum of KrCl fluorescence from a gas mixture of 3350-Torr argon, 100-Torr krypton, and 5-Torr chlorine at maximum beam current is shown in Fig. 6-37. A KrF fluorescence spectrum at the same rare-gas pressures with NF₃ substituted for chlorine and excited by one fourth the maximum current is also given. The spectra were recorded on a 0.5-m grating spectrograph with 0.1-nm resolution using Kodak 101-01 film. The intensity calibration was obtained by overlaying two fluorescence spectra of equal intensity to determine the film-density increment corresponding to a twofold increase in exposure. No corrections were made for wavelength variation of film, grating response, or intermittency effects on the exposure.

The wavelength scale is determined by referring to several HgI lines lying between 184 and 254 nm. The main bands of KrF at 249 nm and KrCl at 222 nm have been identified³ as $^2\Sigma^+_{1/2} - ^2\Sigma^+_{1/2}$ transitions between an ionic upper state (Kr^+F^- or Kr^+Cl^-) and a nearly flat lower curve.

Ab initio calculations of KrF potentials have predicted a $^2\Pi_{1/2}$ ionic state lying above this state at an energy given by the $^2P_{1/2} - ^2P_{3/2}$ spin-orbit splitting of the krypton ion.⁷⁷ The energy splitting of the secondary transitions at 199 nm in KrCl and at 220 nm in KrF from their main bands, 5210 and

Fig. 6-37. Density scans of film spectra produced by electron-beam-excited mixtures of argon, krypton, and NF₃ (a) or Cl₂ (b).

5290 cm⁻¹ respectively, compare well with the spin-orbit splitting of Kr⁺, 5371 cm⁻¹. Hence, these transitions are identified as $^2\Pi_{1/2} - ^2\Sigma^+_{1/2}$ with the same lower state as the main bands. Such secondary transitions appear to be quite common in the rare gas halides, occurring at 264 nm in XeF and at 236 nm in XeCl with energy splitting from the main band appropriate to Xe⁺. Although their gain is greatly reduced from the main bands, these secondary transitions are also potential laser candidates.

Other experimenters also have identified the $^2\Pi_{1/2} - ^2\Sigma^+_{1/2}$ bands.^{78,79} The $^2\Pi_{1/2}$ state appears to be collisionally quenched under electron-free conditions. Its appearance in our spectra suggests that there may be a strong coupling of the ionic states via inelastic electron processes, tending to equilibrate the $^2\Pi_{1/2}$ populations to the electron temperature.

The identification of the upper and lower states of the broad-band transition at 275 nm in KrF as well as at 235 and 272 nm in KrCl is discussed in a following section on theoretical calculations. The transition at 193 nm in Fig. 6-37 is the ArF $^2\Sigma_{1/2}^+ - ^2\Sigma_{1/2}^+$ band while the transition at 257 nm is a chlorine band.⁸⁰

The KrCl laser output with the above gas mixture and using mirrors of 42% and 99% reflectance at 222 nm is a single peak centered at 222.1 ± 0.1 nm. It has a resolvable width of approximately 0.3 nm (see Fig. 6-38). Figure 6-39 shows the time dependence of KrCl laser output and fluorescence for these conditions. The detector is an ITT F 4115 CsTe photodiode with a 230 ± 10 -nm bandpass filter. The laser pulse energy transmitted by the 42% mirror is 50 mJ, as detected by a thermopile calorimeter.

The laser is delayed by about 20 ns from the rise of the fluorescence and terminates before the end of the fluorescence pulse. The 4115 photodiode, located 75 cm from the laser cell, has a geometric collection efficiency approximately 10^{-4} of the total fluorescence power. Laser threshold is presumed when the stimulated emission into this solid angle exceeds the fluorescence transmitted through the high-reflectivity mirror. With mirrors of 92% and 78% reflectivity, the KrCl laser threshold is slightly less than three-eighths of the maximum current.

The KrCl fluorescence rise is coincident with the excitation pulse and it falls before the end of the excitation pulse at maximum beam current. The peak

Fig. 6-38. Density scans of film spectra showing the distribution in wavelength of the KrCl laser output (lower curve) with respect to the KrCl fluorescence (upper curve). Both curves have been normalized.

Fig. 6-39. Time dependence of KrF and KrCl fluorescence and laser emission (time axis = 50 ns/div).

fluorescence intensity is proportional to the electron-beam current over the range from one-sixteenth to full current. The fluorescence tracks the excitation pulse more closely at lower beam currents but always shows an extended tail. The dependence of laser and fluorescence intensities on gas partial pressures has not been fully explored yet but is known to be similar to that reported for other rare gas halides.

The performance of the KrCl laser is comparable to the performance of KrF under similar conditions (see Fig. 6-39). For a gas mixture of 3350 Torr argon, 100 Torr krypton, and 5 Torr NF_3 , and with mirrors of 90% and 54% reflectance at 249 nm, the laser pulse energy transmitted by the 54% mirror is 600 mJ at maximum beam current. The laser pulse tracks the fluorescence with a short delay. Laser threshold occurs at three-sixteenths of the maximum beam current, using two mirrors of 90% reflectance. The fluorescence from the 249-nm KrF band is approximately twice as intense as the fluorescence from the 222-nm KrCl band. This agrees well with the ratio of laser thresholds. The 249-nm KrF fluorescence intensity is linear with beam current from one-sixteenth to one-half maximum beam current and shows some superfluorescence along the long axis of the cell at maximum current. However, the KrF fluorescence tracks the excitation pulse unlike the KrCl fluorescence.

It is not clear from our measurements to date whether the lower output energy in KrCl compared to KrF suggests less favorable kinetics for KrCl formation, more serious intrinsic optical losses in the KrCl system, or an insufficient gain-time product to reach an intensity that can saturate the laser output and overcome nonradiative losses. The delay of the KrCl laser with respect to fluorescence and the failure of KrCl laser output to track the fluorescence suggests that the laser may not be fully saturated. The difference in the time dependence KrCl and KrF fluorescence also suggests differences either in radiative lifetimes or in formation kinetics.

We have also investigated the $\text{ArF } ^2\Sigma \rightarrow ^2\Sigma$ laser¹⁶ in this apparatus. For these experiments, one external 96% reflecting laser mirror was aligned with the perpendicular end windows of the cell. Superfluorescent energy output was obtained on this very-high-gain transition under these conditions in gas mixtures of fluorine, argon, and neon. In other rare gas halide lasers (e.g., KrF), optimum performance is observed when the krypton is present at about 100- to 200-Torr pressure and the electron energy is stopped in the argon.

Analogous behavior was observed in ArF and the best performance was found using neon rather than argon as the majority gas. This behavior may be caused by the suppression of Ar_2^+ formation which, at high argon pressures, competes with the presumed $\text{Ar}^* + \text{F}_2 \rightarrow \text{ArF}^*$ production mechanism for the upper state. Other investigators have suggested this same phenomenon to explain similar results observed in KrF and xenon halides.

To illustrate some other effects of neon on rare gas halide lasers, Fig. 6-40 compares the superfluorescent laser output from KrF with the electron energy stopped in either argon or neon, using an arrangement similar to that designed for the ArF experiments. High argon pressures suppress laser oscillation whereas high neon pressures do not. The output energy saturates at a value that is proportional to the fluorine pressure up to 20-Torr F_2 ; however, this saturation value does not rise beyond this pressure. At low stopping power ($\rho Z = 320$ amagat), the peak laser intensity is higher by the ratio of the pumping rates. In addition, the pulse length is proportionally smaller, resulting in an approximately constant energy pulse.

Fig. 6-40. Superfluorescent laser output of ArF (left) and KrF (right) as a function of gas mixture with respect to stopping power (ρZ) and energy deposited in the laser volume. Shown also are the corresponding densities (in amagats) of neon (ρ_{Ne}) and argon (ρ_{Ar}) appropriate to the stopping power.

Fig. 6-41. Iodine singlet fluorescence excited by an ArF laser at 336 K (I_2 pressure = 5 Torr). The peak at 249 nm is KrF background fluorescence from a krypton impurity in the ArF cell.

The ArF laser shows a similar trend as the neon pressure is varied. This behavior suggests that a kinetic step in the KrF production requires the presence of molecular fluorine and that KrF production ceases when the fluorine concentration is depleted. The importance of reaction channels such as $Kr^* + F_2 \rightarrow KrF + F$, or even perhaps $F_2 + e \rightarrow F + F$, followed by $Kr^+ + F + M \rightarrow KrF + M$ is indicated. In fact, these reaction channels are preferred over other postulated mechanisms in which atomic fluorine is recycled several times through KrF during a pulse.

Fluorine concentrations greater than 20 Torr may cause significant absorption of KrF radiation or collisional quenching of KrF that competes with laser extraction. The suppression of laser oscillation by high argon pressures may result from absorption in Ar_2^+ , for example, or in kinetic differences between argon- and neon-dominated mixtures. These mixtures also differ in fluorescence intensities of the identified KrF transitions. In addition, several unidentified broad bands at longer wavelength are seen from KrF. The superfluorescence of ArF lasers is a convenient source for studies of conversion of the RGH laser output to other wavelengths.

Tellinghuisen⁸¹ has suggested optical pumping of the diffuse iodine singlet McLennan bands and other transitions as an interesting candidate for a tunable "dye laser" for the middle ultraviolet region. Figure 6-41 shows the iodine fluorescence as excited by an ArF laser, suggesting that optical pumping of iodine may be an interesting application for the ArF laser. It may even allow an extension of the range of operation of intense tunable sources in the ultraviolet range. We must also note that an iodine laser avoids the photochemical instability of

short wavelength dyes. The calculated⁸¹ gain cross section of $3 \times 10^{-17} \text{ cm}^2$ near 320 nm, together with the measured⁸² absorption cross section of 10^{-17} cm^2 at 193 nm indicate that, even though both cross sections are ten times smaller than typical organic dyes, laser oscillation should be feasible with reasonable cell dimensions.

Discharge Excitation Studies

Rare gas halide lasers can also be excited by discharge techniques; energy input to the gas results from electron drift in an applied electric field. We have observed laser output from both UV preionized discharges⁸³ and electron-beam sustained discharges similar to those used for CO_2 laser excitation.⁸⁴ The discharge lasers have the potential to operate at high-repetition rates and high average powers.

During 1976, we constructed a small electron beam system to study the kinetics of electron-beam-sustained and discharge-pumped RGH lasers. A diagram of the electron beam and discharge construction is shown in Fig. 6-42. A commercial gun modified to supply a higher beam-current density served as the electron beam source. The diode was driven directly by a 250-kV Marx bank. The output impedance of the pulsed power supply was adjusted with tuned circuits in series with the diode to give a nominally flat-topped beam current pulse with a risetime of 20 ns and a width of 110 ns (window area measured 2 by 40 cm). Beam-current densities between 2 and 15 A/cm^2 were obtained by varying the anode-cathode spacing of the diode.

Fig. 6-42. Diagram of pulsed electron beam source used for electron-beam sustained discharge studies.

The discharge chamber was constructed of Teflon. The sustainer electrodes were cut to a semi-Rogowski profile. The cathode was made of screen to allow the electron beam to penetrate; the electrode gap of 2.7 cm. The sustainer power supply consisted of capacitors, arranged near the electrodes to give a low-inductance current loop. Voltages of up to 30 kV could be applied to the electrodes.

We used this system to study the correlation of laser output with the electrical characteristics of the discharge. These studies concentrated on KrF. The principal diagnostic (Fig. 6-43) was the measurement of small signal gain. The probe laser was a small discharge KrF laser with an output of approximately 1 mJ and a 10-ns FWHM. The output of this laser was timed with respect to the electron-beam sustainer system so that the probe beam could be adjusted to any time during the discharge pulse. We also monitored side fluorescence.

We determined the characteristics of the external sustainer driving circuits that affect laser performance. The most important parameter was found to be the inductance of the external circuit (see Fig. 6-44). The characteristic risetime of the sustainer current density, $\tau_r \approx \sqrt{LC}$, was adjusted to approximately 150 ns, substantially longer than the 110-ns duration of the electron beam pulse. The voltage across the electrodes was measured with a resistive

divider and corrected for inductive effects. The discharge voltage was nominally constant during the duration of the electron beam pulse. At the end of the pulse, the voltage collapsed because of the onset of an arc.

The power input to the discharge was calculated from the voltage and current waveforms [see Fig. 6-44(b)]. The gain generally follows the power input to the discharge, suggesting that the laser-excitation kinetics involve a quasi-steady state on a time scale of tens of nanoseconds. Therefore, substantial improvement in laser performance is expected if the power input is increased during the electron beam pulse time by reducing the external inductance.

This improvement is shown in Figs. 6-44(c) and (d). The characteristic current risetime is reduced to about 40 ns. The gain does follow the input power but it now rises rapidly and is maintained at high values throughout the pulse. Under suitable conditions, the energy stored in the capacitor can be dissipated during the discharge pulse and no arcing is observed when the electron beam pulse is terminated.

We also determined the electrical characteristics of the electron-beam sustained discharge (see Fig. 6-45). At low applied voltages, the discharge conductivity is dominated by the equilibrium between electron production by the beam and loss of electrons

by attachment. The discharge conductivity is low and low values of discharge current are observed. Above some applied voltage threshold, the discharge current rises linearly with excess voltage. This behavior is characteristic of discharge operation in a regime of volume ionization where the voltage across the discharges remain constant both temporally and as a function of current density. However, the detailed mechanisms responsible for this transition to constant field-volume ionization have not yet been resolved.

We expect the power input to the discharge to display similar characteristics. Because the voltage is constant, the discharge power input should be linear above threshold. For a constant efficiency excitation process, the gain peak-power input should follow the power input. Figure 6-46 shows this variation of gain in KrF as a function of power input from both the electron beam and discharge. The gain follows the total power input. At low discharge voltages, the gain is predominantly a result of the electron beam power input whereas at high applied voltages, the gain follows the discharge power input.

This general behavior is observed over a wide range of gas mixtures. We observed gains of up to 12%/cm at input power densities of 1.5 MW/cm³ for a mixture of 1000:100:10 Torr, Ar:Kr:F₂. The power input to the discharge is a strong function of the fluorine concentration. Much of the gross variation of gain can be attributed to changes in the matching of the discharge impedance to that of the external circuit. Weaker variations were observed with changes in electron beam current density and buffer gas concentration.

The fluorescence efficiency, η_F , of the laser in the discharge-pumped regime can be estimated from the measurements of the small signal gain,

$$\eta_F P_T = h\nu \frac{G}{\sigma_s \tau_r},$$

where P_T is the power input, $h\nu$ is the photon energy, G is the gain, σ_s is the stimulated emission cross section, and τ_r is the KrF lifetime. The product $\sigma_s \tau_r$ can be estimated from the KrF

Fig. 6-43. Experimental system used for measurements of KrF gain in an electron beam sustainer discharge. A small T laser shown on the right was used as the source of the KrF probe signal.

Fig. 6-44. Electrical characteristics and gain of a KrF electron beam sustained discharge laser for two sustainer source inductances. Duration of the electron beam pulse is 110 ns. In the high-inductance case (a,c), the electron beam pulse terminates before maximum power density is reached. In the low-inductance case (b,d), the external circuit is matched to the duration of the electron beam pulse and improved performance is observed.

fluorescence linewidth. A value of $\sigma_r \tau_r = 2 \times 10^{-24} \text{ cm}^2 \text{ s}$ gives $\eta_F \approx 3\%$; this is approximately half the efficiency observed under optimum conditions in electron beam pumping.

RGH Laser Tuning Studies

The emission bandwidth of the RGH laser molecules is relatively broad. Therefore, some degree of tunability should be possible with these lasers. The bound-free emitters such as KrF and ArF emit in a continuum over a bandwidth of approximately 200 cm^{-1} . The bound-bound emitters such as XeF emit in several bands about 20 cm^{-1} wide on individual rotational-vibrational transitions.

Efficient extraction on a narrow bandwidth requires rapid vibrational and rotational cross relaxation in the laser molecule. The short radiative lifetime of the RGH molecules ($\tau_r \approx 15 \text{ ns}$) and the short pulse excitation that is typical of discharge lasers makes these cross-relaxation requirements particularly severe. We have begun experiments to investigate these processes and their effect on the tunability of RGH lasers. To date, we have been able to demonstrate tuning of XeF with a resolution of 2 cm^{-1} in using intercavity etalons.

The output spectrum of the XeF laser has two main emission bands at 351 and 353 nm. The spectrum within each band is a multitude of transitions between various rotational states of the upper and lower laser states. Selective tuning of XeF requires the suppression of competing transitions in other vibrational bands plus a narrow-band cavity for tuning within one vibrational band. This can be accomplished with intercavity etalons, prisms, or a combination of the two.

The experimental system used in these studies is shown in Fig. 6-47. The active medium was a 1-m-long discharge laser. The energy output of this laser was a few tens of millijoules in the absence of intercavity etalons; the pulse length was 20 ns. Emission on the 351 or 353-nm band was selected with the 5- μm thick etalon. Tuning within each band was accomplished with the 100- μm etalon (bandwidth $\approx 2 \text{ cm}^{-1}$). The output was viewed with an integrating silicon photodiode array attached to a 1-m spectrometer operating in fourth order. We were able to obtain spectral resolutions of 0.2 cm^{-1} with this combination.

Fig. 6-45. Sustainer voltage-current characteristics of the electron beam discharge laser. The gas mixture was argon, krypton, and fluorine at respective pressures of 10, 100, and 800 Torr. The electron beam current density was 16 A/cm^2 . At low-charge voltages, the discharge impedance is determined by the electron beam alone. At higher voltages above a threshold, V_T , the discharge operates in avalanche mode in which the discharge impedance is determined by the external electrical circuits.

Fig. 6-46. Variation of gain and input power density in the KrF discharge laser. The input power density is the sum of components from the electron beam and from the sustainer discharge. The gain exhibits a similar variation and is proportional to the total power input over a wide range of parameters.

The tuning characteristics of the XeF laser are shown in Figs. 6-47 and 6-48. With the 5- μm etalon alone, the 351- or 353-nm band can be selected. The energy output on either band was approximately 1 mJ. With the insertion of the 100 μm etalon, the peak output decreased slightly and the line width narrowed.

Tuning in the 351-nm band was not continuous (see Fig. 6-47). The spectrum in this band consists of three prominent lines with weaker emission on their wings. We could select any one of these lines but only marginal enhancement of the emission between the lines was possible. The line width of these prominent features was narrower than that of the etalon. Similar energy output was obtained on any of the three lines. However, tuning in the 353-nm band displayed different characteristics. The bandwidth of the tuned emission was determined by the etalon and continuous tuning across the 353-nm band was possible.

The peak amplitude followed the envelope of the output (measured without the 100- μm etalon). This suggests that the various features of the spectrum are not coupled. However, the losses introduced by the etalons to suppress the 351-nm emission were sufficiently large that none of the lines in the 353-nm band reached saturation during the excitation pulse. Therefore, the laser was operating in a super-fluorescent mode rather than in a saturated laser mode.

Theoretical Studies

The potential energy curves for several RGH molecules have been calculated to identify features in the emission spectra and to estimate radiative lifetimes for the excited states. We have studied

Fig. 6-47. Apparatus and results of experiments demonstrating narrow-bandwidth output from an XeF laser. The laser is tuned by the insertion of two etalons into the optical cavity—a 5- μm etalon to select one vibrational band and a 100- μm etalon to tune within the band. The upper oscillograph shows the laser output on the 351-nm band without etalons and the lower oscillograph shows the output with both etalons inserted.

ArF, ArCl, and KrCl molecules. This work, combined with the previous work of Dunning and Hay,⁷⁷ allows a comparison of the fluorides and chlorides of both argon and krypton.

The potential curves for KrCl (plotted in Fig. 6-49) are typical of all the rare gas halide molecules. Because of the increased size of the chloride ion, the excited states for the chlorides have a larger equilibrium internuclear separation than do the fluorides. Also, the larger spin-orbit interaction for chlorine causes a slightly larger splitting between the lower covalent curves. However, as shown in Tables 6-9 and 6-10, the calculated lifetimes for the fluoride and chloride main bands are quite similar. The fluorides have a somewhat larger transition moment but this is compensated by the shorter wavelength for the chloride transitions.

Tables 6-9 and 6-10 also compare the calculated and experimental wavelengths for the emission features. In each case, the calculated values are smaller than the experimental results. When determining the excited state curves, the two major sources of error are the electron affinity of the halogen and the ionization potential of the rare gas. In general, good calculations can only account for half the halogen electron affinity; usually, the errors tend to cancel out and are essentially constant along the potential curve for each state. Therefore, if we know the experimental wavelength for one transition (usually the main band, $B^2\Sigma_{1/2} \rightarrow X^2\Sigma_{1/2}$) the curves can be adjusted and we can accurately predict the remaining transitions.

For KrCl, the features at 222 and 199 nm are obviously the result of the $B^2\Sigma_{1/2} \rightarrow X^2\Sigma_{1/2}$ and $D^2\Pi_{1/2} \rightarrow X^2\Sigma_{1/2}$ transitions. Shifting our calculated wavelengths by 8 nm (the error in the $B \rightarrow X$ transition), we predict transitions at 208 nm, 228 nm, and 234 nm. The KrCl spectrum in Fig. 6-37 does show a feature at about 235 nm, in agreement with the shifted $B^2\Sigma_{1/2} \rightarrow A^2\Pi_{1/2}$ transition. The contribution from the $C^2\Pi_{3/2} \rightarrow A^2\Pi_{1/2}$ transition at 228 nm may underlie this feature; however, its relative intensity depends on the relative populations in the $B^2\Sigma_{1/2}$ and $C^2\Pi_{3/2}$ states.

The weak broad feature at approximately 272 nm cannot be explained on the basis of the calculated KrCl transitions. Because of the smaller spin-orbit interaction in the upper states of ArF and ArCl, the transition energies are all much closer to the main emission feature. With the exception of the $D^2\Pi_{1/2} \rightarrow X^2\Sigma_{1/2}$ transition at 169 nm in ArCl, it is difficult

Fig. 6-48. Tuning in the 353-n band of XeF.

to compare the weaker transitions with experiment.

The shifted theoretical values for the emission wavelengths should give a very good estimate of their position. For ArF with the 190-nm transition as a calibration, the remaining features for ArF are predicted at 182, 192, 195, and 201 nm. These are all obscured by the main emission band (a similar situation exists for ArCl).

Fig. 6-49. Calculated potential energy curves for KrCl.

Table 6-9. Comparison of ArF and ArCl emission features

Transition	ArF ^a			ArCl ^b		
	λ calc, nm	λ exp, nm ^c	τ calc, ns	λ calc, nm	λ exp, nm ^d	τ calc, ns
$B^2\Sigma_{1/2} \rightarrow X^2\Sigma_{1/2}$	183	190	3.6	173	175	4.4
$D^2\Pi_{1/2} \rightarrow X^2\Sigma_{1/2}$	175	—	34	167	169	19
$C^2\Pi_{3/2} \rightarrow A^2\Pi_{3/2}$	188	—	53	175	—	79
$D^2\Pi_{1/2} \rightarrow A^2\Pi_{1/2}$	185	—	64	174	—	223
$B^2\Sigma_{1/2} \rightarrow A^2\Pi_{1/2}$	194	—	227	180	—	62

^aEvaluated at $R = (4.5)a_0$.

^bEvaluated at $R = (5.5)a_0$.

^cReference 85.

^dReference 86.

Table 6-10. Comparison of KrF and KrCl emission features

Transition	KrF			KrCl		
	λ calc, nm ^a	λ exp, nm ^b	τ calc, ns ^a	λ calc, nm	λ exp, nm ^b	τ calc, ns
$B^2\Sigma_{1/2} \rightarrow X^2\Sigma_{1/2}$	239	248	7	214	222	6.4
$D^2\Pi_{1/2} \rightarrow X^2\Sigma_{1/2}$	211	220	13	191	199	11
$C^2\Pi_{3/2} \rightarrow A^2\Pi_{3/2}$	264	275	75	220	—	87
$D^2\Pi_{1/2} \rightarrow A^2\Pi_{1/2}$	228	236	96	200	—	278
$B^2\Sigma_{1/2} \rightarrow A^2\Pi_{1/2}$	259	—	180	226	—	77

^aReference 77.^bReference 87.

Summary

The research conducted this year has significantly improved our understanding of the excitation of rare gas halide lasers. Measurements of fluorescence spectra excited by high-energy electron beams have been used in conjunction with theoretical calculations to document the energy levels responsible for the laser emission. Laser emission was observed for the first time in KrCl during the course of these studies. In studies of discharge-excited lasers, the electrical characteristics of the external circuit elements have been demonstrated to play a significant role in the laser performance. Gains of up to 0.12/cm and efficiencies of approximately 5% have been observed with both electron beam and discharge pumping.

These results suggest that rare gas halide lasers will prove to be useful in several fusion related applications. In addition, these lasers can be efficiently excited by several electrical techniques. Operation at output energies of a few kilojoules or greater seems feasible. The laser outputs are in the ultraviolet region of the spectrum. These characteristics make rare gas halide lasers particularly suitable for applications such as optical pumping of new laser media. The development of a new laser system based on this technique will have a major impact on future laser fusion systems.

References

73. C. W. Werner, E. V. George, P. W. Hoff, and C. K. Rhodes, *Appl. Phys. Lett.* **25**, 235 (1974); C. W. Werner, E. V. George, P. W. Hoff, and C. K. Rhodes, *Radiative and*

Kinetics Mechanisms in Bound-Free Excimer Lasers, Lawrence Livermore Laboratory, Rept. UCRL-77412 (1976); D. C. Lorents, *Physics T2C*, 19 (1976).

74. J. J. Ewing and C. A. Brau, *Appl. Phys. Lett.* **27**, 363 (1975); J. R. Murray, J. C. Swingle, and C. E. Turner, *Appl. Phys. Lett.* **28**, 530 (1976); *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976), p. 513.
75. C. A. Brau and J. J. Ewing, *Appl. Phys. Lett.* **27**, 435 (1975); C. A. Brau and J. J. Ewing, *J. Chem. Phys.* **63**, 4640 (1975).
76. J. J. Ewing and C. A. Brau, *Appl. Phys. Lett.* **27**, 350 (1975).
77. T. H. Dunning and P. J. Hay, *Appl. Phys. Lett.* **28**, 649 (1976).
78. J. E. Velazco, J. H. Hotz, and D. W. Setser, *J. Chem. Phys.* **65**, 3468 (1976).
79. S. K. Searles (private communications). S. K. Searles has also communicated independent observation of KrCl laser oscillation.
80. C. H. Chen and M. G. Paynes, *Appl. Phys. Lett.* **28**, 219 (1976).
81. J. Tellinghuisen, *Chem. Phys. Lett.* **29**, 359 (1974).
82. J. A. Myer and J. A. R. Samson, *J. Chem. Phys.* **52**, 716 (1970).
83. R. Burnham, F. Y. Powell, and N. Djieu, *Appl. Phys. Lett.* **29**, 30 (1976).
84. J. H. Jacobs and J. A. Mangano, *Appl. Phys. Lett.* **28**, 724 (1976).
85. M. F. Golde, *J. Mol. Spect.* **58**, 261 (1975).
86. L. A. Gundel, D. W. Setser, M. A. Clyne, J. A. Coxon, and W. Nip, *J. Chem. Phys.*, to be published (1977).
87. J. R. Murray and H. T. Powell, *Appl. Phys. Lett.* **29**, 252 (1976).

Authors

L. D. Pleasance
N. W. Winter

Major Contributors

J. Goldfar
J. R. Murray
H. T. Powell
L. Bradley
C. V. Duncan

6-8 Developments in Theoretical and Computational Methods

Reviews of our wide-ranging activities in advanced quantum electronics have revealed many collisional phenomena that cannot be investigated directly. These phenomena are often studied by means of theoretical computational models. This year, because of the growing urgency of questions about collisional phenomena, our Theoretical Atomic and Molecular Physics (TAMP) group has pressed to expand its broad-based modeling capabilities by developing new codes, upgrading and modifying existing codes, and importing some that were developed elsewhere. In some areas supporting theories have not been developed; we are now pursuing long-range fundamental research activities to address such needs. The studies and developments reported here, spanning 1976, augment those described in last year's Annual Report.⁸⁸

Atomic and Molecular Structure

Two codes developed elsewhere were installed, tested, and implemented at Livermore. Part of the EOM code, developed at California Institute of Technology by McKoy and coworkers,⁸⁹ is now operational. The random-phase, Tam-Dancoff, and higher-order random-phase approximations have been installed. EOM has been interfaced to the POLYATOM and SCREEPER codes and has been used successfully in calculations involving electron scattering, potential energy surfaces, and photoionization. A model potential code originally developed by Kahn has been installed. This program evaluates the integrals in a Gaussian-basis set for the potential function

$$V(\vec{r}) = \sum_k u_k(r) |k\rangle\langle k| \quad (18)$$

where

$$u_k(r) = \sum_i c_i r^{-n_i} e^{-\alpha_i r^2}$$

The function $u_k(r)$ is a general expansion and can be used to represent the effects of the atomic core electrons in a molecular calculation. During the past year the code has been run as a stand-alone program, but it is now being incorporated into the POLYATOM molecular integral program. This code will be used in studies including heavy atoms (lanthanides and actinides).

To establish a collection of codes for a variety of calculations on atoms, we have initiated major modifications and extensions of Schaefer's atomic configuration interaction (CI) code.⁹⁰ When completed, the package will provide:

- Energies of ground and excited states of neutral atoms and positive ions.
- Transition energies and oscillator strengths for bound-bound transitions in atoms.
- Energies and total decay lifetimes of autoionizing states of neutral atoms and of autodetaching states of negative ions.
- Wavefunctions and transition moments required for the calculation of photoionization cross sections using the Stieltjes imaging technique.⁹¹
- Matrix elements required for the calculation of electric dipole polarizabilities of atomic excited states.

In 1976, several changes in ATOMCI, the atomic CI code, were implemented. A new version of the data handling section was installed to increase program speed eightfold. The code now contains a new matrix diagonalization routine that can calculate energies and wavefunctions for up to 30 excited states of a given symmetry. The code's overall size was increased substantially so it could treat highly excited (Rydberg) states, as well as autoionizing and autodetaching states. It now handles primitive basis sets containing up to 16s, 16p, 12d, and 6f Slater-type orbitals. The maximum number of Slater determinants is 2000; the maximum number of configurations, which are LS eigenfunctions, is 400. The present version of the code can handle any atom or ion with up to 22 electrons without the use of pseudopotentials.

We have completed and successfully tested a new code that computes dipole transition moments between atomic states described by CI wavefunctions.

This code, NEWPROP, calculates both the "length" and the "velocity" form of the transition moment and provides the corresponding oscillator strengths for bound-bound transitions. It also provides a pseudospectrum for use in the Stieltjes imaging of photoionization cross sections.

Improvements were incorporated into CLEMENTI, a modified version of an atomic Hartree-Fock code developed by Clementi.⁹² The version operational at Livermore will now handle Slater-type orbitals and Cartesian-Gaussian (uncontracted and contracted) type orbitals. Basis-set optimization techniques were extensively modified, since the main application of CLEMENTI is basis-set determination for subsequent larger atomic or molecular *ab initio* calculations.

Significant changes, modifications, and additions were incorporated into the SCREEPER code, which is now capable of automatically generating complex potential energy surfaces and properties (dipole moments, transition moments between surfaces, electric field gradients, etc.). This "production code" was used by numerous theorists on over 25 different studies during 1976. Improvements involved speeding up various steps in the configuration interaction section (SVM), particularly formula tape generation and extraction of the lowest eigenvalues. Modifications were made in the self-consistent-field section SCF to allow calculation of excited states. Additions included a new integral program, molecular properties program, and a pseudopotential code. The new integral code utilizes a transformation driven technique that allows the use of larger basis sets with more than one contraction per set. One version of this integral program includes a basic Gaussian integral program developed under contract. The molecular properties code, developed at Livermore, has been interfaced to the SVM section, so dipole moments, transition moments, etc., can be calculated for large-configuration interaction wavefunctions. The contraction section CONTRACT, also developed at Livermore, is used to reduce the number of electrons by modifying the one-electron-potential energy matrix elements and the nuclear-nuclear repulsion. Typically this code is run after an SCF calculation to reduce calculation times for subsequent steps. For example, the configuration interaction calculation of KrCl is reduced to that of NeF.

The code IONPAC was developed at Livermore for studying f-f dipole and magnetic-dipole-allowed

transitions in the actinides and lanthanides. This code, using a modified Judd-Ofelt theory,⁹³ replaces an earlier, more restrictive code, NUION. Execution times of the new code are tenfold to twentyfold times faster.

Several codes were developed to analyze the results of atomic and molecule structure calculations.

The SPECTRA code accepts the potential energy curves for initial and final states and computes the bound and free wavefunctions for the nuclear motion. From these it determines the bound-free Franck-Condon factors which, combined with the computed transition moments and upper state populations, produce a synthesized emission spectrum for the molecule. The program can also be used to determine potential energy curves for a diatomic molecule by iteratively matching the experimental spectra.

The SPIN code accepts the potential energy curves for the $^2\Sigma$ and $^2\Pi$ states of a diatomic molecule and computes the $\Omega = 1/2$ and $\Omega = 3/2$ curves. The initial LS curves can be either numerical or analytic functions. Spontaneous emission coefficients, transition moments, and lifetimes are also determined for the spin orbit curves.

A one-dimensional spline-interpolation code, SPLINE, was written that accepts the potential energy curve for a molecule over a grid of points and determines the curve over a denser grid appropriate for plotting. Also, a number of computer graphic programs were developed to display potential energy curves (POCC) and surfaces (PLOTPEs), including a movie generator (MOVIE).

Heavy Particle Dynamics Codes

The recently developed LEPS code evaluates the London-Eyring-Polanyi-Sato semiempirical reaction surface and prepares a data file to be plotted by standard contour or three-dimensional plot packages. The program is useful in determining the Sato parameters before a classical trajectory calculation and has proved valuable in comparing *ab initio* and semiempirical surfaces.

Photoionization Codes

Several atomic and molecular photoionization studies were carried out during the year based on a

moment theory approach that "synthesizes" the continuum photoabsorption profile of an atom or molecule in terms of a discrete set of transition energies and oscillator strengths (or, equivalently, power moments). The code, IMAGE, originally developed by Langhoff and coworkers at the University of Indiana, has been adapted to the LLL Octopus network. The present code incorporates the most recent developments to the theory, including the use of the Tchebycheff derivative⁹⁴ to provide a continuous representation of the continuum oscillator strength. The code has also been interfaced with appropriate graphics routines, and a cubic spline option was added to provide a smooth interpolation of the calculated Stieltjes histograms.⁹⁵

The input to IMAGE is provided by finite Hilbert space calculations. These have been obtained from our atomic CI programs or from one of our molecular codes. In certain cases, calculations were performed using the frozen core options in our molecular SCF codes or, for closed shell molecules, using the equations-of-motion programs. Work on a new code, VPQ, was also initiated in 1976. This code is specifically designed to construct energies and oscillator strengths optimally for cases where a single electron is to be coupled to an arbitrary, multiconfiguration, open-shell target function.

Electron—Molecule Scattering Codes

Substantial progress was made during 1976 in the development of electron — molecule scattering codes. Emphasis was placed on the implementation of both approximate techniques for quickly estimating cross sections as well as detailed *ab initio* evaluation of scattering amplitudes. A molecular Born code, FAUST, was installed. This code, originally developed at Caltech,⁹⁶ calculates generalized oscillator strengths (Born cross sections) for molecules that have closed-shell ground states. The restriction to closed-shells is imposed by the interfacing of this code with the equations-of-motion programs. Compatibility between FAUST and our molecular configuration-interaction codes would remove this restriction, and work along these lines was also initiated. FAUST was used to study the excited states of F_2 .⁹⁷

A new version of the low-energy electron molecule code was completed. This program,

HEITLER, solves the integral equation for the reactance matrix in a Gaussian basis. The new code incorporates many improvements on the original code, DIATOM. Matrix elements of the free-particle Green's function are now calculated analytically, and a decomposition of the scattering amplitude in terms of spherical harmonic has eliminated the need for numerical quadrature of the molecular orientation dependence of the cross section in the laboratory frame.

Calculations on H_2 and N_2 using these codes gave encouraging results, but extensive work on the $e^- - CO_2$ system showed the difficulty of trying to represent long-range multipole interactions in terms of localized basis states. We have therefore initiated work on a new code, HYBRID, which will use the wavefunctions generated by HEITLER as starting values for a numerical integration of the coupled radial equations in the asymptotic regions where only long-range multipole forces are important. By adopting this hybrid approach, we will be able to take advantage of the analytic expansions in the difficult regions where exchange forces are significant and rely on numerical integration only in regions where the interaction potential is local. The implementation of these techniques is still in progress.

Laser-Kinetic Modeling

Lowell Morgan, now at Joint Institute for Laboratory Astrophysics, Boulder, CO, has developed a code, EEDAP, that computes the partitioning of e-beam primary electron energy among the electronic and ionic states of an arbitrary mixture of gases. It also computes the heating of the secondary electron gas. The code requires as input the partial pressures of the constituent gases, the fractional ionization, and the gas and electron temperatures. The inelastic electron excitation and ionization cross sections of the states considered are computed using three semiempirical formulas.

A generalized kinetics code, LASKIN, was developed at Livermore to model kinetic processes in lasers and photolytic pumps being studied in the LLL Advanced Laser Program. The code basically sets up the ordinary differential equations (ODE's) that describe the kinetic processes, and solves the ODE's using a variable-order, variable-step, stiff-equation integration routine called EPISODE. Chemical reactions and other kinetic processes,

such as electron pumping, are input to LASKIN in a very general and convenient way, which allows for quick changes in kinetic models. The code has extensive diagnostic and plotting capabilities that were provided to identify the most important kinetic processes easily.

LASKIN provides a framework to which we could add several pumping mechanisms, e.g., e-beams, electric discharge, and fluorescence on laser photolytic pumping. EEDAP has already been married to LASKIN as a subroutine to model e-beam-pumped rare-gas excimer and rare-gas oxide fluorescence.

Photon Dynamics

During the last year, several codes pertaining to photon dynamics were written or enlarged. These solve in various ways sets of coupled first-order ordinary differential equations, often carrying out sums or averages over a distribution of initial conditions or equation parameters. The results are displayed in graphical form.

TIMED (B. W. Shore) (superseded by BLOCHB). Solves the Schrödinger equation in the rotating-wave approximation (RWA) for an $N \leq 40$ -level atom and monochromatic light. Finds eigenvalues and eigenvectors of the dressed atom and then uses Magnus (exponentiation) integration. Does Doppler averages.

BICENT (J. Ackerhalt) (superseded by BLOCH). Solves the Bloch equations (in RWA) for $N \leq 3$, monochrome light, Doppler average. Uses high-order series-expansion integrator.

RATE (J. Ackerhalt). Compares rate equations and Bloch equations (in RWA) for $N \leq 5$ and monochrome light. Fixed-order integrator.

BLOCH (J. Ackerhalt). Solves Bloch equations (in RWA) for $N \leq 5$ and monochrome light, Doppler averages. Fixed-order integrator.

BLOCHB (B. W. Shore). Solves Schrödinger (for $N \leq 20$) or Bloch equations (for $N \leq 5$). Monochrome light or pulse shapes; Doppler averages; can plot frequency scans. Uses Magnus integration.

SAGA2 (P. Renard). Solves coupled Maxwell and Bloch equations (for $N \leq 3$) to treat propagation of two near-resonant laser fields.

MLEV (A. Goldberg). Solves the Schrödinger equation (in RWA for $N \leq 50$) for

monochrome light or pulse shapes. Uses fixed second-order integrator.

MAKE3D (B. W. Shore). Constructs two-dimensional projections of three-dimensional surfaces showing probability vs time vs detuning. Uses LASL hidden-line program.

References

88. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975).
89. C. W. McCurdy, B. V. McKoy, T. N. Rescigno, and D. L. Yeager, "The Equations of Motion Method: An Approach to the Dynamical Properties of Atoms and Molecules," in *Modern Theoretical Chemistry*, Vol. III, H. F. Schaefer III, Ed. (Plenum Press, New York, to be published).
90. H. F. Schaefer, R. A. Klemm, F. E. Harris, *Phys. Rev. A*, **181**, 137 (1969).
91. T. N. Rescigno, C. F. Bender, B. V. McKoy, and P. W. Langhoff, Lawrence Livermore Laboratory, Rept. UCRL-78882 (1976). (Submitted to *Phys. Rev. A*.)
92. E. Clementi, *IBM Journal of Research & Development* **92**, 1 (1969).
93. B. R. Judd, *Phys. Rev.* **127**, 750 (1962); G. S. Ofelt, *J. Chem. Phys.* **37**, 511 (1962).
94. P. W. Langhoff and C. T. Corcoran, *Chem. Phys. Lett.* **40**, 367 (1976).
95. P. W. Langhoff, *Chem. Phys. Lett.* **22**, 60 (1973).
96. C. W. McCurdy and V. McKoy, *J. Chem. Phys.* **61**, 2820 (1974).
97. T. N. Rescigno, C. F. Bender, and V. McKoy, *J. Phys. B* **45**, 307 (1977).

Author

C. F. Bender

Major Contributors

A. V. Hazi
M. J. Killian
K. Rajnak
T. N. Rescigno
N. W. Winter
R. D. Franklin
R. A. Haas
H. Goldberg
B. W. Shore
J. Ackerhalt

6-9 Photoionization

Gaseous photoionization processes are important in determining the overall efficiency of short-wavelength fluorescence pumps and the ultimate

gain possible in many gaseous ultraviolet lasers. The reason, of course, is that production of a photoelectron from an excited species (either the upper laser level itself or some metastable species which feeds this level) represents the loss of both photons and the excited species that produce photons.

Photoionization is a potential loss mechanism in any system where the lowest excited state is more than halfway from the ground state to the threshold of the ionization continuum so that this excited state can be ionized by the laser photons themselves. This will be typical in rare-gas-excimer systems, such as Xe_2^* or Kr_2^* .⁹⁸ However, if the molecular excimer state is deeply bound, photoionization may not be energetically possible. Indeed, the strong ionic bonding in the rare-gas halides such as KrF^* or XeF^* pushes these species below the photoionization threshold, which undoubtedly contributes to their high fluorescence efficiency.

Electron-beam pumping of systems containing electronegative gases (F_2 , Cl_2 , etc.) may produce significant concentrations of negative ions through dissociative electron attachment.⁹⁹ The binding energy of these ions is typically several electron volts. Thus, the importance of photodetachment in such systems should be carefully assessed, both as a photon loss mechanism and in kinetic studies of the negative ion concentration, which strongly affects the stability of the gaseous plasma.

Significant improvements in ways to measure ground state photoionization cross sections have been made in the last decade. These refinements came about principally through the use of synchrotron radiation sources¹⁰⁰ and forward-scattering electron impact techniques.¹⁰¹ However, measuring absolute cross sections for excited-state photoionization is still extremely difficult. And, while precise theoretical calculations are possible for many atomic systems, until quite recently molecular calculations have been limited to the simplest one- and two-electron diatomic systems. For molecules, the primary difficulties come from the construction of many-electron continuum functions that describe an unbound electron in the presence of a non-spherical ionic molecular field.

We have made significant progress in implementing a new theoretical technique for evaluating photoabsorption cross sections. The technique is applicable to both atoms and molecules in ground or excited states. It does not rely on the numerical construction of continuum wavefunc-

tions but makes use of standard bound-state techniques and the classical method of moments.¹⁰²⁻¹⁰⁷

Theory: Stieltjes Imaging

The total photoionization cross section of an atom or molecule is conveniently defined in terms of the continuum oscillator strength through the relation¹⁰⁹

$$\sigma(\omega) = \frac{2\pi^2}{c} g(\omega) \quad (19)$$

$$g(\omega) = 2/3 \psi$$

where

$$g(\omega) = 2/3 \omega |\langle \psi_f | \vec{D} | \psi_i \rangle|^2 \quad (20)$$

The photon frequency, ω , is related by energy conservation to the kinetic energy of the photoejected electron through the equation

$$\omega = IP + k_e^2/2 \quad (21)$$

In Eq. (20), $\vec{D}$ represents the dipole operator, ψ_i is a bound wavefunction describing the initial state of the system, and ψ_f is a final-state, continuum wavefunction for a free electron of momentum k_e in the field of the residual core.

Evaluating Eqs. (19) and (20) apparently requires prior knowledge of the discrete and continuum portions of the appropriate oscillator-strength profile. However, another approach is to consider the cumulative oscillator strength distribution which is defined as a Stieltjes integral,

$$f(\epsilon) = \int_0^\epsilon \left[\sum_i f_i \delta(\epsilon_i - \epsilon') + g(\epsilon') \right] d\epsilon'$$

$$= \int_0^\epsilon df(\epsilon') \quad (22)$$

and is uniquely determined by its power moments¹⁰⁹

$$S(-k) = \int_0^{\infty} \epsilon^{-k} df(\epsilon), \quad k = 0, 1, \dots \quad (23)$$

The first term in Eq. (22) represents the contribution of the bound oscillator strengths to the distribution. The continuum oscillator strength, and hence the cross sections, may be obtained by differentiation of $f(\epsilon)$:

$$g(\omega) = \frac{d}{d\epsilon} f(\epsilon) \Big|_{\epsilon = \omega} \quad (24)$$

Following the Stieltjes procedure,¹⁰²⁻¹⁰⁴ the cumulative oscillator strength [Eq. (22)] is approximated by an n -term histogram of the form

$$f(\epsilon) \approx F^{(n)}(\epsilon) = \sum_{\alpha=1}^n f_{\alpha}, \quad \epsilon_{\alpha} \neq \epsilon, \quad (25)$$

where the n points and weights $\{\epsilon_{\alpha}, f_{\alpha}\}$, which are distinct from the correct discrete spectrum $\{\epsilon_{\alpha}, f_{\alpha}\}$, of Eq. (22), are obtained by solving the generalized quadrature problem¹¹⁰ associated with the specification of $2n$ values of the moments

$$S(-k) = \sum_{\alpha=1}^n f_{\alpha} \epsilon_{\alpha}^{-k}, \quad k = 0, 1, \dots, 2n-1. \quad (26)$$

If the $2n$ sequential moments in Eq. (25) are precisely those of Eq. (23), the n -associated quadrature points and weights provide a *principal representation* of the oscillator-strength distribution, and the histogram of Eq. (25) rigorously bounds the correct distribution through the Tchebycheff inequalities¹¹⁰

$$F^{(n)}(\epsilon_{\alpha} - 0) < f(\epsilon_{\alpha}) < F^{(n)}(\epsilon_{\alpha} + 0), \quad (27)$$

and converges to $f(\epsilon)$ in the limit $n \rightarrow \infty$. When variationally determined or other approximate

spectral moments are used in Eq. (26), the bounds of Eq. (27) and the associated convergence properties are correspondingly weakened.

To obtain an approximation to the photoionization density $g(\epsilon)$, we need to differentiate the cumulative histogram of Eq. (25). The bounds of Eq. (27) suggest that convergent approximations to the continuum oscillator strength can be obtained at the successive points

$$\omega_{\alpha} = (1/2) (\epsilon_{\alpha} + \epsilon_n + \epsilon_{\alpha+1}) \quad (28a)$$

from the slopes of straight line segments connecting adjacent Stieltjes values of the cumulative histogram $F^{(n)}(\epsilon)$ in the form of the so-called Stieltjes derivative,¹⁰²⁻¹⁰⁴

$$g(\omega_{\alpha}) \approx G^{(n)}(\omega_{\alpha}) = 1/2(f_{\alpha} + f_{\alpha+1})/(\epsilon_{\alpha+1} - \epsilon_{\alpha}). \quad (28b)$$

A continuous convergent approximation to the cumulative oscillator strength distribution is obtained from the Tchebycheff development¹⁰⁵ by pre-assigning the energy ϵ and solving the moment problem of Eq. (26) for its associated weight $f_0(n, \epsilon)$ and $n-1$ additional points and weights $\epsilon_{\alpha}(\epsilon)$ and $f_{\alpha}(n, \epsilon)$, which depend parametrically on ϵ . The discrete and continuum portions of the oscillator-strength profile are obtained from the Stieltjes values of the cumulative distribution in the form of the so-called Tchebycheff derivative

$$G^{(n)}(\epsilon) = 1/2 \frac{df_0(n, \epsilon)}{d\epsilon} + \sum_{\alpha} \frac{df_{\alpha}(n, \epsilon)}{d\epsilon}, \quad (29)$$

where the sum is overall weights for which $\epsilon_{\alpha} < \epsilon$. The analytic properties of Eq. (29) have been investigated in detail and its convergence in the limit $n \rightarrow \infty$ has been established.¹⁰⁷

Although it is not generally possible to obtain an exact principal representation [Eq. (25)] for the oscillator-strength profile of an arbitrary many-electron system, experience indicates that finite-Hilbert-space calculations, which give N discrete energies and f -values, can provide $2n$ accurate

Fig. 6-50. Total photoionization cross section in N_2 for the production of N_2^+ ions. The solid line shows Stieltjes-Tchebycheff results in the static-exchange approximation; data points (●) show electron-ion coincidence measurements of Ref. 115. The $\pm 10\%$ error bars are suggested nominal values and do not correspond to the combined random and systematic errors in the measurements.

Fig. 6-51. Partial photoionization cross section in N_2 for the production of $(X^2\Sigma_g^+)N_2^+$ ions. The solid line shows Stieltjes-Tchebycheff results in the static-exchange approximation; dots (●) show synchrotron radiation measurements (Refs. 100 and 114); triangles (Δ) show electron-electron (Ref. 115) and electron-ion (Ref. 113) coincidence measurements. Error bars of $\pm 15-20\%$ are suggested for the experimental values.

Fig. 6-52. As in Fig. 6-51, for the production of $A^2\Pi_u$ (upper curve) and $B^2\Sigma_u^+$ (lower curve) states in N_2^+ .

Fig. 6-53. Total photoionization cross section for Ne^+ ($1s^2 2s^2 2p^3 3s^3 P$) in the static exchange approximation. Results are shown using both the dipole-length (lower curve) and dipole-velocity (upper curve) form of the oscillator strength.

power moments for $n \ll N$. This observation forms the basis for an attractive computational procedure in which pseudostate spectra from normalizable basis functions provide the information required for a Stieltjes-Tchebycheff moment analysis. We can thus entirely avoid using many-electron continuum molecular wavefunctions in photoionization calculations.

Examples

In the last part of 1976, we successfully completed the first rigorous *ab initio* study of the photoionization cross section of a nontrivial molecule.¹¹¹ The Stieltjes-Tchebycheff technique was used to calculate photoionization cross sections in molecular nitrogen. Excitation processes in nitrogen have been studied experimentally in considerable detail, partly due to a continuing aeronomic interest in its role as an atmospheric constituent. Moreover, since there are three ionization thresholds in the excitation energy interval between about 15 and 19 eV, molecular nitrogen provides a useful test of the Stieltjes-Tchebycheff technique when applied to a relatively complex spectrum.

An important conclusion of our work is that spurious results can be obtained when the excitation spectrum studied is a superposition of weakly interacting, physically distinct components. Such cases have traditionally proven difficult because the structures associated with autoionizing states and the opening of new ionic continua at the various thresholds are poorly imaged in total cross section calculations unless very large basis sets are used or the effects of molecular symmetry are particularly favorable.

We found a useful approximate solution of the coupled-channel problem by separating out the various physically distinct, low-lying ionic states of N_2^+ , by constructing wavefunctions for such states, and by using these wavefunctions to define ionic molecular fields in which the free electron is allowed to scatter. Coupling between the different ionic channels is ignored, providing results equivalent to the use of static-exchange potentials for each ionic channel. The total photoionization cross section is obtained by summing the contributions from all such channels.

We considered only the three lowest ionic states of $N_2^+ - X^2\Sigma_g^+, A^2\Pi_u$, and $B^2\Sigma_u^+$ — which have

vertical ionization potentials of 15.6, 16.7, and 18.8 eV, respectively,¹¹² and which are expected to be major contributors to the formation of N_2^+ in photoionization. Pseudospectra of transition energies and oscillator strengths were obtained from separate calculations on each channel, using Hartree-Fock ionic core functions and normalizable Gaussian orbitals to describe the photoejected electron.

The total cross section obtained from these calculations is shown in Fig. 6-50, along with the accurate experimental data of Van der Wiel, et al.¹¹³ We also show in Figs. 6-51 and 6-52 the partial photoionization cross sections for production of the three lowest states of N_2^+ , which agree well with experiments.¹¹³⁻¹¹⁵ The experimental feature near 27 eV is clearly identified in our calculations as a shape resonance in the channel leading to production of the $X^2\Sigma_g^+$ state of N_2^+ .

In 1976 we also began a study of the photoionization of the lowest metastable (3P) state of neon.¹¹⁶ This prototype study can be extended to other rare gas metastables. As previously mentioned, excited state photoionization is a critical issue in the rare gases and previous to this study accurate cross sections were unknown except for the case of helium.¹¹⁷

The wavefunctions for both the initial ($2p^5 3s^3P$) and final ($2p^4 kp^3S, ^3P, ^3D$) states were expressed in the L-S coupling scheme in terms of normalizable Slater-type orbitals. Discrete pseudospectra of energies and oscillator strengths were constructed for the three possible final states and separately imaged using the Stieltjes technique. For the case of the discrete $3p$ and $4p^3D_3$ final states, our calculated line strengths of 52 and 0.25, respectively, compare favorably with the values of 47 and 0.27 obtained previously.¹¹⁸

In our initial studies, we assumed that a frozen core model was valid; that is, that the $1s^2 2s^2 2p^5$ core does not rearrange upon ionization of the $3s$ electron. The total cross section obtained under this assumption is shown in Fig. 6-53. The cross section reaches a maximum value of about $1.4 \times 10^{-19} \text{ cm}^2$ at about 5 eV above threshold. This somewhat surprisingly small value is more than an order of magnitude smaller than the threshold photoionization cross section of the analogous state of He (3S) which is accurately known theoretically.¹¹⁷

We have also begun a careful study of the effects of polarization and electron correlation on the

calculated cross sections. While these configuration-interaction studies are still in progress, preliminary results indicate that the static-exchange data shown in Fig. 6-53 will not change by more than $\pm 10\%$, except in the regions where autoionization is important. These processes only become important for photon energies greater than about 30 eV.

We must emphasize that the moment theory technique uses only normalizable basis functions. By contrast, continuum functions of appropriate symmetry, especially for molecules, are very difficult to construct. The Stieltjes analysis provides results equivalent to those resulting from such functions; however, it avoids their explicit construction. With this technique, we hope to calculate photoionization cross sections of excited molecular species, which are not amenable to experimental determination.

References

98. See, for example, K. K. Rhodes, *IEEE J. Quant. Elec.* QE-10, 153 (1974).
99. T. N. Rescigno and C. F. Bender, *J. Phys.* B 9, L329 (1976).
100. L. C. Lee, R. W. Carlson, D. L. Judge, and M. Ogawa, *J. Quant. Spectrosc. Radiat. Transfer* 13, 1023 (1973).
101. J. S. Lee, T. C. Wong, and R. A. Bonham, *J. Chem. Phys.* 63, 1643 (1975).
102. P. W. Langhoff, *Chem. Phys. Lett.* 22, 60 (1973).
103. P. W. Langhoff and C. T. Corcoran, *J. Chem. Phys.* 61, 146 (1974).
104. P. W. Langhoff, J. Sims, and C. T. Corcoran, *Phys. Rev. A* 10, 829 (1974).
105. P. W. Langhoff and C. T. Corcoran, *Chem. Phys. Lett.* 40, 367 (1976).
106. P. W. Langhoff, C. T. Corcoran, J. S. Sims, F. Weinhold, and R. M. Glover, *Phys. Rev. A* 14, 1042 (1976).
107. C. T. Corcoran and P. W. Langhoff, *J. Math. Phys.* 18, 651 (1977).
108. See, for example, U. Fano and J. W. Cooper, *Rev. Mod. Phys.* 40, 441 (1968).
109. P. W. Langhoff, *J. Chem. Phys.* 57, 2604 (1972).
110. J. A. Shohat and J. D. Tamarkin, *The Problem of Moments*, *Mathematical Surveys* 1, (American Mathematical Society, Providence, 1943).
111. T. N. Rescigno, C. F. Bender, B. V. McKoy, and P. W. Langhoff, "The Photoionization of N_2 : An Application of Moment Theory to the Results of a Discrete Basis Set Calculation," submitted to *Phys. Rev. A*.
112. A. J. Blake and J. H. Carver, *J. Chem. Phys.* 47, 1038 (1967). See also D. W. Turner, C. Baker, A. D. Baker, and C. R. Brundle, *Molecular Photoelectron Spectroscopy* (Wiley, New York, 1970).
113. Th. M. El-Sherbini and M. J. Van der Wiel, *Physica* 59, 433 (1972); see also G. R. Wight, M. J. Van der Wiel, and C. F. Brion, *J. Phys. B* 9, 675 (1976).
114. E. W. Plummer, T. Gustafsson, W. Gudat, and D. E. Eastman, "Partial photoionization cross sections of N_2

- and CO using Synchrotron radiation," *Phys. Rev. A* 15, 2339 (1977); see also J. W. Rabalais, T. P. Debies, J. L. Berkosky, J. T. J. Huang, and F. O. Ellison, *J. Chem. Phys.* 61, 516 (1974) and J. L. Gardner and J. A. R. Samson, *J. Chem. Phys.* 62, 1447 (1975).
115. A. Hammett, W. Stoll, and C. E. Brion, *J. Elect. Spec. and Rel. Phen.* 8, 367 (1976).
116. T. N. Rescigno and A. U. Hazi, Lawrence Livermore Laboratory, Rept. TAMP 77-632.
117. D. L. Yeager, A. A. C. Nascimento, and V. McKoy, *Phys. Rev. A* 11, 1168 (1975).
118. A. F. Starace, *J. Phys. B* 6, 76 (1973).

Authors

T. N. Rescigno
A. V. Hazi

6-10 New Infrared Lasers

Several new and potentially quite efficient lasers that utilize discrete infrared transitions spanning the wavelength region from about 6 to 35 μm have been developed in experiments with a two-photon excitation technique employing a pair of CO_2 TEA lasers.¹¹⁹ This excitation method relies on detailed spectroscopic data for high-lying vibrational states—in our case obtained from studies on Doppler-free, two-photon molecular absorptions made with counterpropagating CO_2 laser beams. Investigations using this approach have been recently reported for $^{14}\text{NH}_3$ (Refs. 120 and 121) and $^{12}\text{CH}_3^{19}\text{F}$ (Refs. 122 and 123). Such spectroscopic information is the key to devising a means for intense two-photon pumping of these transitions so as to create population inversions between the final absorbing state and a plethora of less energetic levels. In this report we describe the first unambiguous demonstration of laser action resulting from simultaneous two-photon molecular excitation—specifically for $^{14}\text{NH}_3$ and $^{12}\text{CH}_3^{19}\text{F}$. For completeness, we note that a possible two-quantum mechanism has been proposed¹²⁴ to explain the appearance of 16- μm laser radiation from SF_6 . Stimulated optical transitions created in this manner can serve as highly sensitive probes to study the collisional properties of excited molecular vibrational states. They may also have practical application in a variety of laser-induced isotope separation processes¹²⁵ and in the general area of laser photochemistry.

In what follows, details are given first for the laser experiments with $^{14}\text{NH}_3$, which illustrate the method in general, after which the results for $^{12}\text{CH}_3^{19}\text{F}$ are described more briefly.

The NH_3 two-photon transition involved in this experiment is shown in Fig. 6-54. With the notation (ν_2, J, K) the transition is identified¹²⁰ as $(0^-, 5, 4) \rightarrow (2^-, 5, 4)$ and is readily excited by the P(34) and P(18) lines in the $10.4\text{-}\mu\text{m}$ band of the CO_2 laser. Although the total energy of the two CO_2 laser frequencies falls short of the precise resonance energy by about 0.3 GHz, the optical Stark effect¹²⁰ can be utilized to obtain exact resonance. Using the spectroscopic information in Ref. 120 one can estimate that saturation of the two-photon transition at 1

Torr pressure of NH_3 for this off-resonance condition requires that the product of the two laser intensities be about $10^{13} (\text{W}/\text{cm}^2)^2$. Although in this work the off-resonance pumping case was implemented, we note that the required pump intensity constraint, as indicated, can be appreciably reduced (in this example by about 10^4) by use of a Stark cell. This will permit use of conventionally Q-switched low-pressure CO_2 lasers for excitation at pulse rates approaching 1 kHz.

The experimental approach is illustrated in Fig. 6-55. A dielectric-coated Ge beam splitter is employed to combine the TEM_{00} modes from two high-repetition-rate grating-tuned TEA CO_2 lasers (Lumonics 801A). The P(34) and P(18) laser pulses

Fig. 6-54. Partial energy-level diagram of the ν_2 mode of $^{14}\text{NH}_3$, illustrating (1) the two-photon absorption utilized to populate the $2\nu_2(5,4)$ state, and (2) the $35.50\text{-}\mu\text{m}$ and $15.88\text{-}\mu\text{m}$ transitions serving as examples of the generated laser wavelengths.

had energies of about 10 and 24 mJ, respectively, upon entering the NH_3 cavity. These outputs yield a power product of about $2 \times 10^{13} (\text{W}/\text{cm}^2)^2$ at the beam waist of the ammonia cell. A 2-m-radius mirror is used to mode-match¹²⁶ these beams with the ammonia laser cavity, which consists of two 0.5-m-radius gold-coated mirrors separated by 93.3 cm. Input coupling is accomplished by reflecting the polarized CO_2 beams from a KRS-5 flat placed at Brewster's angle for the ammonia resonator. Measurements indicate that about 45% of the energy incident on this window is focused into the NH_3 cell. The KRS-5 flat enforces a polarization on the ammonia laser which is perpendicular to that of the incident CO_2 beams. The generated laser

radiation is coupled from the cavity through a 1-mm-diam hole in one of the gold mirrors.

The NH_3 laser output is directed onto the entrance slits of a Spex 0.75-m scanning monochromator equipped with a 30-line/mm grating blazed at $35 \mu\text{m}$. The monochromator was wavelength-calibrated by observing high orders of both a He-Cd laser operating at $4416 \text{ \AA}$ and a He-Ne laser at $6328 \text{ \AA}$, in addition to the second and third orders of a grating-tuned CO_2 laser. The results of all three calibration techniques were in agreement. Accuracy of the measured infrared wavelengths is estimated to be within about $\pm 0.01 \mu\text{m}$. The laser radiation was monitored by a Ge:Zn photoconductive detector placed at the

Fig. 6-55. Schematic diagram of the experimental arrangement. The dots indicate polarization of the CO_2 TEA laser radiation perpendicular to the figure plane. Mirrors (denoted by M) are gold-coated; curved mirrors have radius of curvature shown, e.g., M, 0.5-m.

Fig. 6-56. Observed laser lines in the ν_2 mode of $^{14}\text{NH}_3$. The depicted wavelengths are accurate to $\pm 0.01 \mu\text{m}$; to within this accuracy, these wavelengths agree with those in Ref. 127, which also gives the indicated vibrational state identifications.

monochromator exit slits. The signal was observed on a Tektronix 7903 oscilloscope and a PAR 162-164 boxcar integrator. Infrared filters with suitable transmission characteristics were utilized to prevent the CO_2 laser radiation from scattering into the detector.

Stimulated emission was observed at ten different wavelengths after two-photon excitation of the $2\nu_2$ (5,4) level at 2115.88 cm^{-1} . Some of these laser transitions, along with their probable state designations, are depicted in Fig. 6-56. These level assignments are based on the previous spectroscopic studies of $^{14}\text{NH}_3$ by Garing, Nielsen, and Rao.¹²⁷ The following laser wavelengths are identified: in the ν_2 mode, 12.11, 13.72, 15.88, 15.95, 18.93, 19.55, 26.10, and $35.50 \mu\text{m}$; in the ν_4 mode, 6.27 and $6.69 \mu\text{m}$, with the latter two lines corresponding to transitions between $1\nu_4^+(2,2) \rightarrow 0^+$ and $1\nu_4^+(8,1) \rightarrow 0^+$, respectively.

Collisions coupling the $2\nu_2^+$ and $1\nu_4$ levels may cause rapid energy transfer between these two modes, since they are known to be strongly perturbed by Coriolis mixing.¹²⁸ Although violating the dipole selection rule ($\Delta K = 0$) for collisions, states with $K = 1$ and $K = 2$ have the same nuclear spin symmetry for the protons as the $K = 4$ states. A line in the same region involving the $2\nu_2^+(3,3)$ level¹²⁷ at $6.27 \mu\text{m}$ is quite improbable, since it would require a change in the proton nuclear spin symmetry. Several other lines were detected, but their assignments are still not certain due to the very weak relative intensities involved.

For the identified lines, conclusive tests such as blocking each beam one at a time, delaying one beam with respect to the other by an interval longer than the CO_2 laser pulsedwidths, and removing the ammonia from the cell were performed and resulted

in disappearance of the Ge:Zn detector signal. Several tests were used to distinguish laser action from fluorescence: (1) The output NH_3 laser power was extremely sensitive to minute angular adjustments of the cavity mirrors. Typically, a power ratio greater than 50:1 was obtained by rotating the mirrors a few seconds of arc, causing misalignment of the resonator. (2) The generated laser pulsewidths (FWHM) were about 200 ns, roughly equivalent to the CO_2 laser pulsewidths. By comparison, a calculation of the spontaneous lifetime τ_{sp} using the Einstein A coefficient ($\tau_{sp}^{-1} = 64 \pi^4 \nu^3 \mu^2 / h c^3$, where μ is the measured matrix element for the relevant transition¹²⁰, yields values of 66 and 64 ms for the 35.50- and 15.88- μm transitions, respectively. (3) The calculated¹²⁶ beam radius at the NH_3 cavity mirrors for the 16- μm laser is 3.1 mm, a value consistent with tests involving intracavity apertures of varying size. (4) Translation of the output mirror beyond the 100-cm length for stable resonator performance resulted in a very well-defined oscillation threshold.

As shown in Fig. 6-56, three of the ammonia laser lines utilize the $2\nu_2(5,4)$ level as their initial state. Five other lines have upper levels which are pumped in turn by the indicated 35.50- and 26.10- μm laser transitions. We note that the unusually large vibrational matrix element for the $2^- \rightarrow 2^+$ transition ($\sim 0.83D$) produces an enormous gain ($\sim 3 \text{ cm}^{-1}$) on the 35.50- and 26.10- μm lines, causing these levels to be strongly coupled by stimulated emission which selectively populates the $2\nu_2$ states. As noted, the remaining two lines in the $^{14}\text{NH}_3 \nu_4$ mode at 6.27 and 6.69 μm occur most probably as a direct consequence of collisional coupling between the Coriolis-coupled¹²⁸ $2\nu_2$ and $1\nu_4$ ammonia vibrational modes.

The relative strengths of the laser lines vary widely from barely observable to about 1 $\mu\text{J}/\text{pulse}$. The transitions at 12.11 and 26.10 μm are the strongest. The strength of the 35.50- μm line is difficult to evaluate due to the existence of water-vapor absorption bands at this wavelength.¹²⁹ It is strongly emphasized that these values do not represent optimized laser performance. Currently, no obstacles are envisaged to substantial scale-up the NH_3 laser via increased CO_2 laser absorption leading to increased ammonia-laser energy output. The efficiency of producing the various ammonia-laser lines can be enhanced by use of dispersive resonator elements or suitable selectively absorbing

gases in the cavity to prohibit oscillation of chosen transitions originating at the $2\nu_2$ state.

Investigations have been made of the effects of ammonia vapor-pressure variation on laser output power. It has been observed that the peak laser power occurs between 100 mTorr and 25 Torr depending on the specific transition. In addition, the laser output powers were examined as a function of varied Ne and D_2 pressures for a fixed amount of ammonia. In these studies, laser action was sustained for pressures of these buffer gases up to 200 Torr for Ne and 120 Torr for D_2 , again depending on the particular transition. Such observations suggest that this experimental approach will not only allow one to devise additional laser transitions via transfer of population through collisions, but will also serve as a sensitive technique to monitor collisional processes in excited vibrational states with NH_3 and other colliding species. Extensive related work has been performed by Oka on ground vibrational states of NH_3 using a two-microwave method.¹³⁰

Laser action following two-photon excitation of $^{12}\text{CH}_3^{19}\text{F}$ was demonstrated using the same experimental approach. In this case, two-photon absorption occurs between the $(\nu_3, J, K) = (0, 1, 1)$ and $(2, 3, 1)$ vibrational levels in CH_3F with the two CO_2 TEA lasers operating on the P(14) and P(30) lines of the 9.4- μm CO_2 band. Subsequently, lasing takes place between the $(2, 3, 1)$ and $(1, 4, 1)$ states at 9.75 μm . For a cavity with selective loss at 9.75 μm the possibility exists of generating additional laser transitions originating from the $(2, 3, 1)$ level such as $2\nu_3 \rightarrow \nu_2$ at 16 μm and $2\nu_3 \rightarrow \nu_6$ at 11 μm . Lasing occurred at 9.75 μm for CH_3F pressure varying from 0.1 to 8 Torr with the maximum output occurring at about 2 Torr. As in the case of $^{14}\text{NH}_3$, the laser output power was studied as a function of Ne and D_2 pressure for a fixed amount of methyl fluoride. The results of these studies will soon be submitted for publication.

References

119. Ralph R. Jacobs, D. Prosnitz, William K. Bischel, and Charles K. Rhodes, *Appl. Phys. Lett.* **29**, 710 (1976).
120. William K. Bischel, Patrick J. Kelly, and Charles K. Rhodes, *Phys. Rev. A* **13**, 1829 (1976).
121. William K. Bischel, Ralph R. Jacobs, and Charles K. Rhodes, *Phys. Rev. A* **14**, 1294 (1976).
122. William K. Bischel, Patrick J. Kelly, and Charles K. Rhodes, *Phys. Rev. Lett.* **34**, 300 (1975).

123. William K. Bischel, Patrick J. Kelly, and Charles K. Rhodes, *Phys. Rev. A* **13**, 1817 (1976).
124. W. E. Barch, H. R. Fetterman, and H. R. Schlossberg, *Opt. Commun.* **15**, 358 (1975).
125. Reed, J. Jensen, John G. Marinuzzi, C. Paul Robinson, and Stephen D. Rockwood, *Laser Focus* **12**, 51 (1976). In this review of laser-based uranium isotope separation using UF_6 , the following infrared laser wavelengths were indicated as necessary: 7.74, 8.62, 12.1, and 15.9 μm .
126. H. Kogelnik and T. Li, *Appl. Opt.* **5**, 1550 (1966).
127. J. S. Garing, H. H. Nielsen, and K. Narahari Rao, *J. Mol. Spectrosc.* **3**, 496 (1959).
128. J. W. C. Johns, A. R. W. McKellar, and A. Trombetti, *J. Mol. Spectrosc.* **55**, 131 (1975).
129. *American Institute of Physics Handbook*, 3rd Ed., coordinating editor, D. E. Gray (McGraw-Hill, New York, 1972). Ch. 6, p. 290.
130. Takeshi Oka, in *Advances in Atomic and Molecular Physics*, Vol. 9, edited by D. R. Bates (Academic Press, New York, 1973), p. 127 and references cited therein.

Author
R. R. Jacobs

Major Contributors
D. Prosnitz
W. K. Bischel
C. K. Rhodes
B. R. Schleicher
R. B. Lopert

ween 0.2 and 5 MeV, a current range between 1 and 1000 A/cm², and a pulse length range between 10 and 10 000 ns to determine the overlap between existing electron-beam technology and the laser-fusion program needs. Several critical issues were defined and are being studied.

System Components

A laser system is essentially a power amplifier for electromagnetic energy starting with the relatively low power available from commercial lines and ending with the extremely high peak-power laser output. Figure 6-57 shows the essential components of this electron-beam power conditioning system used to pump a laser medium. An energy storage reservoir is needed to integrate over time the low-power input from the line for delivery on the shorter time scale of the electron-beam pulse. Isolation between the energy storage reservoir and the line is needed during the storage medium discharge. A voltage gain stage will also probably be needed to generate the desired output voltage of the electron-beam system. A switch is necessary to isolate the energy storage medium from the electron-beam source load during the charging portion of the system cycle. An additional intermediate energy storage reservoir may be needed to obtain the desired pulse length.

These elements comprise the power-conditioning portion of the system. They deliver an appropriate voltage pulse to the electron-beam source, which converts the electromagnetic energy to electron kinetic energy for transmission to the laser medium. There the energy is deposited and the desired inversion established. Though all systems will contain

6-11 Electron Beam Physics

Relativistic electron beams for pumping gas laser media interest us because of their ability to deposit rapidly large amounts of energy in great volumes with high efficiency and reasonable spatial uniformity. We undertook a general study of electron-beam technology¹³¹ covering a voltage range bet-

Fig. 6-57. System components.

Fig. 6-58. Experimental measurements of beam pinch angles at $x = 2.75$ cm for $V = 0.5 - 2$ MV and $d = 1.5 - 10.0$ cm.

these components, changes of the component order are possible, and a single subsystem may perform more than one task.

There are seven readily identifiable steps in the transfer of energy from the power line to the laser medium; each has a potential for energy loss:

- Charging the energy storage reservoir.
- Extracting energy from the reservoir, including possible transfer to immediate stores.
- Coupling energy to the electron-beam source.
- Forming the electron beam so that energy is not deposited within the gun.
- Constructing the mechanical support for the anode foil to minimize the intercepted beam energy.
- Absorbing energy in the foil.
- Depositing energy within the laser medium.

If an overall system efficiency of 50% is desired and if the inefficiencies are uniformly distributed among these seven steps, then each step must have an efficiency of at least 91%. Thus, each component of the overall system will require careful design to minimize energy losses.

Electron Beam Source

Our primary efforts have been to define, understand, and alleviate the physical factors limiting the performance or scalability of electron-beam sources. Eight areas are currently being investigated.

- Beam pinch.
- Vacuum breakdown.
- Cathode emission.
- Requirements for magnetic isolation of adjacent cathode modules.
- Optimum design of mechanical support for anode foil.
- Cathode plasma closure.
- Anode foil materials.
- Anode cooling.
- Insulator flashover.

Beam Pinch

We have formulated an analytical description of beam pinch in rectangular and cylindrical

geometries.¹³² Relativistic mechanics and magnetostatics were combined with expressions for space-charge-limited current flow to obtain a general scaling relationship describing the onset of beam pinch:

$$\frac{w}{d} V^{1/2} = \alpha \sin \theta, \quad (30)$$

where w is the width of beam, d is the anode-cathode spacing, V is the applied voltage, θ is the angle between the electron trajectory at the anode and the normal to the anode, and α is a weak function of diode geometry. This analysis suggests that simple two-element diodes producing a wide-area beam will be restricted to voltages smaller than about 2 MeV. Complex two-dimensional diode geometries have been simulated with the computer code EGUN to investigate the validity of the analytic scaling relationship above and to permit the simulation of radially converging electron beams in cylindrical geometries. These analyses agree with the analytical model.

Figure 6-58 shows an experimental confirmation of this scaling relationship. The figure shows a linear relationship between $\sin \theta$ and $\sqrt{V}/d$ at fixed w for voltages ranging from 0.5 to 2 MeV and anode-cathode spacings from 2 to 10 cm. The solid line is a least-squares fit to the data, and the dashed line is the analytic prediction with the appropriate evaluation of α . Since the size, pressure, and composition of the medium determine the required V , pumping requirements fix J , which in turn sets d , and since $\sin \theta$ must be less than 1, there is a maximum width for the electron beam that is generally smaller than that required by the overall system design. To produce large beam areas, we need to subdivide the overall area into smaller electron-beam modules with return current paths interspersed between cathodes to isolate each module from the magnetic fields produced in adjacent modules.

Vacuum Breakdown

Using modular construction necessarily involves applying large potential differences between the current conductors (diode sidewalls) and the cathode current feed. Electron flow between such

Fig. 6-59. Space-charge-limited current determined by vacuum breakdown field.

surfaces results in the deposition of energy in the sidewalls rather than in the laser medium, and this flow must be minimized. The maximum electric field that can be applied between these surfaces without vacuum breakdown places a lower limit on the separation between them. This minimum separation, when combined with a module geometry that results in a uniform beam at the anode surface, effectively limits the current density that such a module can produce. An exact calculation of this limiting current density is complex; however, it is of the same order of magnitude as the space-charge-limited current density that would flow between the cathode and the sidewalls if breakdown occurred. Figure 6-59 shows a plot of this current density as a function of breakdown field E_b with the applied voltage as a parameter. Breakdown field strengths exceeding 500 kV/cm for 50-ns pulses have been achieved by using dielectric coating of metal surfaces to suppress emission. The resulting maximum current densities are several hundred amperes per square centimeter; however, the operational lifetime of such coatings is not

Fig. 6-60. Energy loss due to backscatter and bremsstrahlung at $E = 1$ MeV.

known. Breakdown strengths of 250 kV/cm for 50-ns pulses have been obtained for polished bare aluminum surfaces, with a resulting current density limit of perhaps 100 A/cm². However, the maximum static breakdown strength is about 80 kV/cm for polished stainless steel, resulting in maximum current densities of a few tens of amperes per square centimeter.

Other Considerations

The interface between the electron-beam diode and the laser medium must be transparent to electrons and must withstand the pressure difference between these regions. Unsupported foils may be adequate in cylindrical geometries at modest pressures. In rectangular geometries, however, a mechanical support structure for the foil will be required. The optimum geometry and materials for this structure involve a trade-off between mechanical strength and electron-beam transmission; they have not been completely analyzed, though work in this area is continuing. The diode insulator forming the interface between the diode itself and the energy source that drives the diode is also a critical component of the overall system. Its voltage standoff capabilities strongly affect system performance, and the relative merits of insulator

configurations will influence the choice of the electron-beam geometry.

Energy Deposition

At pressures above 1 atm in the rare gases, energy transfer from an electron beam to the gas occurs through collisions of beam electrons with bound electrons of the gas atoms; the spatial distribution of deposited energy is controlled by the scattering of beam electrons by screened atomic nuclei. The three-dimensional, Monte Carlo, electron-photon transport code SANDYL¹³³ has been the major source of information on the magnitude and spatial distribution of energy deposited in the laser medium by beam electrons through collisions, including both general scaling relationships and detailed information used in the interpretation of experimental measurements.

To assess the maximum efficiency for depositing beam energy in the laser medium, we performed a series of calculations to determine the amount of energy backscattered by various media. The results are shown in Fig. 6-60, where the total energy loss (backscatter plus bremsstrahlung) is plotted as a function of the atomic number of the gas medium.

Fig. 6-61. Spatial distribution of deposited energy in neon at $P = 4$ atm and $E = 1.5$ MeV.

Fig. 6-62. Energy deposition efficiency for given uniformity in neon at $P = 4$ atm and $E = 1.5$ MeV.

The results are not sensitive to variations in electron energy or medium density but only to the average Z of the medium. Clearly, if an efficient system is desired, the primary constituent of the medium will have to have $Z \gtrsim 10$.

A typical spatial distribution of deposited energy is shown in Fig. 6-61. Two 1.5-MeV electron beams, each 2×5 m, are incident from opposite sides on a 1.7-m-thick laser cell. Neon gas at a pressure of 4

atm was used with a 25- μ m-thick nickel foil. Contours of equal energy deposition per unit volume are plotted. The contour interval is 10% of the peak deposition density.

To assess the achievable efficiency of depositing energy with a specified uniformity, we performed a series of calculations for different aspect ratios of beam height (h) to medium width (s). High efficiency can be obtained only at large aspect ratios or low uniformities (Fig. 6-62).

References

131. L. Schlitt and L. Bradley, *The Scaling of Electron-Beam Sources for Laser Fusion Applications*, Lawrence Livermore Laboratory, Rept. UCID-16864 (1973).
132. L. Schlitt and L. Bradley, "The Physics of Relativistic Electron Beam in Rectangular and Cylindrical Geometries," in *Proceedings of the International Topical Conference on Electron Beam Research and Technology*, Albuquerque, N. M. 11, 239 (1976).
133. H. M. Colbert, *SANDYL*, Sandia Laboratories, Livermore, Calif., Rept. SCL-DR-720109 (1973).

Author
L. G. Schlitt

Major Contributor
J. Taska

ADVANCED QUANTUM ELECTRONICS PROGRAM

Bill Krupke - Program Leader

Judith Johnson - Secretary

Theoretical Atomic and Molecular Physics Group

Charles Bender - Group Leader

Wendy Grady - Secretary

Andy Hazi - Physicist - Electron scattering, resonance theory, dissociation

Tom Reigno - Physicist - Electron Scattering, photoionization, molecular structure

Bruce Shore - Physicist - Atomic structure, photon physics

Nick Winter - Physicist - Molecular structure, reactive/electron scattering

Dick Franklin - Laser systems/kinetic modeling, numerical analysis

Abe Goldberg - Physicist - Photon dynamics

Mathilde Killian - Computer programming; large code development

Geylord Larson - Computer code development; production support

Terry Cox - Student - Empirical modeling, numerical analysis, small computer use

Terri Homann - Student - Computer Graphics, programming

Advanced Lasers Group

Victor George - Group Leader

Patti Anderson - Secretary

J. J. Ewing - Physicist - Group VI, photon kinetics

Julius Goldhar - Physicist - Rare gas halides

Roger Haas - Physicist - Modeling and theory

Steve Hargrove - physicist - Dye Lasers

Ralph Jacobs - Physicist - Rare earth ion lasers

Tehmau Kan - Physicist - Copper vapor and dye lasers

John Miller - Physicist - Raman compressors

Lyn Pleasance - Physicist - Rare gas halides

Howard Powell - Physicist - Group VI photolytic lasers

Lee Schlitt - Physicist - Electron beam physics

Jim Taska - Physicist - Electron beam physics

Charlie Turner - Physicist - Rare gas excimer lasers

Don Ball - Electronics Engineer - Copper vapor

Rich Calliger - Electronics Engineer

Chuck Fetterman - Electronics Technician Supervisor

Buddy Swingle - Mechanical Engineer

R. C. Barnes - Electronics Designer

Jim Hill - Electronics Technician

Glenn Newman - Electronics Technician

Woody Souza - Electronics Coordinator and Program Manager

Steve Brown - Mechanical Technician

Will Davis - Mechanical Technician

Homer Lohr - Mechanical Designer

Craig Riley - Mechanical Technician

Dave Roberts - Mechanical Technician

Barry Schleicher - Mechanical Technician Supervisor

Ed Schmitt - Mechanical Technician
Bill Smiley - Mechanical Coordinator
Ray Weber - Mechanical Designer
Ray Wilder - Mechanical Technician
Bryan Lopert - Student

Section 7

SYSTEM STUDIES AND APPLICATIONS

Contents

Section 7 — SYSTEM STUDIES AND APPLICATIONS	7-3	Graphite Issues	7-23
7-1 Overview	7-3	Evaluations	7-24
Commercial Applications	7-3	7-4 Laser System Studies	7-25
Reactor Concepts for Laser Fusion	7-3	System Efficiency	7-27
Lasers for Laser Fusion	7-5	Scaling Considerations	7-31
Fusion-Fission Hybrids	7-6	Evaluations	7-35
Military Applications	7-6	7-5 Fusion-Fission Hybrids	7-36
Long-Range Planning	7-7	Laser Fusion Hybrid Design	7-36
7-2 Fusion Reactor Studies	7-7	Hybrid Reactor Design	7-37
Comparison Criteria	7-7	Fission Blanket Design	7-38
Source Abundance	7-7	Fuel Material Selection	7-40
Reactor Safety	7-8	Lithium-Cooled Radial Blanket	7-41
Environmental Acceptability	7-8	Top and Bottom Blankets	7-41
Technical Feasibility	7-8	Final Laser Optical System	7-42
Economic Feasibility	7-8	Pellet Apparatus	7-42
Reactor Concepts	7-8	First-Wall Considerations	7-42
Liquid-Lithium-Cooled Stainless		Design Analysis	7-43
Steel Manifold	7-9	System Performance	7-43
Gas-Cooled Graphite Manifold	7-11	System Capital and Operating Costs	7-43
Fluidized Wall ("Waterfall")		Evaluations	7-46
Concepts	7-11	7-6 National Security Applications	7-47
Evaluations	7-13	7-7 Long-Range Planning for Inertial-	
7-3 First-Wall Studies	7-14	Confinement Fusion	7-50
Analytical Methodology	7-14	Developmental Phases	7-51
First-Wall Designs	7-16	Exploratory Development	7-51
Laser Fusion-Fission Hybrid	7-16	Advanced Development	7-53
Inertially Confined Fusion		Engineering Development	7-53
Reactor	7-20	Commercial Development	7-55
		Time Schedules and Options	7-55

Section 7

SYSTEM STUDIES AND APPLICATIONS

7-1 Overview

System studies are being conducted to give perspective to the laser program's milestones and accomplishments, and to help direct the program's resources toward lines of research that will yield the maximum benefit in the shortest possible time. As the program advances toward accomplishing its civilian and military goals, system studies become increasingly important. They support the long-term, higher risk goal of commercial fusion-power production with conceptual design studies, parametric systems analyses, cost-benefit analyses, and new application studies. In addition, system studies support the short-term, lower risk military-applications goals by evaluating the potential applications and capabilities of the existing and planned laser facilities.

Laser fusion is presently in the scientific feasibility stage of development. Accordingly, the majority of the program's resources are being applied toward demonstrating a high-gain implosion and developing suitable lasers. The System Studies Group has developed a long range plan to bridge the gap between present efforts and the ultimate goals of applying the developed technology to national security problems and to the realization of commercial fusion power.

Commercial Applications

In our system studies dealing with the commercial aspects of laser fusion, we have tried to relate the end products (neutrons and energy) to significant commercial applications. Some of the more attractive applications identified to date include electric power production, propulsion, high-temperature process heat, fissile fuel production, burnup of radioactive fission waste, and synthetic gas production. In Fig. 7-1 these applications have been separated into three categories: applications that

use the fusion reaction for (1) its energy, (2) its neutrons, or (3) both its neutrons and energy. We have found that by far the largest markets and highest payoffs for laser fusion are associated with electric power production. Hence a major portion of our effort has been devoted to analyzing the technical feasibility and economic incentives for producing electricity with laser fusion. Specifically, we are supporting the long-term goal of commercial power production with conceptual-reactor design studies, first-wall analyses, and laser scale-up studies.

We have also investigated the possibility of producing both fissile fuel and electricity in a laser fusion-fission hybrid. Here we have tried to evaluate the potential of a fusion-fission hybrid that produces fuel for existing light-water reactors and makes sense as part of the evolution of a fusion power economy.

Reactor Concepts for Laser Fusion. We have initiated scoping studies to identify attractive reactor concepts for producing electric power with inertial confinement fusion. These studies are being carried out by developing several exploratory reactor concepts and then comparing them on the basis of weighted criteria that encompass the major issues affecting desirability as a commercial power plant: source abundance, safety, environmental acceptability, technical feasibility, and economic competitiveness. In each of these categories the criteria have been assigned relative weighting in order to score the different reactor concepts and provide a succinct documentation of the comparative judgments.

The technical feasibility of a practical power plant employing inertial confinement fusion depends on the solution of two major reactor-vessel problems:

1. The effects of high energy neutrons and cyclical stresses on the first-wall and blanket structure.

Fig. 7-1. Applications of laser fusion can be separated into those making use of the energy produced, the neutrons produced, or both the energy and the neutrons.

2. The effects of x rays and debris from the fusion microexplosions on the first wall.

Our level of confidence in developing the technology to solve these problems has been estimated on the basis of the amount of required system development that is beyond present capabilities. Economic feasibility will be strongly dependent on the solution to these technical problems, and it has been assessed in terms of factors such as reactor size, power density, first-wall and blanket lifetimes, duty cycle, fabrication costs, and recirculating power fractions.

Reactor concepts that have been developed to cope with the technical problems listed above include:

- A liquid-lithium-cooled stainless steel manifold.
- A gas-cooled graphite manifold.
- Fluidized wall concepts such as (1) a liquid-

lithium "waterfall," (2) falling ceramic-lithium pellets.

These reactor concepts are described and analyzed later in this section.

Approximately 25% of the energy from a thermonuclear microexplosion is in the form of x rays and energetic debris. This energy is deposited over a very short range in the first wall causing high temperatures, ablation of the wall material, and cyclical stresses. Several different approaches to the first-wall problem have been considered, including use of a wetted wall, magnetically protected wall, dry wall, and fluidized wall. These approaches differ primarily by the way the inner surface of the vacuum chamber interacts with the x rays and microexplosion debris. The wetted wall concepts feature a thin layer of liquid metal which covers the metal wall and it protects it from the blistering and structural ablation that would otherwise occur. The

magnetic protection concept, which was developed at LASL and is also being pursued by the University of Wisconsin, uses a solenoid to divert the pellet debris away from the sides of a cylindrical blanket and into conical collectors at the top and bottom. In the dry wall approach a sacrificial metal or ceramic liner is placed between the fusion chamber and the blanket. Our first-wall studies during this past year have focused on the design and analysis of dry wall concepts, which we believe would become increasingly attractive if beam propagation or target considerations limited allowable fusion chamber vacuums to less than 10^{-3} torr. The results of these studies, as presented later in this section, indicate it may be possible to design a graphite liner which operates with low enough ablation rates to last a year.

The fluidized wall concept is a new and promising approach developed in our scoping studies. In this approach, the first structural wall is shielded from x rays, neutrons, plasma, and shock effects by a thick "waterfall" of lithium in liquid or solid-pellet form. We hope to get enough moderating material in the falling region to attenuate the fusion neutron flux by more than an order of magnitude, thereby allowing us to consider blanket structures that could last for the useful lifetime of the plant.

The reactor scoping studies are still in progress, and not all of the concepts have been developed to the required degree of detail. Notwithstanding, the liquid-lithium waterfall scheme for first-wall protection has emerged as an extremely promising reactor concept for a laser-fusion power plant. The feasibility of this concept is less dependent on advances in material development because the effects of cyclical stresses and high energy neutrons are substantially reduced. During the next year we will continue with our evaluation of all the reactor concepts, and we will begin a conceptual design study of a laser-fusion power plant based on the liquid-lithium waterfall concept. In the conceptual design study we will try to evaluate the integrated engineering performance of a complete laser-fusion power plant. The design will include the first wall, the reactor cavity, the laser and optical transport, fuel pellet injection, thermal conversion and tritium recovery systems, as well as plant layout and costing.

Lasers for Laser Fusion. The laser systems effort during this past year has been in evaluating alternate options for high-average-power gas laser systems which appear to offer the required energy,

power, wavelength, beam quality, and efficiency for power plant operation. This analysis is being carried out in three parts. First, a methodology for comparing different laser systems on a common basis is being developed. This is basically a power flow and energy balance analysis which includes the electrical power conditioning, laser gas pumping and chemical regeneration, and radiation and photon energy transport. Second, a laser-optical-cavity scaling analysis is being performed to determine the size and configuration of the laser system for a full-scale power plant. Finally, different laser systems are being characterized and compared by their overall electrical efficiency, the minimum number of beams required, and the severity of the anticipated technology requirements.

Recent breakthroughs in the laser target designs indicate the serious possibility of achieving higher fusion-energy gains from high density implosions. These significant results, when combined with an analysis of a power plant system, have the effect of considerably relaxing the laser performance requirements to the following values:

Pulse energy	500-1000 kJ
Peak power	300-500 TW
Pulse repetition rate	1-10 Hz
Wavelength	$<2 \mu\text{m}$
Pulse duration	1-2 ns
Overall efficiency	$>1\%$

The physics requirements for laser media which have the potential to meet these less stringent performance requirements are well known, favoring an electronic transition in a gas which can be efficiently pumped in a volumetrically scalable manner. Candidate lasers which we have considered in our technology assessment are:

- Optically pumped Group VI atoms (O, S, Se).
- Optically pumped iodine.
- E-beam-pumped rare-gas-oxide excimers (XeO, KrO).

These laser systems are being conceptually scaled up in size and average power by considering damage limits, cavity Mach number and pressure, superfluorescence and parasitic limits, density nonuniformities, and pumping and flow geometries. Efficiencies included are those of pulse forming, e-beam and optical generation and transfer, quantum processes, extraction, flow cooling and pumping, and chemical regeneration.

Two major conclusions emerge from the analysis. First, optical distortion of the beam due to changes

in the linear index of refraction (density disturbances) may be a serious problem for large visible-wavelength lasers. The rare-gas-excimer lasers, XeO and KrO, suffer greatly in this respect because of their need for high pressure gases of high molecular weight. Because of this problem, fusion lasers are likely to be helium-buffered, one-atmosphere devices of the longest wavelength useful for target coupling.

The second conclusion is that the photolytic Group VI lasers appear attractive, offering overall efficiencies in the 1 to 2% range, in addition to large-volume amplifiers. The photolytic iodine laser is less attractive because its efficiency is limited to around 0.5% for two reasons: a poorer coupling efficiency between the uv pump radiation and the C_3F_7I lasing molecule, and relatively higher energy costs for regenerating the more complex molecule.

As a result of these laser studies, a photolytically pumped Group VI laser will be selected for incorporation into the power-plant conceptual design study next year. This laser system will be developed to a level of detail consistent with the lithium water-fall reactor and the balance of the plant. The laser's optical transport system will have to be properly interfaced with the reactor. Moreover, its power supply and gas conditioning system will significantly impact the plant layout and costing.

Fusion-Fission Hybrids. Earlier neutronic studies reported in the 1975 Annual Report (UCRL-50021-75) identified several promising concepts for producing fissile fuel and electricity with a laser-fusion-driven subcritical fission blanket. The results were encouraging, but it was apparent that a more accurate assessment of the hybrid's potential would require studies that deal with the engineering and economic issues as well as neutronic aspects. With this in mind, we engaged Bechtel Corporation to assist us in a joint effort to conceptually design a laser-fusion hybrid reactor. The design which has evolved in a depleted-uranium-fueled fast fission blanket which produces fissile plutonium and electricity. A major objective of the design study was to evaluate the feasibility of producing fissile fuel with laser fusion. This feasibility evaluation was carried out by analyzing the integrated engineering performance of the complete conceptual design and by identifying the required/pellet performance. The performance of the laser fusion hybrid has also been compared with that of a typical fast-breeder reactor. The results show that the laser fusion hybrid

produces enough fissile material to fuel more than six light-water reactors (LWRs) of equivalent thermal power while operating in a regime which requires an order of magnitude less laser and pellet performance than pure laser fusion. In comparison to a fast breeder reactor the hybrid produces 10 times more fissile fuel. An economic analysis of the design shows that the cost of electricity in a combined hybrid-LWR scenario is insensitive to the capital cost of the hybrid, increasing by only 20 to 40% when the capital cost of the hybrid ranges from two to three times that of an LWR.

Military Applications

The milestones that we are using to gauge our process in the development of laser fusion have been presented in the program overview. In discussing the military applications of laser fusion it is useful to separate these milestones into two categories:

Scientific Milestones

1. Demonstrate laser-driven thermonuclear fusion. (Janus)
2. Implode a target to above 100 times liquid density. (Argus)
3. Achieve significant thermonuclear burn by isentropic compression. (Shiva)
4. Demonstrate high-gain microexplosions; i.e., thermonuclear energy output greater than 50 times the laser light-energy input on target. (Shiva Nova)

Application Milestones

1. Demonstrate laser-fusion reactor feasibility: net energy gain (thermonuclear energy output greater than electric energy input) and high repetition rate. (New laser)
2. Demonstrate electric power and tritium production with an experimental power reactor.
3. Demonstrate a commercial-scale power plant.

The scientific milestones are steps in demonstrating the feasibility of laser-driven high-gain microexplosions. As such they support both the civilian and military goals. The application milestones are concerned with demonstrating the feasibility of producing commercial power with laser fusion.

All of the major laser-fusion facilities at LLL (operating, being built, or planned) support the scientific milestones and they are therefore common to both the civilian and military application goals. The last scientific milestone will be achieved when

high-gain targets are irradiated in the Shiva Nova facility. This facility will have two immediate applications:

- It will drive pellets suitable for commercial power plants on a single-shot basis.
- It will provide a laser capable of conducting significant national-security experiments.

During the past year we initiated a study to develop the national security applications of the Shiva Nova facility. A scoping study identified potential experiments including exposure of satellites and reentry vehicles to neutrons and x rays, and nuclear-explosive physics studies. We began a detailed analysis of exposure experiments late in 1976. The preliminary results are encouraging. They indicate that Shiva Nova will significantly improve the nuclear-effects simulation capability of the United States. Satellites and RVs could be exposed to the high neutron and x-ray fluences of Shiva Nova at a fraction of the cost of underground nuclear-effects testing.

Long-Range Planning

A long-range plan for inertial confinement fusion has been developed to relate present efforts to the ultimate goals and to provide input to the national program's long-range planning. The broader term "inertial confinement fusion" is being used here to indicate that high-average-power sources other than lasers could be used to drive high-gain microexplosions, namely ion beams and electron beams. With this in mind, we have developed a plan which provides for optional technical paths to commercial fusion power. The plan is not a roadmap of the most direct route to the program's end goals. Rather, it is a dynamic tool which will allow management to control the pace of the program effectively and keep it in line with changes in technical progress, national needs, and the nation's commitment to fusion.

The plan provides a broad overview of the major R&D facilities required to commercialize fusion. The functional requirements of these facilities are presented along with an indication of the long lead times necessary to plan and construct them. We intend to review the long range plan continually so that it reflects the most up-to-date information, thereby providing management with a relevant document which will change and evolve as scientific and technical progress occurs. Moreover, by con-

tinually updating our long range plan we will be able to provide timely input to the national program's long range planning. Our progress in long range planning is presented in a later article in this section.

Author

J. A. Maniscalco

7-2 Fusion Reactor Studies

This year, scoping studies were initiated to identify and evaluate attractive reactor concepts for electrical power production with laser fusion. Several reactor concepts have been developed and are being evaluated on comparison criteria that reflect our views of the major issues concerning fusion as a future energy source — leaving aside the question of scientific feasibility, which must be demonstrated in the laboratory.

Fusion has long held the promise of providing an inexhaustible, safe, and clean source of energy. Other important considerations are economic feasibility and environmental acceptability. The comparison criteria we have chosen are source abundance, reactor safety, environmental acceptability, technical feasibility, and economic feasibility. We can judge the relative potential of various reactor concepts by scoring them on the basis of these criteria. Relative weightings have been assigned to the criteria to facilitate the scoring and to document the way the comparative judgments are made.

Comparison Criteria

Source Abundance. A stoichiometric mixture of deuterium and tritium is by far the easiest fusion fuel to ignite. With tritium being regenerated by lithium, the DT fuel cycle basically involves the consumption of deuterium and lithium. These fuels are abundant enough to ensure that fusion will represent a virtually inexhaustible source of energy. It is imperative that reactor concepts for fusion do not seriously diminish fusion's potential as a long-range source of energy by relying on materials that are not abundant.

We have defined an "abundant" energy source as one having the capability of supplying our projected electrical energy needs for several hundred years while using only a fraction of our estimated reserves of any required material. Determination of the fraction of a resource assumed to be available for fusion will take into account other uses of that resource and will also allow for unforeseen future demands. This abundance criterion must be applied to all materials used in the construction, operation, or maintenance of the fusion power plant concept. Specifically we must consider the abundance of the fuel, coolant, and materials used in the fusion pellet, first wall, and blanket regions.

Reactor Safety. Fusion reactors will inherently be safer than fission reactors in view of the following advantages:

- No use of weapons-grade material, thus avoiding the possibility of diversion of such materials for blackmail or sabotage.

- No afterheat cooling problem in case of a loss-of-coolant accident.

- No nuclear runaway from a reactivity insertion or criticality accident.

It is true that fusion reactors will contain tritium and radioactive isotopes created by neutron activation of structural materials. Tritium, however, is a radioactive material with a uniquely low biological hazard potential, and the activation products are essentially fixed in the structure and represent more of a disposal and maintenance problem than a safety problem. The relative safety of fusion reactors may vary for different concept designs. The possibility and consequences of a release of tritium or some chemically toxic material such as LiOH are hazards to be considered in comparing fusion reactors under the safety criteria. These hazards are primarily a function of the particular concept's tritium fuel cycle. Basically, the fuel cycle includes target fabrication, ignition, recovery of unburnt tritium, breeding of tritium in a lithium blanket, and recovery of the bred tritium. The nature of the breeding zone — whether lithium is used as a solid, liquid, or compound — is an important comparative feature since it determines the reprocessing scheme, schedule and thus represents the principal difference in fuel cycles in terms of both tritium inventory and mobility.

Environmental Acceptability. Any major source of energy in the future must be compatible with the environment. Fusion can be expected to have less of

an environmental impact than coal-fueled power plants or fission power plants. Mining requirements for fusion will be orders of magnitude less than for uranium and coal. Different fusion reactor designs may have different environmental effects which must be considered when comparing concepts. Environmental impact will occur before, during, and after the useful life of the fusion reactor. Initially there will be environmental effects associated with the procurement of required raw materials to build the device. During operation, low-level tritium releases will occur as the material diffuses from the reactor. This effect will depend on both the total tritium inventory and the chemical form in which it exists. The degree of thermal pollution will depend on thermal cycle efficiency, which is a function of the allowable operating temperatures in the heat transfer system. Disposal of radioactive waste materials generated by neutron activation may present a significant problem for fusion reactors. Concepts are compared on the basis of both quantity and activity of the waste generated.

Technical Feasibility. The technical feasibility of laser-fusion power plants depends on the solution of two difficult problems. One is the effect of high-energy neutrons and cyclical stresses on the first-wall and blanket structure. The other is the effect of x rays and debris from the fusion microexplosion on the first-wall and final focusing elements. The various concepts are compared on the basis of the degree of engineering complexity and the amount of advanced technology required to solve these problems.

Economic Feasibility. The solutions to the problems of source abundance, reactor safety, environmental acceptability, and technical feasibility will directly determine the concept's economic feasibility. It is being assessed in terms of reactor size, power density, first-wall and blanket lifetimes and special material requirements, fabrication costs, duty cycle, recirculating power fractions, and fuel cycle costs.

Reactor Concepts

The reactor concepts which have been developed and are being compared include:

- A liquid-lithium-cooled stainless steel manifold.
- A gas-cooled graphite manifold.
- Fluidized wall concepts such as (1) a liquid

lithium "waterfall" or (2) a lithium pellet "waterfall."

Before describing these concepts, we introduce some background information on fusion reactor technology and the design parameters and constraints which are common to all of the reactor concepts. This discussion of reactor technology deals primarily with the functions that a blanket system is required to perform and the problems associated with performing these functions in the hostile environment created by the fusion microexplosion.

All of the reactor concepts are based on an inertially confined deuterium-tritium fusion reaction. We have selected thermonuclear yields ranging from 400 to 4000 MJ and pulse repetition rates from 1 to 10 Hz. These parameters result in a reactor system that produces 4000 MW of thermal power and 1200 to 1500 MW of electrical power. The variance in electrical power output results from the different thermal efficiencies and recirculating power requirements of the various concepts. At fuel pellet yields of 400 to 4000 MJ, a fuel cycle cost of 3 mills/kWh will allow fuel-pellet fabrication costs ranging from 10¢ to \$1. The selected parameter space for fusion neutron flux at the first wall ranges from 1 to 10 MW/m², resulting in first-wall radii ranging from 5 to 15 m.

As previously mentioned, the effects of neutrons, x rays, and debris from the thermonuclear microexplosion represent the primary technical concerns that must be dealt with in laser-fusion reactor concepts. High-energy neutrons damage and activate most structural materials, while x rays and debris constitute the principal damage mechanism for first-wall materials. The blanket system must perform several functions while coping with this hostile environment created by the fusion microexplosion. It must:

1. Convert the fusion energy into thermal energy.
2. Provide for efficient removal of the thermal energy.
3. Breed enough tritium to replace that which was burned in the fusion reaction.
4. Maintain the required vacuum in the fusion chamber.

Approximately 75% of the fusion energy is in the form of high-energy neutrons. Therefore a neutron-moderating material is required to convert kinetic energy to thermal energy. In general, elements with low atomic numbers and high scattering cross sec-

tions are effective moderators; water, hydrides, beryllium, and graphite are common examples.

Since there is no significant natural supply of tritium, a DT fusion reactor must breed its own tritium. Several neutron reactions produce tritium, but the only tritium-producing reactions with high enough cross sections to be useful are those involving lithium:

The ⁷Li reaction has a threshold of approximately 4 MeV and a much lower cross section than the ⁶Li reaction; nevertheless it is very important since it produces a T atom without depleting the neutron population. If the neutrons are moderated before reaching the fertile lithium, the ⁷Li reaction is not utilized (since it requires a high energy neutron) and any lost neutrons would result in a tritium-breeding ratio less than 1.0. In such cases the blanket must also contain some sort of neutron multiplier to maintain an adequate breeding ratio. Beryllium with its high (n, 2n) and low capture cross sections is an example of a good neutron multiplier.

The vacuum requirements in the fusion chamber are primarily determined by considerations of laser beam propagation and damage to the injected fuel pellet. If the DT fuel can be incorporated into the pellet in a noncryogenic form, and hence be less subject to damage, beam propagation considerations will limit the fusion chamber pressures to approximately 0.1 Torr. Our calculations show that this vacuum can be maintained under the worst conditions with a vacuum pump that requires approximately 10% of the surface area and uses less than 2% of the plant's power (the worst conditions resulting when all the debris and x-ray energy is used to vaporize lithium).

Liquid-Lithium-Cooled Stainless Steel Manifold. This concept (Fig. 7-2) represents a more conventional approach to a laser-fusion power plant, requiring less advanced technology than the fluidized wall concepts. The microexplosion is surrounded by a cylindrical annulus of stainless steel into which vertical coolant channels have been drilled to form a manifold. Liquid lithium flows down through these channels and is recirculated to the top through a

Fig. 7-2. The first wall of this reactor concept is a stainless steel manifold containing coolant channels through which liquid lithium is circulated.

bulk coolant region which separates the annular manifold from an outer pressure vessel. Liquid lithium serves as the primary coolant, as a neutron moderator, and as the fertile material.

This stainless steel manifold concept is compatible with either a dry or wetted first-wall approach. In the dry-wall approach, we are analyzing a graphite liner which is supported by stainless steel and cooled with liquid lithium. The graphite liner is being designed for an operational lifetime of 1 yr. In the wet-wall approach, we are investigating the possibility and effects of maintaining a thin (3-mm) film of liquid lithium on the inner surface of the manifold.

Tritium-breeding considerations limit the thickness of a structural wall of solid stainless steel to 10 cm or less. However, it would be impossible to utilize a structural wall even this thick without inter-

Fig. 7-3. This reactor concept has a first wall made of graphite blocks containing coolant channels filled with pellets of ceramic lithium through which cooling gas is circulated.

nal cooling. The solid manifold design was conceived to provide additional cooling in that region and also to improve the tritium-breeding performance for a given mass of structural material. In fact, we have obtained tritium-breeding ratios greater than 1 for 40-cm-thick manifolds containing 50% stainless steel and 50% lithium by volume.^{1,2}

It should also be noted that lithium is a corrosive element whose corrosive effects increase with increasing temperature. For use with stainless steel, lithium temperatures must be limited to about 500°C. This peak temperature corresponds to a conventional steam cycle thermal efficiency of 38%. A major disadvantage will result if neutron damage limits the lifetime of the manifold to a few full-power years; this concept will then produce large amounts of radioactive waste in the form of activated steel.

Aspects of the liquid-lithium-cooled stainless steel manifold being investigated include:

1. Structural strength of the manifold.
2. First-wall analysis.
3. Methods of reprocessing tritium from liquid lithium.
4. Neutron damage and activation of structural material.
5. Corrosion of structural material by lithium.

Gas-Cooled Graphite Manifold. The graphite manifold (Fig. 7-3) is similar to the stainless steel manifold concept except that the vertical coolant channels are drilled into an array of graphite blocks which make up the fusion chamber. The vacuum vessel is an outer shell of reinforced, prestressed concrete. High-pressure helium gas is pumped through the coolant channels, some or all of which are filled with pellets of a lithium-bearing ceramic. Tritium is removed from these channels by the gas coolant as it diffuses out of the lithium compound in which it is bred.

The graphite manifold design is a reactor concept involving low activation and low tritium inventories. Moreover, the possibility of an accident occurring which could release radioactivity to the environment is greatly reduced because the lithium is present in solid ceramic form. The graphite moderates the neutrons below activation energy levels. It also moderates the neutrons to energies below the threshold for the ${}^7\text{Li}$ tritium-producing reaction. This makes it advantageous to enrich the lithium in ${}^6\text{Li}$, thereby reducing the required lithium and tritium inventories. Without the tritium-breeding contribution from ${}^7\text{Li}$, a neutron multiplier such as beryllium is required to maintain a tritium-breeding ratio greater than 1.^{1,2}

Some potential problem areas with this concept have been identified. The use of beryllium to multiply neutrons and enhance tritium-breeding presents a problem in terms of beryllium's toxicity and relative scarcity. We are presently investigating the possibility of using lead as the neutron-multiplying material. Large amounts of pumping power will be required for cooling the system and purging the tritium from the pellet-filled channels. Finally, the structural integrity of the graphite chamber in the microexplosion environment may be inadequate.

Specific areas of the graphite manifold which will be studied include:

1. Structural strength of the graphite manifold.

2. Tritium-breeding performance.

3. Diffusion and/or permeation rates of tritium from the lithium ceramic and resulting tritium inventory.

4. Pumping requirements for coolant and vacuum.

5. Corrosion of structural material by lithium.

Fluidized Wall ("Waterfall") Concepts. We are investigating two fluidized-wall concepts: the liquid lithium "waterfall" and the lithium pellet "waterfall."

Liquid Lithium "Waterfall." While wet-wall concepts have previously been proposed to protect the metallic first wall from the soft x rays and pellet debris of fusion microexplosions, the liquid-lithium waterfall concept (Fig. 7-4) offers several additional advantages. Its principal feature is a thick continuous fall of liquid lithium which shields the first structural wall from the microexplosion. The lithium is continuously recirculated to the top of the vacuum chamber through a reservoir region between the first wall and the pressure vessel. Liquid lithium serves as the primary coolant, the neutron moderator, and the fertile material for tritium-breeding.

Ordinarily a 4000-MWt reactor would require a first-wall radius of 10 to 15 m to maintain a 14.1-MeV neutron flux at 1 to 2 MW/m². One of the major benefits of the liquid-lithium waterfall concept is that it allows a reduction in the first-wall radius since the 14.1-MeV fusion neutron spectrum is degraded as it passes through the lithium fall. A 40-cm-thick lithium fall is sufficient to reduce the neutron damage levels in structural materials by more than an order of magnitude. Thus, for a given power, the first-wall radius can be reduced by a factor of 3. The net effect, of course, is a reduction in the capital cost of the reactor vessel.

As one might suspect, the liquid-lithium waterfall concept has excellent tritium-breeding characteristics. With no structural material between the fusion neutrons and the lithium fall, the design takes full advantage of the high-energy ${}^7\text{Li}(n,n'\text{T})$ reaction. For a 40-cm-thick lithium fall followed by a 2-cm stainless steel first wall and a 1-m reservoir region, a tritium-breeding ratio in excess of 1.5 can be obtained.^{1,2}

The liquid lithium waterfall concept also exhibits inherently good cooling characteristics. Fusion neutrons passing through the 40-cm fall, the 2 cm of stainless steel, and the 1-m reservoir region have an

energy multiplication of 1.12 and deposit 98% of their energy directly in the lithium coolant. Since the flow rate of the recirculating lithium fall is much larger than the flow rate to the heat exchanger, the lithium-fall inlet temperature is only 10 to 50 K cooler than the bulk coolant temperature. With an operating temperature in the neighborhood of 750 K, the vapor pressure of lithium is sufficiently low ($\sim 2 \times 10^{-3}$ Torr) to permit adequate vacuum conditions to be maintained in the fusion chamber. In fact, the liquid lithium fall will itself act as a vacuum pump by condensing the lithium that is vaporized

by the microexplosion. The effectiveness of this process depends on the fraction of incident gas atoms absorbed in the liquid surface, and therefore additional vacuum systems may be required. Also, 10 to 75 MWe will be required to recirculate the lithium fall, depending on the particular geometry.

The reactor chamber and primary coolant loops contain on the order of 10^6 kg of lithium. At a tritium-reprocessing capability of 10 ppm, this represents a tritium inventory of about 4 kg in the liquid lithium systems, which is equivalent to the amount of tritium injected as fuel pellets in just a

Fig. 7-4. In the liquid lithium "waterfall" concept, the stainless steel first wall of the reactor is shielded from the microexplosion by a thick screen of falling liquid lithium.

couple days of operation of this system. Of course, one must deal with the corrosive attack of liquid lithium on reactor materials.

Further study of the liquid-lithium waterfall concept will include investigations in the areas of:

1. The hydrodynamics of the falling lithium and its effects on the chamber vacuum conditions.
2. Methods of reprocessing tritium from liquid lithium.
3. Neutron activation of structural material.
4. Corrosion of structural material by lithium.

Lithium Pellet "Waterfall." This fluidized-wall concept is similar to the liquid lithium "waterfall" but with solid ceramic-lithium pellets replacing the liquid lithium. The thick layer of falling pellets (Fig. 7-5) protects the inner liner from direct exposure to the microexplosion. The pellets are either transported through heat exchangers or cooled by the flow of high-pressure helium gas in the reservoir region surrounding the fusion chamber. Tritium is bred in the ceramic lithium compound and recovered as it diffuses out.

As with the liquid lithium waterfall, the region of falling pellets will moderate and absorb neutrons before they reach the first structural wall, and this will result in a significant reduction in the degree of first-wall damage and the amount of radioactive waste produced by neutron activation. The use of lithium in a ceramic form is an important feature of this concept in that it eliminates the corrosive problems of liquid lithium and essentially eliminates the associated chemical hazard.

Major questions, such as tritium diffusion from the pellets and structural integrity of the ceramic compound, cannot be answered satisfactorily with existing data. More information may be forthcoming from the University of Wisconsin study³ which uses Li_2O as a blanket and heat-transport material. Other areas for future study include:

1. Dynamics of falling pellets.
2. Tritium-breeding performance.
3. Methods of tritium recovery.
4. Power required for coolant and vacuum pumping and for pellet transportation.
5. Neutron activation of reactor materials.

Evaluations

It has been the experience of the nuclear fission industry that once scientific feasibility has been achieved, the materials development program paces

Fig. 7-5. The lithium-pellet "waterfall" concept is similar to the liquid lithium waterfall except that the screen of falling material is solid ceramic-lithium pellets rather than liquid lithium.

the demonstration of technical and economic feasibility. The evaluation of the fluidized wall concepts is, however, less dependent on materials development since damage due to x rays and debris is eliminated and high-energy neutron damage is significantly reduced. The analysis of the liquid lithium system is further facilitated by the availability of data on the properties of liquid lithium and the existence of liquid-metal experimental facilities built in support of the liquid metal fast breeder reactor (LMFBR) program. Therefore, while the evaluation of all reactor concepts and further development of the comparison criteria will be continued, a conceptual design of a laser-fusion power plant based on the liquid lithium waterfall concept will be started during the coming year.

References

1. E. F. Plechaty and J. R. Kimlinger, *TART Monte Carlo Neutron Transport Code*, Lawrence Livermore Laboratory, Rept. UCID-17026 (1976).
2. *An Integrated System for Production of Neutronics and Photonics Calculational Constants, Vol. 15, the LLL Evaluated Nuclear Data Library (ENDL)*, Lawrence Livermore Laboratory, Rept. UCRL-50400 Vol. 15 (1975).
3. R. W. Conn et al., *Studies of the Technological Problems of Laser Driven Fusion Reactors, Annual Report I*, University of Wisconsin, Rept. UWFD-190 (1976).

Author

W. R. Meier

7-3 First-Wall Studies

The first wall of a laser fusion reactor stands between the microexplosion cavity and the remainder of the reactor. In about $1 \mu\text{s}$, the first wall absorbs about 20 to 35% of the microexplosion energy in a layer less than $50 \mu\text{m}$ thick. Thus, the surface layer of the first wall experiences temperature and stress pulses of large amplitude, short wavelength, and short duration.

Several conceptual designs have been proposed for pure-laser-fusion reactors to cope with the first-wall problems typical of inertially confined fusion reactors. Four different types of first wall have been proposed: a dry wall, a wet wall, a flowing-fluid wall, and a magnetically shielded wall. They differ primarily in the way the first wall interfaces with the laser-pellet interaction and burn debris.

Previous reactor studies have been conducted on wet or magnetically protected first walls.^{4,6} This report focuses on the design of dry wall concepts featuring either a sacrificial liner or an unprotected metal wall.

The dry wall concept uses an unprotected metal or graphite wall between the blanket and microexplosion chamber. A metal first wall is desirable because the fabrication is relatively simple and the vapor pressure is low so that the vacuum-system power requirements are small. Because the dry wall does not renew itself after each microexplosion as the more complex wet-wall or flowing-fluid-wall concepts do, we have arbitrarily specified (for comparison purposes) that a dry first wall must have a lifetime of at least a year in the harsh environment

of an inertially confined fusion reactor to be eligible for consideration in the matrix of conceptual first-wall designs.

In this report we present analytical methodology of the response of a dry first wall to the interaction between the ignition beam and the pellet and to the subsequent microexplosion. We show the response of a dry first wall to microexplosions of two grossly different yields. The small-yield case is a 10-MJ microexplosion in a laser-initiated, fusion-fission hybrid reactor with a fusion power of 200 MW.⁷ The large-yield case is an ion-beam-initiated (4000-MWt), inertially confined fusion reactor using 4000-MJ microexplosions.⁸

The results of these two studies show that a graphite first-wall liner is one of the more viable concepts in the matrix of conceptual first-wall designs. In fact, if the microexplosion chamber pressure must be less than 10^{-2} Torr before each microexplosion (to avoid beam propagation losses that occur at higher pressures), a dry wall may be the simplest viable first-wall concept.

Analytical Methodology

The methodology we have used in our studies to determine the response of the first wall to the environment created by the thermonuclear microexplosion is shown in Table 7-1. This analysis starts with the laser-pellet interaction and thermonuclear burn. The two-dimensional hydrodynamic-energy-transport code LASNEX is used to calculate the energy partition and spectra from laser-pellet interaction and thermonuclear burn.⁹ The energy deposition in the first wall from laser photons reflected from the pellet is estimated using classical relationships for the propagation of electromagnetic radiation in homogeneous, isotropic conducting media at rest.^{7,10-12} The energy deposition from the x rays produced from the thermonuclear burn is calculated using the code BUCKLE (LLL's version of a code developed by Cole¹³). The energy deposition in the first wall from the charged particles in the pellet blast debris is estimated by coupling range-energy relationships of the particles in the first-wall material with the energy distribution of the debris.^{11,12} The neutron energy deposition in the first wall is calculated using coupled neutron-gamma transport codes such as ANISN¹⁴ or TART¹⁵ with the cross sections from LLL's Evaluated Nuclear Data Library.

The response of the first-wall material to the energy deposition from various sources is calculated using the coupled radiation-diffusion, hydrodynamic code CHART D.¹⁶ The thermal response of the first wall to the various energy sources is coupled together to determine the amount of material vaporized from the surface of the first wall per microexplosion.

The coupled thermal response analysis assumes that all the x-ray and debris energy is deposited at the surface of a semi-infinite solid. The initial temperature of the solid is assumed fixed, and the thermal properties of the solid are assumed to be invariant with temperature. During the times when no energy flux is acting on the surface, the surface is assumed to be adiabatic. Finally, the solid is assumed to undergo no phase change, and the surface position does not move even when the surface temperature exceeds the melting point or the boiling point of the material.

Another consideration in the design of a fusion-reactor first wall is the mass of first-wall material vaporized during a shot cycle. This mass transfer

will, in part, determine the vacuum pumping requirements for the reactor system. The mass transfer analysis assumes only surface vaporization due to the difference in the vapor pressure of the first-wall material and the cavity pressure as a function of the surface and cavity gas temperatures and time. The initial cavity partial pressure of the first-wall material is fixed depending on the type of reactor. When the partial pressure in the chamber due to the vaporization of the first-wall material is the same as the vapor pressure, mass transfer from the wall is assumed to cease. Mass transfer from the cavity to the first wall is not considered during the portion of the shot cycle that the surface temperature is less than the cavity gas temperature. An upper limit of the mass transfer is established, based on the latent heat of vaporization at the boiling point of the first-wall material.

Another consideration for the first-wall materials is the thickness of material lost per shot. This loss, assuming no condensation of the gas in the cavity back onto the surface, will determine the lifetime of the first wall (neglecting fatigue, neutron damage,

Table 7-1. Analytical methods used in first-wall design studies

Information provided	Computational tool	Description
Yields and spectra (temporal and energy) for x rays, charged particles, and neutrons at the first wall	LASNEX code	A two-dimensional hydrodynamics code which mathematically simulates thermonuclear microexplosions
X-ray energy deposition profiles in the first wall	BUCKLE code	An x-ray transport code which treats photoelectric absorption, Compton scattering, pair production, and fluorescence
Charged-particle energy deposition profiles	Range-energy relationships	Solves LSS derived transport equation
Neutron energy deposition profiles	ANISN code	One-dimensional discrete ordinates code which treats coupled neutron/gamma-ray transport
Response of the first wall (temperature, pressure, and stress) to the energy deposition profiles	CHART D code	A one-dimensional coupled energy-flow/Lagrangian-hydrodynamics code

and chemical reactions with hydrogen isotopes). The design criterion used is that the first wall will lose about 1 cm of material per year.

First-Wall Designs

Laser Fusion-Fission Hybrid. A joint JLL-Bechtel effort to conceptually design a laser fusion-fission hybrid power plant to produce fissile fuel was performed in 1976. This 1400-MWt plant, based on a fusion driver with a power of 200 MW using 10-MJ microexplosions, will produce about 1300 kg of plutonium a year from the depleted uranium blanket. The overall plant description is given by Maniscalco¹⁷; Hansen¹⁸ provided the neutronic analysis of the reactor.

The laser system's energy output is delivered with a time-shaped, variable-wavelength pulse, with a final pulse wavelength of 0.5 μm containing 80% of the laser output energy and delivered over a time of 0.4 ns.¹⁹ The total laser output energy is 477 kJ, with 320 kJ absorbed by the pellet. The remainder of the laser output energy is reflected from the pellet because of Brillouin scattering during the final portion of the high power pulse.

The solid DT pellet has a mass of 0.38 mg. Pellet gain based on the laser output energy is 21, and the thermonuclear yield of the microexplosion is 10 MJ. The burn fraction of the pellet is 0.082. Table 7-2 gives the energy partition from the laser-pellet interaction and microexplosion.

The x-ray and neutron spectra are as presented in earlier reports.^{5,20} The x-ray energy spectrum is peaked at about 3 keV, and the neutron energy spectrum closely resembles that of a 14-MeV monoenergetic source. Most of the alpha energy is assumed to be deposited within the pellet. About 30% of the alpha energy escapes from the pellet with

an average particle energy of 2 MeV. The pellet debris is assumed to have a Maxwellian energy distribution with an average energy of 53 keV/amu.

The reference first wall, located 3.5 m from the microexplosion, consists of a 20-mm-thick layer of graphite blocks mounted on a stainless steel backing plate as shown in Fig. 7-6. Each graphite plate is mounted by a single fastener to the backing plate to minimize the mechanical constraints on the plates. The graphite plates are loosely overlapped to prevent the reflected laser light and microexplosion debris from directly striking the stainless backing plate. The heat is transferred from the graphite

Fig. 7-6. Reference first wall for the fusion-fission hybrid reactor.

Table 7-2. Energy partition from laser-pellet interaction and microexplosion

Energy form	Energy (MJ)
Reflected laser light	0.16
X rays	0.10
14-MeV neutrons	7.7
Energetic alpha particles (2-MeV average)	0.7
Pellet debris	1.8

plates by thermal radiation and conduction to the stainless backing plate, which is cooled by a liquid metal coolant.

The stresses and temperature rise in the reactor are a function of the energy deposition of the laser-pellet interaction and various burn products in the reactor. The present models used to estimate the energy deposition in the reactor for the laser light reflected from the pellet, x rays, energetic alphas, and pellet debris from the microexplosion are described earlier in this section. The times of arrival at the first wall of the various energy sources are shown in Fig. 7-7.

The density of the energy deposited in the first wall by the reflected laser light is, for the 3.5-m-radius graphite first wall and 157 kJ of reflected 0.5- μ m laser light,

$$\frac{q_L'''(x)}{\rho} = 28.6 \exp(-5 \times 10^7 x) \text{ kJ/g}$$

where x is in m. The reflected laser light energy from

Brillouin scattering is assumed to be deposited on the first wall over a span of 0.2 ns.

For the typical x-ray spectrum from solid-DT laser fusion, the energy deposition as a function of depth for the graphite first-wall liner design is shown in Fig. 7-8 for a 10-MJ-yield microexplosion with a first-wall radius of 3.5 m (650 J/m² of x rays). The fraction of the incident x-ray energy flux that escapes through the graphite liner is about 20%. About 2% of the x-ray flux escapes through the combined graphite and stainless steel of the first wall. The x-ray energy is deposited on the first wall over a span of 10 ps, which is the pellet burn time.

The pellet blast debris from a laser-fusion reaction consists of tritons, trapped alphas, and deuterons, as well as residual products (first-wall material, etc.) from the previous microexplosion. The range of various debris ions in the graphite as calculated by Lee Haggmark of Sandia-Livermore is shown in Fig. 7-9. The tritons contain about 59% of the debris energy, the deuterons contain about 39%, and the trapped alphas contain the remainder. The debris energy deposition in the graphite wall is

Fig. 7-7. Energy vs arrival time at first wall for the various kinds of energy produced in the microexplosion. Radius of first wall (distance from microexplosion) is 3.5 m.

shown in Fig. 7-10. The pulse time over which 95% of the debris energy arrives at the first wall is 1.23 μ s.

The 2-MeV alpha particles that escape from the pellet have a range of about 6.9 μ m in the graphite first wall. The alpha-particle energy deposition is 400 J/g over their range for a 3.5-m-radius chamber. The energy is assumed deposited in a time pulse of 10 ps.

The neutron energy of 0.09 J/g is deposited uniformly in the graphite over a time span of 10 to 1000 ps. The response of the graphite to the neutron energy deposition is negligible.

A summary of the surface energy deposition, deposition depth, and deposition time is given in Table 7-3 for the various energy sources, together

Fig. 7-8. X-ray energy deposition in 3.5-m-radius first-wall liner for x-ray fluence of 650 J/m^2 .

Fig. 7-9. Range-energy relations for three ion species in graphite of density 1.65 g/cm^3 .

with the response of the graphite first-wall liner. The largest temperature rise and stress in the graphite is produced by the laser light energy reflected from the pellet. The pellet debris causes the second-largest temperature rise, while the high energy alphas that escape the pellet cause the second-largest stress. The temperature rise and stress from the x rays and neutrons are negligible.

Energy from the laser light reflected from the pellet will spall off a $0.1\text{-}\mu\text{m}$ -thick layer from the front surface of the graphite first wall, according to calculations assuming a short-time tensile strength of 100 MPa as given by Varnado and Carlson.²¹ For 20 microexplosions a second, this spall gives a wall recession rate of about 10 mm/hour. To eliminate this spall, the surface energy deposition from the reflected laser light must be reduced to 20 kJ/g, which will also result in a reduced surface-temperature rise (to only 2400°C rather than 2900°C).

This temperature rise above the ambient graphite temperature is decreased to 1050°C in 1 ns. Thus, at the time the debris arrives at the wall, the graphite temperature should be within 50°C of its steady-state value.

Fig. 7-10. Energy deposition in graphite liner by charged particles produced in the microexplosion (particle fluence = 11.8 kJ/m^2 , graphite density = 1.65 g/cm^3). Particle energy distribution: $D = 0.389$, $T = 0.583$, $\alpha = 0.028$. High-energy alpha particles that escape the pellet are not included.

The surface recession rate per microexplosion due to vaporization of the graphite is given in Table 7-4 for several steady-state surface temperatures. The analysis assumes that the deposition of reflected laser-light energy is reduced below the spall limit as described above. Also given in Table 7-4 is the mass of graphite lost per microexplosion as well as the lifetime of a 10-mm thickness of graphite. The heat transfer from the graphite slab to the stainless plate must be increased above that permitted by pure thermal radiation to have a reasonable graphite lifetime. Since the temperature rise across the graphite thickness is about 200°C , the surface thermal conductance between the graphite slab and the stainless plate must be more than $1.5 \text{ kW/m}^2\text{-}^\circ\text{C}$.

An additional loss of graphite may be caused by the interaction of the deuterons and tritons with the graphite to form acetylene or methane.^{22,23} If we

Table 7-3. Calculated energy deposition in the graphite first wall from the various energy sources, and corresponding response of the graphite

Energy source	Fluence (kJ/m ²)	Surface deposition (kJ/g)	Deposition depth (μm)	Deposition time (ns)	Surface temperature rise (°C)	Peak tensile stress (MPa) ^a
Reflected laser light	1.0	28.6	0.02 ^b	0.20	2900.0	>100 ^c
X rays	0.65	0.006	7.2 ^b	0.01	2.0	0.2
14-MeV neutrons	50.0	9×10^{-5}	—	0.01	—	—
High energy alphas	4.5	0.40	6.9	0.01	200.0	33.0
Pellet debris	12.0	4.7	1.6 ^b	1230	950.0	<0.1

^aSpall strength of graphite is 10^2 MPa .

^bDepth at which energy deposition is e^{-1} of the surface deposition.

^cSpalls at a depth of 0.1 μm . Surface deposition of reflected laser light would have to be reduced to 20 kJ/g to prevent such spalling.

Table 7-4. Calculated surface recession of graphite due to vaporization at various operating temperatures (for microexplosion frequency of 20 per second)

Steady-state surface temperature (K)	Peak surface temperature (K)	Recession rate ($\mu\text{m}/\text{microexplosion}$)	Mass lost (g/s)	Lifetime (time to reduce graphite thickness by 10 mm) (hours)
1200	3600	1.7×10^{-5}	0.088	8000
1782	4180	8.5×10^{-3}	43	16
2072	4470	0.11	550	1.3

Reference temperatures

Lithium (B.P. = 1620 K)

Stainless (M.P. = 1450 K)

Niobium (M.P. = 2740 K)

Graphite (S.P. = 3900 K)

Base = 800 K

assume that each hydrogen isotope chemically reacts with a carbon atom, the wall recession rate due to the chemical reaction is $1.3 \times 10^{-4} \mu\text{m/s}$ for a microexplosion frequency of 20 s^{-1} .

Inertially Confined Fusion Reactor. A first-wall design study for a 4000-MJ-per-microexplosion, 4000-MWt fusion reactor was performed for the ERDA Summer Study of Heavy Ions for Inertial Fusion.⁶ The total yield in x-ray and debris energy was fixed at 32% of the thermonuclear yield.

The materials considered for the first wall included liquid lithium (wet wall), niobium, stainless steel, and two types of graphite. The first type of graphite was assumed isotropic, while the second type was assumed to be highly anisotropic, with the maximum thermal conductivity in the radial direction of the reactor.

The peak temperature at the surface of the first wall for the various materials as a function of the reactor radius is shown in Fig. 7-11 for a surface temperature of 800 K prior to each microexplosion. The mass lost from the surface of the reactor first wall is shown in Fig. 7-12. The inflections in the curves occur where the energy is conducted away from the surface at a rate such that the mass lost is less than that possible considering only the latent heat of vaporization. The surface recession of first wall material per shot is shown in Fig. 7-13. The

Fig. 7-11. Peak liner surface temperature as a function of reactor radius for a 4000-MJ microexplosion.

Fig. 7-12. First-wall mass loss per 4000-MJ microexplosion as a function of reactor radius for several candidate first-wall materials.

results from Figs. 7-11 through 7-13 are summarized in Table 7-5 for a surface recession rate of 10^{-3} μm per microexplosion (10 mm/year). Lithium is not listed in Table 7-5 since the surface recession rate of lithium is not relevant; the lithium is replenished after each microexplosion.

If the cavity pressure is limited to a maximum of the order of 10^{-2} Torr prior to each microexplosion because of ignition beam injection considerations, then lithium is not a viable candidate for a first-wall material. If the maximum cavity pressure is not a limitation on the efficiency of the ion beam injection,

however, then the lithium wet-wall concept is a viable alternative to the dry wall concept since the recirculation of 70 kg of lithium between shots is not anticipated to be troublesome. Since the maximum allowable chamber pressure between shots is currently an open question, the use of lithium as a first-wall material will not be discussed further.

For a given blanket design (including structure) several first-wall designs are apparent. Basically they consist of using a liner which is mounted independently of the blanket so that the liner can be replaced without removing all the blanket. The

Fig. 7-13. First-wall recession per 4000-MJ microexplosion as a function of reactor radius for several candidate first-wall materials.

Table 7-5. Characteristic performance of several first-wall materials in a 4000-MWt reactor with a 4000-MJ yield per microexplosion and a surface recession of 10^{-3} μm per microexplosion

Material	Radius (m)	Neutron flux (MW/m ²)	Peak temperature (K)	Mass lost (g/s)
Niobium	15.1	0.95	2980	25
Stainless steel	23.1	0.41	1700	52
Graphite	15.7	0.88	2700	5.1
Pyrolytic graphite	10.2	2.1	2700	2.2

arrangement that makes it easiest to remove the liner without removing much of the blanket is a hollow cylindrical blanket with covers on the top and bottom. Thus, to change all the liners, only the top cover of the blanket need be removed. Since the impulse load from the pellet can be handled for millions of shots (without consideration of neutron damage) by a 2- to 3-cm-thick cylindrical shell of either niobium or stainless steel at 800 K, the following designs are possible:

1. A stainless steel or niobium liner 4 cm thick.
2. A niobium inner liner 2 cm thick in a 3-cm-thick stainless steel shell.
3. A graphite inner liner 2 cm thick in a 3-cm-thick stainless steel shell.

The back side of these liners can be cooled by a gas or a liquid metal as shown in Fig. 7-6. The inner liner is not a load-carrying member but serves only to reduce the vacuum pumping loads, increase the lifetime, and decrease the cost of the liner by using a cheaper material (stainless steel) as a structural material to support the more expensive material (niobium), or to support a material that is weak in tension (graphite).

The fabricated costs of the first-wall materials are given in Table 7-6. These costs are only best guesses, and should not be regarded as written in stone. For comparison, Fleischer et al.²⁴ give a fabricated cost of 316 stainless steel as \$13.2/kg and Nb-1% Zr as \$176/kg.

The volume of the first wall is based on a "square" cylinder (height equal to diameter) with top and bottom covers. The cost of the first-wall liner for various material combinations in a 4000-MWt reactor using 4000-MJ microexplosions is

Table 7-6. Estimated fabricated costs of various first-wall materials (Ref. 25)

Material	Cost (\$/kg)
Stainless steel	30
Niobium	120
Graphite (isotropic)	22
Pyrolytic graphite	3000

given in Table 7-7, based on data from Tables 7-5 and 7-6. The cost of the first-wall liner per unit of electrical power for various combinations of materials and pellets is also given in Table 7-7. This cost assumes a liner lifetime of 4000 MWt-years (1320 MWe-years). For a first-wall liner lifetime of one year based on a 10^{-3} - μ m surface recession per microexplosion, the isotropic graphite over stainless steel is the least expensive first-wall liner, and the solid stainless steel is next to least expensive.

Graphite Issues

Graphite appears to be a viable first-wall material for inertially confined fusion reactors based on the two examples considered. However, there are many issues with graphite that have not been answered in these designs.

The synergistic effects of the energy deposited in the graphite from each source were not very well investigated. Also, while the formation of acetylene

Table 7-7. Estimated cost of first-wall liner for various materials. Basis 1 is cost from Table 7-6; Basis 2 is cost based on estimates of Fleischer et al.²⁴ for stainless steel and niobium

Material(s)	Cost (\$10 ⁶)		Cost (mills/kWhe)	
	Basis 1	Basis 2	Basis 1	Basis 2
Stainless steel	94.3	41.5	3.35	1.47
Niobium	178	261	6.27	9.19
Niobium/stainless	119	144	4.20	5.07
Graphite/stainless	36.0	17.7	1.27	0.625
Pyrolytic graphite/stainless	210.0	202.0	7.14	6.88

from the interaction of hydrogen isotopes with graphite does not appear to be a large problem, the effect of sputtering of the graphite has not been investigated. This will require development of high-energy pulsed ion sources which can produce roughly 10^{20} hydrogen isotope ions in 1 μ s, and roughly 10^{19} high-energy alpha particles in 10 ps. The effect of intense pulses of neutrons on the lifetime of graphite has also not been investigated. Finally, the effects of repetitive stresses need to be investigated.

Evaluations

This report does not cover all the issues of a dry wall concept for inertially confined fusion reactors. Other considerations and problems are discussed in the literature.^{7,8,21,26,27} However, we have developed a methodology for the analysis of the first-wall response to the beam-pellet interaction and microexplosions, and we are continually developing analytical tools to assist us in implementing the methodology. At some time we must have experimental data to use with our analytical tools for first-wall analysis, and experimental results of the effects of short-time pulses of energetic particles on candidate first-wall materials. These experimental results are necessary to normalize the results from our analytical tools.

Graphite is a viable first-wall material for inertially confined fusion reactors, especially for beam/pellet combinations that minimize the amount of beam energy reflected from the pellet, and for reactors that require low cavity pressures due to beam propagation considerations. The cost of a graphite first wall and its response to the microexplosions used in these calculations are encouraging; lifetimes greater than a year appear possible with first-wall neutron fluxes on the order of 1 MW/m^2 , at costs less than 1 mill/kMWe.

References

1. L. A. Booth, "Central Station Power Generation by Laser-Driven Fusion," *Nucl. Eng. Design* 24, 263 (1973).
2. J. Hovingh, J. A. Maniscalco, M. Peterson, and R. W. Werner, "The Preliminary Design of a Suppressed Laser Induced Fusion Reactor," in *Proc. 1st Topical Meeting on Technology of Controlled Nuclear Fusion*, San Diego, Calif. (1974), Vol. I, p. 96.
3. T. Frank, D. Freiwald, T. Merson, and J. Devaney, "A Laser Fusion Reactor Concept Utilizing Magnetic Fields for Cavity Protection," in *Proc. 1st Topical Meeting on Technology of Controlled Nuclear Fusion*, San Diego, Calif. (1974), Vol. I, p. 83.
4. J. Hovingh, "First Wall Studies of a Laser-Fusion Hybrid Reactor Design," in *Proc. 2nd Topical Meeting on Technology of Controlled Nuclear Fusion*, Richland, Washington (1976).
5. J. Hovingh, "Ion-Beam Reactor First Wall Design," *ERDA Summer Study of Heavy Ions for Inertial Fusion*, Lawrence Berkeley Laboratory, Rept. LBL-5543 (December 1976), Appendix I.3.
6. G. B. Zimmerman, *Numerical Simulation of the High Density Approach to Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-74811 Preprint (October 1973).
7. M. Born and E. Wolf, *Principles of Optics* (Pergamon Press, Oxford, 1975), 5th Ed., p. 614.
8. J. Hovingh, "First Wall Response to Energy Deposition in Conceptual Laser Fusion Reactors," *J. Nucl. Materials* 63, 158 (1976).
9. J. Hovingh, *Design Considerations in Inertially-Confined Fusion Reactors*, Lawrence Livermore Laboratory, Rept. UCRL-78499 Preprint (August 1976).
10. R. K. Cole, Jr., *BUCKL: A Program for Rapid Calculation of X-Ray Deposition*, Sandia Corporation, Rept. SC-RR-69-855 (1970).
11. W. W. Engle, Jr., *Users Manual for ANISN*, Union Carbide Corporation, Rept. K-1963 (March 1967).
12. E. F. Plechaty and J. R. Kimlinger, *TART Monte Carlo Neutron Transport Code*, Lawrence Livermore Laboratory Internal Document UCIR-522 (1971). Readers outside the Laboratory who desire further information on LLL internal documents should address their inquiries to the Technical Information Department, Lawrence Livermore Laboratory, Livermore, California 94550.
13. S. L. Thompson, *Improvements in the CHART D Energy Flow Hydrodynamic Code: V. 1972/73 Modifications*, Sandia Laboratories, Albuquerque, Report SLA-73-0477 (1973); see also S. L. Thompson and H. S. Lauson, *Improvements in the CHART D Radiation Hydrodynamic Code: II. A Revised Program*, Sandia Laboratories, Albuquerque, Rept. SC-RR-71-0713 (1972).
14. J. A. Maniscalco, "A Conceptual Design Study for a Laser Fusion Hybrid," in *Proc. 2nd Topical Meeting on Technology of Controlled Nuclear Fusion*, Richland, Washington (1976).
15. L. F. Hansen and J. A. Maniscalco, "Neutronic Study of a Laser-Fusion Hybrid Reactor Design," in *Proc. 2nd Topical Meeting on Technology of Controlled Nuclear Fusion*, Richland, Washington (1976).
16. A. R. Thiessen and J. Nuckolls, "Pellet Design for a Laser-Fusion Reactor," in *Laser Program Annual Report - 1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), pp. 391-395.
17. J. Nuckolls, J. Emmett, and L. Wood, "Laser-Induced Thermonuclear Fusion," *Physics Today* (August 1974), p. 1.
18. S. G. Varnado and G. A. Carlson, "Considerations in the Design of Electron-Beam-Induced Fusion Reactor Systems," *Nucl. Technol.* 29, 415 (June 1976).
19. M. Balooch and D. R. Olander, "Hydrogen Attack of Fusion Reactor First Walls Made of Graphite," *Trans. ANS 1975 Winter Meeting, San Francisco, Calif.* (1975), p. 164.
20. B. Feinberg and R. S. Post, "Graphite Surface Erosion and Blistering," *J. Vac. Sci. Technol.* 13, 443 (Jan./Feb. 1977).
21. L. R. Fleischer, R. R. Holman, and H. B. Kellogg, "Trade-Offs in Laser Fusion Power Systems: Module Size," *Trans.*

ANS 1975 Winter Meeting, San Francisco, Calif. (1975), p. 69.

25. J. A. Maniscalco, Lawrence Livermore Laboratory, private communication (August 9, 1976).
26. M. Williams, F. T. Finch, T. G. Frank, and J. S. Gilbert, "Engineering Design Considerations for Laser Controlled Thermonuclear Reactors," in *Proc. 5th Symposium on Engineering Problems of Fusion Research, Princeton, N.J.* (1973), p. 102.
27. J. A. Maniscalco, *Reactor Design for Ion Beam Fusion*, Lawrence Livermore Laboratory Internal Memorandum SS&A 76-079 (August 10, 1976).

Author

J. Hovingh

7-4 Laser System Studies

A completely suitable high-average-power gas laser for a fusion power plant has not yet been identified. The critical deficiency appears to be overall efficiency rather than scalability to high energy per pulse or average power. Gas laser technology is still young, but we believe it is not premature — using the most promising short-wavelength gas lasers — to begin the problem-solving process that accompanies the conceptual design of full-scale systems.²⁸ We have launched such an investigation, with the following objectives:

- To construct a parameterization — a simple systems model of a high-average-power gas laser system (400 to 1000 kJ, 1 to 10 pps) — to facilitate comparison of candidate lasers on a consistent and realistic basis.

- To define such laser subsystem requirements as electrical power conditioning, gas conditioning, chemical regeneration, and optical interfacing with a reactor.

- To perform initial system performance and cost tradeoffs, both within the laser system and in conjunction with the reactor system.

- To identify key technical issues for advanced gas laser research and development.

To fulfill these objectives, one does not have to model any particular laser in great detail. Rather, a generic class, such as the photolytic lasers to be discussed, may adequately posit the pulsed power, e-beam, gas flow, chemical regeneration, optical quality and damage problems characteristic of high-

average-power systems, thus allowing the beginning of a fruitful assessment of technology and systems.

The class of lasers chosen for the first comparison study consists of electronic-transition atomic species formed by photolytic dissociation from a parent molecule carried in a rare gas buffer such as helium.^{29,30} The source of photolysis photons would be e-beam-excited rare gas fluorescence, possibly doped with another molecule to enhance fluorescence radiation in the absorption band of the molecule to be photolyzed. Table 7-8 lists features of photolytic lasers that recommend them for fusion power plants. These features include favorable target coupling characteristics, high energy storage per aperture, promising overall efficiency, and a choice of lasing atom and pump molecule combinations.

Figure 7-14 shows the configuration of a high-average-power photolytic laser system that appears very scalable to large volumes and high energy per pulse. The fluorescer gas and laser gas regions are kept apart by the stability of coflowing streams of different gases. The pressure and velocity of the two gases are matched; the density, temperature, and mach number generally will be different. This has the tremendous advantage of not requiring uv-transmitting windows, which probably would not be able to withstand damage from high fluence levels of uv photons and 1-Mev electrons in addition to the steady and shock pressure loads over large spans (greater than 30 cm).

The configuration chosen is not the only possible photolytic laser. If a window can be found allowing operation of the fluorescer gas at significantly higher pressure than the laser gas, or if an efficient uv laser-pumped scheme can be devised, higher overall efficiencies may result. The flowing windowless-fluorescer geometry was chosen for this study because we have sufficient information on fluorescer efficiency and because it is demonstrably scalable to high average power. Further improvements in efficiency will no doubt come through future innovations in pumping configurations.

The lasing sequence is begun by the firing of two opposed ~1-Mev e-beams for approximately 1 μ s. In the case of the selenium laser sketched in Fig. 7-14, electrons radiolyze the xenon, resulting in copious xenon excimer (Xe₂) fluorescence radiation. The lasing medium consists of approximately $\times 10^{16}$ cm⁻³ of OCSe in 1 atm of helium buffer gas, the purpose of which is to pressure-broaden the

Table 7-8. Features of pyrolytic lasers

1. Choice of system:

<u>Lasing atom</u>	<u>Lasing wavelength, nm</u>	<u>Parent molecule</u>	<u>Fluorescer excimer</u>	<u>Fluorescer wavelength, nm</u>
Iodine	1130	C_3F_7I	$XeBr^*$	280
Oxygen	558	N_2O	Ar^*	130
Sulfur	772	OCS	Kr_2^*	150
Selenium	489	OCS ₂	Xe_2^*	170

2. Favorable target coupling characteristics:

- Wavelength: $\lambda = 0.5 - 1.3 \mu m$
- Short pulse duration: $\tau \sim 1 - 10 ns$

3. High-energy storage:

- $F_{saturation} \sim 1 J/cm^2$

4. Favorable scaling characteristics:

- Configurations allow flowing, high-average-power systems.
- Can use low-pressure ($\sim 1 atm$), low-temperature ($\sim 300 K$), low-index gases (e.g. helium) for good beam quality
- Beam quality and gain uniformity limited by gas density uniformity, not by E-beam deposition uniformity.
- Aperture scaling limited by materials and gain constraints rather than by properties of the atoms and molecules.

5. Efficiency $> 1\%$ possible from the physics.

laser transition and provide sufficient heat capacity to minimize the increase in gas temperature. The fluorescence radiation dissociates the parent molecule; the resulting excited Se^* atom stores the energy long enough to achieve high-energy storage fusion amplifiers.³¹

The molecular absorber is optically thick to the fluorescence radiation so that the photolysis occurs by a bleaching wave that is driven into the medium, dissociating the molecule and causing the mixture to become transparent. The sequence ends with injection of a 1-ns laser pulse that causes the medium to depopulate during amplification. The other laser systems using O^* , S^* , and I^* operate similarly, except the iodine is pumped in an optically thin manner.

Note that the configuration shown in Fig. 7-14 is a classic scalable geometry with the pump, flow, and

optical extraction axes mutually orthogonal. This is a convenient way to decouple these important processes and reach the largest possible sizes based solely on constraints of the individual processes. An artist's conception of a full-size flowing gas laser system is presented in Fig. 7-15.

There are two very important and separate aspects to a large laser system: efficiency and scalability. A laser system of high efficiency will have lower recirculating power needs and lower capital equipment costs. The efficiency depends on the losses due to power conditioning, fluorescence production, coupling of the laser molecule, optical extraction, and pumping, cooling, and chemical regeneration of the flowing gases.

On the other hand, a laser built with a large single aperture size and energy per pulse lowers costs by reducing complexity in the number of beams and

Fig. 7-14. End view of flowing windowless geometry. The skewed beam integrates out the effect of bleaching-wave disturbances.

components. The scalability depends on optical and e-beam damage limits, pump constraints, flow and gas uniformity constraints, parasitic suppression, thermal distortion, and arrival at a configuration that simultaneously pushes all the important technology barriers.

In fact, in any given laser system, it is usually possible to trade off efficiency vs scalability to achieve an optimal system. We can summarize both these important aspects for the class of photolytic lasers.

System Efficiency

Figure 7-16 is a power flow diagram of a photolytic laser system. Electrical power is taken continuously from the power plant's generating system for the electrical power conditioning (P_{EPC}),

for the fluorescer gas conditioning (P_{FGC}), and for the laser gas conditioning (P_{LGC}). The laser system output is the laser radiation focusable on target after the optical train, P_o . The overall laser system efficiency is then

$$\eta_{LS} = \frac{P_o}{P_{EPC} + P_{FGC} + P_{LGC}} \quad (1)$$

Discussions of laser efficiency usually omit the flow-conditioning power requirements, which include pumping, cooling, and chemical regeneration power. This is a serious omission, since the flow losses are at least as large as the electrical losses that usually command exclusive attention. The laser system efficiency can be written as follows:

$$\eta_{LS} = \left(\frac{P_O}{P_L} \right) \left[\frac{1}{\frac{P_{ELC}}{P_L} + \frac{(P_{FGC} + P_{LGC})}{P_L}} \right]$$

$$= \frac{\eta_O}{\left[\frac{1}{\eta_{ES}} + \frac{1}{\eta_{FS}} \right]} \quad (2)$$

The laser system efficiency is effectively the product of the optical train efficiency and the smaller of the electrical or flow subsystem efficiencies. It is therefore quite possible for a poorly designed flow and chemical regeneration system not only to overwhelm the electrical losses but, in the extreme case, to become independent of the electrical efficiency.

The optical system efficiency is simply the ratio of

the power on target divided by the power emerging from the final laser aperture, accounting for losses in the optical transport system required to get the beam into the reactor building and focused on target. These losses include absorption and scattering of lenses and mirrors, as well as beam-shaping and diffraction-spillage losses. A typical optical train might require ten optical elements. We have assigned a range of values — 80 to 90% — to this optical efficiency.

The electrical system efficiency is the ratio of laser radiation produced to electrical power provided to the pulse-forming network. It is the product of the pulse-forming network, e-beam, fluorescer, quantum, and extraction efficiencies, as follows:

$$\eta_{ES} = \eta_P \eta_{EB} \eta_F \eta_Q \eta_{EX} \quad (3)$$

Fig. 7-15 Artist's conception of photolytic gas laser system.

Fig. 7-16. Laser system power flow.

In Table 7-9, these efficiencies are estimated for the four candidate photolytic lasers. A range of values is given for each laser; the lower figure represents today's technology, whereas the upper figure is a goal, a reasonable number believed achievable with

future development. The larger number in a sense represents the best that can be envisioned for the configuration assumed in Fig. 7-14; further innovation is needed to improve substantially on these estimates.

Table 7-9. Electrical-to-laser efficiencies for photolytic lasers

Parameter	Efficiency			
	Oxygen	Sulfur	Selenium	Iodine
Pulse forming (η_p)	0.65 - 0.70	0.65 - 0.70	0.65 - 0.70	0.65 - 0.70
E-beam diode and foil holder (η_{EB})	0.75 - 0.80	0.75 - 0.80	0.75 - 0.80	0.75 - 0.80
Intrinsic fluorescence and fluorescence geometry (η_F)	0.075 - 0.29	0.075 - 0.29	0.075 - 0.29	0.03 - 0.09
Quantum efficiency (η_Q)	0.2	0.19	0.35	0.21
Extraction and volumetric laser efficiencies (η_{EX})	0.66 - 0.75	0.66 - 0.75	0.60 - 0.67	0.37 - 0.59
Total electrical to laser efficiency (η_{ES})	0.0055 - 0.027	0.0046 - 0.024	0.0076 - 0.39	0.0011 - 0.0062

The fluorescence efficiencies in Table 7-9 are derived from the product of the intrinsic fluorescence efficiency of the gas (40 to 50% for the rare gases, 15% for XeBr in Ar),³²⁻³⁴ and a geometric factor to account for the loss of fluorescence radiation not directed at the laser medium (15 to 50%). The lasing efficiency is the product of quantum efficiency, the extraction fraction determined from the level degeneracies, and a volumetric fraction to account for the fact that optical cavities are usually only 80 to 90% of the volume of excited gas.

Two conclusions are immediately apparent from Table 7-9. The selenium laser seems to be superior because its quantum efficiency is 50% higher than those of the other Group VI atoms. This is due, in turn, to operation on the transauroral line rather than the auroral line, which is not likely in the oxygen or sulfur systems because of the greater gain of the auroral transitions in these atoms. The iodine laser seems greatly inferior for two reasons. First, the match between the XeBr* fluorescence band and the C₃F₇I absorption band is not nearly so close as for the Group VI atoms, resulting in two to three times lower fluorescence efficiency. Second, the quantum and extraction efficiencies are not as favorable. For example, the degeneracies in the iodine levels at best allow for only 67% extraction of the inverted population compared with 75 to 83% for the Group VI atoms. We shall see whether the factor-of-6 advantage of selenium over iodine persists when flow efficiency is taken into account.

The flow system efficiency is simply

$$\eta_{FS} = \frac{P_L}{P_{FGC} + P_{LGC}} \quad (4)$$

The required fluorescence and laser gas conditioning powers are of two kinds. The first is from the pumping power needed to make up stagnation pressure losses (entropy generation) due to screens and flow straighteners, friction in the heat exchangers required to cool the flow, the laser heat addition itself, acoustic absorbers, and the like. This loss is proportional to the power of the circulating flow. The second is that needed for chemically regenerating the parent molecule that was dissociated in the lasing process. This is proportional to the number density of molecules and is otherwise very dependent on details of the chemical engineering. Because our estimates of these losses for N₂O,

OCS, OCSe, XeBr, and C₃F₇I are not yet firm, we reluctantly omit them from this analysis. They may overwhelm the pumping power losses, particularly for the iodine laser, even though the parent molecule density is only 10¹⁶ to 10¹⁷ per cm³.

Returning to the required pumping power, we can write the powers for the fluorescence and laser streams as proportional to the circulating power, which is the product of mass flow ($\dot{m}$) and enthalpy [$C_p T_o = C_p T + (u^2/2)$]:

$$P_{FGC} + P_{LGC} = \xi_f (\dot{m}_f C_{pf} T_o) + \xi_L (\dot{m}_L C_{pL} T_o). \quad (5)$$

The constants ξ are the pumping efficiencies, which are functions of the pressure drops or pressure ratios and are calculated from classical wind-tunnel formulae. Low-pressure-drop flow nozzles can be used in the fluorescer gas stream because flow quality is not important. Let us assume that a wind tunnel with $\Delta p = 0.41$ atm (6 psi) can be designed for the fluorescer gas loop. The laser gas must have exceptionally uniform density to assure that fluctuations of the index of refraction are minimized. This requires a set of small, choked flow nozzles and screens with a high pressure drop, say $\Delta p = 2$ atm, or a pressure ratio of 3. The flow efficiencies that correspond to these pressure drops³⁵ in helium are $\Delta p = 6$ psi, $\xi_f = 0.20$ for the fluorescer gas loop and $\Delta p = 30$ psi, $\xi_L = 0.55$ for the laser gas loop. The two coflowing streams have the same velocity and same pressure (about 1 atm) in the laser cavity.

The circulating power can be written in terms of the pressure (p) and velocity (u) as follows:

$$\dot{m} C_p T_o = \frac{\gamma}{\gamma - 1} p A u, \quad (6)$$

where γ is the ratio of specific heats and A is the flow area (wL). In this expression we take advantage of the fact that the flow mach number needed to clear out the spent laser gases for the next pulse is quite small. For example, if between pulses we typically flow two times the cavity length ℓ in the flow direction, then the minimum velocity — desired because we want to minimize mass flow — is

$$u = 2\ell \text{ (PRF)}. \quad (7)$$

For a length (ℓ) of 2 m, PRF of 10 Hz, and speed of sound in helium (a) of 10^3 m/s, the mach number is

$$M = u/a = 0.04 \ll 1. \quad (8)$$

The power requirements for the flow then become

$$P_{FGC} + P_{LGC} = \frac{2\gamma}{\gamma - 1} p (\xi_F W_F + \xi_L W_L) L \ell (\text{PRF}). \quad (9)$$

We will write the electrical average power in terms of the laser average power, which then can be expressed in terms of the energy extracted per pulse and the pulse repetition frequency:

$$P_L = \eta_{ex} h\nu_L N^* (W_L \ell L) \text{PRF}, \quad (10)$$

where $h\nu_L N^*$ is the energy stored per unit volume in excited states and η_{ex} is the fraction of stored energy that can be extracted. The flow efficiency can be calculated from Eqs. (4), (9), and (10) as

$$\eta_{FS} = \frac{1}{\left(\frac{2\gamma}{\gamma - 1}\right) \left[\frac{\xi_F W_F}{W_L} + \xi_L\right] \left(\frac{p}{\eta_{ex} h\nu_L N^*}\right)}. \quad (11)$$

The flow efficiency depends on the relative sizes and pressure drops of the two streams and on the ratio of overall pressure to excited-state density (more precisely, on the ratio of translational energy density to the extractable energy density of excited states). Obviously it is desirable to operate at low helium pressure and high lasing molecule density. Note that the flow efficiency is independent of cavity volume or pulse repetition frequency, so long as the laser is operated at the minimum mass flow.

The flow system efficiency will vary with the detailed scaling of the laser amplifier itself, but an estimate can be obtained in the following manner. A 1-m-wide laser cavity for a selenium laser would require two fluorescent pump regions about 0.5 m wide on each side, so that the ratio of widths W_F/W_L would be of order unity. The ratio of translational energy density to extractable excited-state density can be calculated from the following characteristic parameters,

$$p = 1 \text{ atm} = 10^5 \text{ n/m}^2,$$

$$h\nu_L \approx 4 \times 10^{-19} \text{ J},$$

$$\eta_{ex} \approx 0.7,$$

$$N^* = 3 \times 10^{16}/\text{cm}^3 = 3 \times 10^{22}/\text{m}^3,$$

which leads to

$$\frac{p}{\eta_{ex} h\nu_L N^*} \approx 12. \quad (12)$$

This corresponds to a flow efficiency (η_{fs}) of 2.2%, very comparable to the laser electrical efficiency and therefore of equal concern. The oxygen and iodine lasers use argon as a fluorescer medium, which requires about five times the width of gas to stop the electrons efficiently. This in turn leads to greater mass flows of fluorescer gas and lower flow efficiencies for the iodine and oxygen systems. There is potential for a twofold improvement in flow efficiency with the development of low-pressure-drop laser cavities.

Table 7-10 gives the flow efficiencies calculated for the four photolytic lasers of interest, using the sizing considerations discussed below. These efficiencies are exclusive of chemical regeneration losses. The electrical and optical losses are repeated in this table in order to display the overall efficiency computed by Eq. (2).

We immediately note that the flow efficiencies are so poor that they significantly influence the overall efficiencies. Because the fluorescer flow and laser flow must be pressure matched in a windowless system, one must operate at high enough total pressures (and therefore mass flows) to stop the e-beam efficiently in the fluorescer flow region. This makes it difficult to reduce the total pressure much below the assumed 1 atm. In addition, the oxygen and iodine lasers use a relatively low-atomic-weight fluorescer, argon, therefore requiring a much greater proportion of mass flow and concomitant loss of power.

Scaling Considerations

Four factors dominate the sizing of photolytic lasers: parasitics, beam quality, e-beam foil damage, and the maximum mirror size one is willing and able to manufacture based on optical-surface finishing and cost constraints. We have taken these factors

Table 7-10. Electrical, optical, and flow efficiencies for photolytic lasers

Subsystem	Efficiency			
	Oxygen	Sulfur	Selenium	Iodine
Electrical (η_{ES})	0.027	0.024	0.039	0.0062
Optical (η_O)	0.90	0.90	0.90	0.90
Flow (η_{FS})	0.004	0.011	0.028	0.002
Laser overall system efficiency	0.0031	0.0068	0.015	0.0014

$$\left(\eta_{LS} = \frac{\eta_O}{\frac{1}{\eta_{ES}} + \frac{1}{\eta_{FS}}} \right)$$

into account in an analysis of the feasibility of constructing 100 kJ/pulse amplifiers. The results are encouraging; it appears that it will be less difficult to obtain size than efficiency.

Parasitic oscillations must be suppressed in large laser amplifiers to prevent unwanted premature depopulation of the excited states. In the laser direction, it is quite likely that saturable absorbers will be used to isolate amplifier stages and prevent target preheating. This allows the use of high-gain-length products particularly if aerowindows rather than solid windows are used, for they obviate the back-reflection problem. Consequently, we shall take a small signal gain-length product $g_0 L = 6$ as our parasitic limit on maximum length, a large but not unreasonable limit.

Parasitic oscillations must also be prevented in the two transverse dimensions. The flow direction is bounded in the upstream direction by a nozzle wall that may reflect light. However, the downstream direction is bounded by an aerodynamic diffuser full of hot absorbing gas, so we would anticipate no reflected radiation. In the pump direction, the laser cavity is bounded by fluorescent gas regions, which may or may not be transparent to the laser radiation depending on the ion density in the fluorescing gas. If they are transparent, the laser radiation could reflect off the e-beam foils, which have some reflectivity in the visible spectrum. We shall set a parasitic limit of $g_0 W_L = 3$ to be conservative, where W_L is the width of the active laser gas in the pump direction.

There are other limitations on the width in the pump direction, such as quenching of the excited states of the photolyzed gas by the parent molecule

during the pump pulse. This limit can be overcome by pumping harder for shorter times, thereby transferring a kinetics problem associated with the speed of the bleaching wave and the width of the absorber region into one of e-beam performance limits. For this analysis we use an e-beam foil damage (F_E) limit of 20 J/cm², corresponding to 20 A/cm² for 1 μ s or 200 A/cm² for 0.1 μ s at electron energies of ~ 1 Mev. The bleaching-wave velocity is simply the fluorescent photon number flux divided by the absorber (parent molecule) density. With an e-beam fluence limit of 20 J/cm², a bleaching wave can be driven approximately 120 cm into a gas with 3×10^{16} absorbers per cm³. This result is relatively independent of the pumping time, which can be chosen to minimize quenching problems.

The transverse dimensions are limited by mirror constraints. Although one can envision apertures exceeding 1 to 3 m², single components then become quite expensive and unwieldy. Furthermore, optical-surface finishing and coating quality become difficult and expensive for optics larger than 1 m. Although a mosaic of smaller mirrors might be used, we will limit the maximum aperture to 2 m in any dimension. This will not prevent us from reaching 100 kJ in one amplifier, but the reader should be aware that if fewer laser beams of larger size become necessary, this limitation might be relaxed.

Mirror damage limits are not really of concern in this example because for a given energy stored and a given fluence constraint for the onset of damage, say 10 J/cm², we can adjust the input fluence to the saturated amplifier to get the correct damage-limited fluence.

Beam quality is an important constraint, particularly for visible gas lasers in which the optical path variations can be significant. The chief sources of phase degradation for the coherent beam are density fluctuations in the gas, which cause nonrandom linear fluctuations in the index of refraction, and the surface finish and thermal distortion of mirrors.

Each optical component is allowed a part of an overall distortion budget, calculated from the greatest beam-quality loss that can be tolerated while still focusing on a fusion target. As an example, we performed the following linearized analysis. Assume that the optical train needed for interfacing with the fusion reactor is composed of 10 mirrors, the last of which is a 2-m-diam focusing mirror.³⁶ This final mirror is located 100 m from the center of the target chamber so as to minimize the chamber's open wall area, through which neutrons escape. Each mirror is polished or diamond-turned to within $\lambda_v/10$ or $\lambda_v/20$ optical quality. The beam quality criterion is the capability to focus on a 1-mm spot.

The gas laser amplifier is assumed to have an input beam of zero phase variance and a minimum level of local gas density variation ($\Delta\rho/\rho$) — due to flow noise — of 10^{-3} . This level is the minimum yet achieved in a laser cavity, although 5×10^{-4} might be attainable. Helium is used as the buffer gas because argon produces 7.5 times more fluctuation in the index of refraction than helium at the same average density and density-fluctuation level. Krypton and xenon, anywhere near 1 atm, would be unusable; the allowed pressure of the heavier rare gases can be scaled from the helium curve (Fig. 7-17) by the ratios of $n - 1$ where n is the linear index of refraction.

In Fig. 7-17 the results are given in terms of the product of gas pressure and length of the optical cavity in the lasing direction. This product is a function of laser wavelength, of course, because it is the optical-path difference compared with a wavelength that is the important factor in the loss of coherence. In helium at 1 atm, we are allowed about 5 m of amplifier length for the selenium laser whereas, at the larger iodine wavelength, a 15-m cavity might be

Fig. 7-17. Constraints on beam quality from target size, wavelength, density fluctuation, and mirror quality. The curves for argon and xenon are off this scale.

tolerated. This simple example is only illustrative; we are now quantifying these considerations with physical optics calculations. Nevertheless, the general scaling relationships and parameter magnitudes are consistent with knowledge gained on large, pulsed, flowing CO_2 lasers. Unfortunately, our belief that the $\Delta\rho/\rho$ scaling is relatively independent of the steady density level is based on data over a very small dynamic range, since few flowing lasers have the necessary path length to produce reliable data at lower pressures.

The parasitic and beam-quality limitations on length are combined in Fig. 7-18 as a function of lasing molecule density. The beam quality, determined by the total gas pressure and index of refraction, sets the length; the parasitic limit sets the maximum lasing molecule density.

The length, height, width, and number density considerations may be combined to calculate the maximum storable energy per amplifier module, i.e., in a single aperture. This is shown in Fig. 7-19. Oxygen, the system with the lowest gain, stores the

Fig. 7-18. Length (lasing-direction) constraints. The crosshatching denotes the frontier bounding the allowed sets of parameters for each atom.

greatest energy because these systems — limited in both flow length and laser length by gain constraints — store more energy by *reducing* the lasing molecule density and increasing the volume by a proportionately greater amount. In fact, only the oxygen system can store more energy than can be

extracted, because of mirror-damage fluence threshold of 10 J/cm^2 . Consequently, in the oxygen-system curve in Fig. 7-19, only number densities less than about 8×10^{16} (to the left of the mark) represent extractable energies.

Evaluations

Figure 7-20 presents a graphic summary of results of this initial study of high-average-power photolytic gas laser systems, displaying maximum overall system efficiency against the stored energy in a given amplifier for the specific case of a fluorecscer-pumped windowless geometry. Amplifiers can be built large enough to achieve 1 MJ with less than a dozen beams. Obtaining adequate efficiency will be the most difficult task; only the selenium system promises an overall efficiency above 1%. The iodine system requires a tenfold higher power input than the selenium system. This could be accomplished only by operating at 10 times the recirculating power or 10 times the fusion pellet gain, circumstances that are either economically or physically unlikely. Moreover, the iodine laser would suffer proportionally greater additional losses in efficiency if the chemical regeneration penalties were included in the analysis.

References

28. R. R. Buntzen and C. K. Rhodes, *Laser Systems for Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-75367 (1974).
29. J. R. Murray and C. K. Rhodes, "The Possibility of High Energy Storage Lasers using the Auroral and Pronaural Transitions of Column VI Elements," *Appl. Phys.* 47 11 (1976).
30. K. Hohla and K. Kompa, "The Photochemical Iodine Laser," p. 667, in *Handbook of Chemical Lasers*, R. W. F. Gross and J. F. Bott, Eds. (Wiley — Interscience, New York, 1976).
31. J. J. Ewing, Lawrence Livermore Laboratory, private communication, December 1976.
32. J. C. Swingle, C. E. Turner, Jr., J. R. Murray, E. V. George, and W. F. Krupke, "Photolytic Pumping of the Iodine Laser by XeBr," *Appl. Phys. Lett.* 28 7 (1976).
33. G. Brederlow, K. J. Witte, E. Fill, K. Hohla, and R. Volk, "The Asterix III Pulsed High-Power Iodine Laser," *IEEE J. Quantum Electron.* QE-12 2, (1976).
34. W. F. Krupke and E. V. George, *High Average Power, Rare Gas Halogen—Pumped Iodine Laser for Fusion Applications*, Lawrence Livermore Laboratory, Rept. UCRL-77523 (1976).
35. H. W. Liepmann and A. Roshke, *Elements of Gasdynamics* (John Wiley & Sons, New York, 1957).
36. H. E. Bennett and P. C. Archibald, "Optical Requirements for Laser Mirrors," in *Laser Induced Damage in Optical*

Fig. 7-19. Energy storage per aperture.

Fig. 7-20. Efficiency vs energy per aperture.

Author

M. Monsler

7-5 Fusion-Fission Hybrids

The 1975 Annual Report discussed the promising possibility of producing fissile fuel and electricity in a laser-fusion-driven subcritical fission blanket. Earlier studies³⁷⁻³⁹ primarily used neutronic methods of analysis to identify the more attractive hybrid systems and to provide an upper estimate on performance. They also demonstrated that fusion-fission hybrids could be designed to meet a broad spectrum of fissile-fuel producing and energy-multiplying requirements. Two most significant features emerged from our neutronic scoping studies.

- Laser-fusion hybrids produce ten times more fissile fuel per unit of thermal energy generated than do fission breeder reactors.

- Laser-fusion hybrids also produce electricity with much lower laser efficiencies and pellet gains than those required for pure laser fusion.

These neutronic results were most encouraging. However, it was apparent that a more accurate assessment of the hybrid's potential and a definitive ranking of the more promising concepts would require studies dealing with the engineering safety and economic issues as well as with the neutronic aspects. With this in mind, we engaged the assistance of Bechtel Corporation in a conceptual-design study of a fusion hybrid. The scope of this investigation was defined by the need to provide enough design detail to realistically gauge the value of a laser-fusion hybrid in an economy based on fission-power generation. In this article, we describe and analyze the laser-fusion hybrid design that has evolved.

The hybrid concept chosen for this design study is a fast-fission blanket fueled with depleted uranium that produces fissile plutonium and electricity. It emphasizes fissile-material generation by maximizing for fuel production at the expense of energy multiplication. This blanket selection was based on

reported neutronic results^{40,41} that indicated that such a fast-fission blanket could provide enough fissile fuel to extend the energy available from economically proven light water reactors (LWRs) by as much as two orders of magnitude.

A comparative analysis⁴⁰ of the neutronic properties of several hybrid concepts has shown that depleted-uranium, fast-fission blankets provide the largest amount of fissile fuel per unit of thermal energy with the lowest laser efficiency and pellet gain requirements. The depleted-uranium blanket selected for our conceptual design produces enough fissile material to fuel more than six LWRs of equivalent thermal power. Thorium-fueled hybrids produce more fissile fuel per unit of thermal energy, but their fusion energy-multiplying capabilities are much lower. Hence, they require a laser fusion system of higher performance. There are blanket concepts with higher energy-multiplication capabilities than those of depleted-uranium blankets. These blankets could efficiently produce electricity with lower fusion-energy gains; however, their enhanced energy multiplication is obtained at the expense of decreased fissile production.

Light water reactors will be the major (and most likely the only) source of commercial nuclear-electric power for the remainder of this century. Their dominance over coal-fired plants as base-load electrical generators will depend strongly on the adequacy of their long-term fissile fuel supply. By converting the ²³⁸U in natural uranium to fissile plutonium, the hybrid could extend the fissile fuel supply for economically proven LWRs by two orders of magnitude.

Fast breeder reactors also offer the prospect of more fully utilizing the uranium resources, but they cannot provide fissile fuel for LWRs. Therefore, the usefulness of fast breeder reactors will hinge entirely on their economic competitiveness as power plants.

Laser Fusion Hybrid Design

Work in the joint laser-fusion hybrid design study was apportioned as follows. Lawrence Livermore Laboratory provided the overall direction, the neutronics data, and the fusion portions of the design. Bechtel Corporation developed the fission portion of the hybrid, the design of the thermal energy transport and conversion system, the tritium recovery system, and the layout of the complete power plant. They also analyzed the fuel cycle,

capital, and operating cost. Bechtel's contribution to the laser-fusion hybrid design is fully documented in their final report to Lawrence Livermore Laboratory.⁴²

For ourselves, we set four major objectives by which to gauge our success in the design study:

- Identify the laser/pellet performance required to economically produce fissile fuel and power with a hybrid.

- Evaluate the integrated engineering performance of the complete conceptual design.

- Compare a laser-fusion hybrid to existing fission breeder options (liquid metal, gas cooled, and light water fast breeder reactors, LMFBR, GCFBR, and LWBR, respectively).

- Identify major technological problems associated with a laser fusion hybrid.

In addition to these objectives, a few philosophical viewpoints significantly affected our design choices. First, we wanted to operate the laser-fusion hybrid in a regime that required reduced laser/pellet performance, i.e., fusion energy gains in the neighborhood of 1.0. This implied blanket-energy multiplications approaching 10.0.

Second, we wanted to employ state-of-the-art fission technology in the design of the hybrid blanket. Thus, we chose stainless steel as the structural and cladding material instead of higher-performing refractory metals.

Finally, we believed that a hybrid reactor producing fissile fuel should be designed to be as safe and with the same environmental impact as the fissile-burning reactors for which it is providing fuel. Here we note that a negligible improvement in the overall environmental impact is the result of making the hybrid environmentally more attractive than the larger number of LWRs for which it supplies fuel.

Hybrid Reactor Design

The functional shape of the laser-fusion hybrid chosen for final evaluation is shown in Fig. 7-21. In its simplest form, it is a cylinder with height equal to diameter. The center of the fusion chamber is the focal point for a six-beam, 100-kJ laser system that irradiates the fusion target from the top and bottom of the cylinder.

The basic features of the hybrid reactor are displayed in Fig. 7-22. A depleted-uranium, fast-fission blanket is positioned radially around the fusion chamber. The energy in the fission zone (90% of the

Fig. 7-21. Geometry of the laser-fusion hybrid reactor.

total energy) is removed with a sodium coolant system. The liquid sodium enters the fission zone from the lower plenum and flows to the upper plenum through hexagonally shaped process tubes.

Lithium-cooled graphite-moderated blankets are positioned in the top and bottom of the reactor as well as behind the fission zone. These lithium blankets moderate and capture neutrons and breed tritium. All penetrations for the laser beams and pellet injectors are made through the top and bottom blankets, leaving the radial fission blanket unencumbered. We originally intended to use fission blankets in the top and bottom regions; however, because of difficulties involved in maintaining coolant flow while the top blanket was being removed to gain access into the fusion chamber and because of requirements for the unconventional fission-blanket design, we were forced to choose lower-performing, nonfissioning blankets for these problem regions. Our decision not to use fissionable fuel in these regions resulted in a 30% reduction in both fissile fuel and energy production. Nevertheless, this decision was consistent with our

desire to use state-of-the-art fission technology in the hybrid design.

As shown in Fig. 7-23, the entire blanket system is enclosed in a spherical shaped, stainless-steel vacuum vessel with a removable top. The final focusing mirrors are placed in beam tubes outside the vacuum vessel to minimize damage caused by the fusion microexplosion and to facilitate replacement of the mirrors.

Fission Blanket Design. An expanded side view and a top view of the radial fission blanket are given in Fig. 7-24. As shown, the fission zone is composed of two rows of hexagonally shaped process tubes that contain the depleted uranium in the form of stainless-steel-clad fuel pins. The process tubes in

the inner row are protected from the fusion cavity environment by a stainless-steel-supported graphite liner.

Our neutronics calculations indicate that energy multiplication and fissile-fuel production are maximized by using uranium metal fuel (instead of oxides or carbides) and by maximizing the ratio of the volume fraction of uranium to structural material. Increasing the residence time of the fuel also increases the average energy multiplication because more energy is produced as plutonium breeds, accumulates, and fissions in the blanket.

Damage by fast neutrons may limit the useful life of the stainless steel and other structural metals in a fusion reactor. Two common design criteria for

Fig. 7-22. Side views of the basic laser-fusion hybrid reactor.

Fig. 7-23. Vacuum vessel for the laser-fusion hybrid reactor.

Fig. 7-24. Side view (a) and top view (b) of the fusion blanket in the laser-fusion hybrid reactor.

both laser- and magnetic-fusion reactors are a first-wall neutron-flux limitation of 1 MW/m^2 and an expected lifetime of less than five full-power years. Neutronic calculations at a first-wall loading of 1 MW/m^2 indicate a maximum power density in a depleted uranium blanket of about 8 W/g , or about 150 W/cm^3 of uranium metal. The average power density in a blanket is less than 4 W/g . Five full-power years of blanket operation would result in an average burnup of less than 7000 MWd/MTU . This low burnup limitation definitely favors the choice of a metallic fuel.

The low-power density burnup capabilities of a depleted uranium (or natural uranium) blanket require care to minimize fuel cycle costs, including the fabrication cost. Large fuel rods would thus be favored over small rods, and long fuel elements would have some advantages over short elements.

The basic configuration of a laser-fusion reactor — a vacuum chamber with laser beams converging from several angles — introduces difficulties in the mechanical design of the blanket. Neutronic calculations show a severe reduction in performance if a thick pressure-vessel wall is introduced between the blanket and the fusion core. The fuel element must therefore operate and be cooled within a surrounding vacuum. Thin process tubes and low-pressure coolants appear to be the most reasonable design approach. However, coolant leaks and process tube reliability will always be potential problems. We also expect that melting of the fuel as a result of loss of coolant will be the most serious safety issue with the hybrid.

Fuel Material Selection. The general design considerations of maximizing neutron energy multiplication, minimizing fuel cycle costs, and developing a concept that could be licensed by the Nuclear Regulatory Commission led to the selection of fuel elements of uranium metal with a sodium coolant, LMFBR technology and balance-of-plant design concepts were used to the maximum extent possible. The selected fuel element is a 19-rod cluster similar to those developed during the early 1960's for use in sodium-graphite reactors. Fuel rods 181 ft long were developed in the 1960's and required care in handling. (Because of the flexibility of the rods, they had a tendency to buckle if they were not handled vertically.) Incorporating this experience into a blanket design with larger-diameter fuel rods and a thicker cladding, we estimated that 7-m (23-ft) long fuel rods and fuel assemblies were

feasible. This, in turn, determined the reference height of the fusion reactor core. A three-dimensional view of the fuel assembly is shown in Fig. 7-25.

Uranium metal, uranium with 7 wt% molybdenum alloy (U-7 Mo), and uranium carbide (UC) were all considered as fuel materials for the sodium-cooled blanket; all are satisfactory. The reference fuel element can accept 30-mm-diameter fuel slugs of each of these materials interchangeably. The U-7 Mo fuel should be capable of burnups to $20,000 \text{ MWd/MTU}$ at maximum center temperatures of 650°C . This burnup would take at least eight full-power years to achieve; the cladding probably would fall first. The U-7 Mo alloy was the reference fuel for the Dounreay fast reactor and performed satisfactorily at the conditions noted. Compared to uranium metal, this alloy has a reduced energy-multiplication and plutonium-production rate and is also more expensive to fabricate and reprocess.

Uranium carbide fuel would be capable of more than $100,000 \text{ MWd/MTU}$ burn-up at maximum temperatures of 1000°C (with a sodium bond) if the cladding were strong enough. However, its energy multiplication is 30% lower than that of uranium metal. In the low-power-density configuration of the reference blanket, the higher burnup capabilities of U-7 Mo and UC cannot be used effectively. If higher power densities were possible, UC would probably be the fuel material of choice. However, we would have to use first-wall fluxes of 3 to 4 MW/m^2 fissile enriched-uranium fuel, or gas cooling.

Uranium metal, "adjusted" with minor alloying additions to control swelling, was chosen as the reference fuel material for several reasons. Its multiplication and breeding performance were superior, its burnup capability was judged to be adequate and it gave a good fit to the blanket's low power density, and finally, it was least expensive to fabricate and reprocess.

Pure uranium metal begins to swell disastrously at temperatures greater than 400°C and burnups greater than 1000 MWd/MTU (about 0.1 atom% fissions). The British developed "adjusted" uranium metal as a fuel for their gas-cooled Magnox reactors during the early 1960's, demonstrating that additions of 800 to 1000 ppm aluminum, 350 to 500 ppm iron, and approximately 500 ppm carbon could control this swelling and allow burnups of 5000 to 6500 MWd/MTU at temperatures of 600°C . Extensive

Fig. 7-25. Fuel element and process tube configuration.

development of similar alloys using aluminum, iron, and silicon (and sometimes molybdenum) has taken place at the Savannah River Laboratory and at Battelle Northwest Laboratory, confirming the satisfactory performance of these fuels.

A maximum fuel temperature of 600°C and a maximum burnup of 6000 MWd/MTU were chosen as a design basis for the blanket. A volume increase (swelling) of 4% is expected at this burnup. However, a volume increase of 8 to 10% is easily tolerated by the sodium-bonded fuel rod. A maximum burnup of 6000 to 6500 MWd/MTU is probably a reasonable expectation for this fuel. Sodium bonding of the cladding to the fuel rod was chosen over contact bonding to accommodate fuel swelling without straining the cladding and to permit the use of a thin cladding.

Lithium-Cooled Radial Blanket. The lithium-cooled radial blanket is located behind the fission blanket and extends from the top to the bottom

sodium plenums. The blanket consists of a cylindrical stainless-steel container, 62 cm wide and 750 cm high. From the inside face of the blanket, there is first a 2-cm-thick stainless-steel inner wall followed by 6 cm of lithium, 50 cm of stainless-steel-clad graphite, 2 cm more of lithium, and a 2-cm-thick stainless-steel outer wall.

The lithium, enriched to 50% ^6Li , enters the reactor from an inlet header and is fed into a plenum at the bottom of the radial blanket. Lithium then flows upward through the two channels provided on either side of the clad graphite and into the top plenum.

Top and Bottom Blankets. The top and bottom blankets are cylindrically curved, pancake-shaped plenums. The shell is 2 cm thick and, from the center of the reactor, each blanket has the identical construction — 2 cm of stainless steel, 10 cm of beryllium, 70 cm of graphite, 10 cm of lithium, and 2 cm of stainless-steel shell. The blankets are located

350 cm from the center of the reactor. The beryllium in these top and bottom blankets provides a tritium-breeding ratio of 1.5. This enables the radial blanket to operate with a tritium-breeding ratio of 0.95, yielding an overall tritium-breeding ratio of 1.1. Reducing the tritium-breeding requirements in the radial blanket make it possible to use a thicker fission zone, thereby increasing the fissile-fuel production capability of the reactor.

Final Laser Optical System. Six laser beams approach the reactor from one side of the reactor-containment facility. To prevent radiological hazard in the laser facility, a radiation shield is provided for each beam. The horizontal beams enter the reactor through a double mirror system on the outside of the reactor. The laser light is focused on the fusion target by six metal mirrors located at the top and bottom of the reactor. The mirrors have a 12-m focal length; the final mirror is designed to accommodate a beam diameter of 1.2 m and a maximum energy flux of 1.5 J/cm^2 .

To be good reflecting and focusing elements, mirrors must be smooth to approximately one-fourth of the wavelength of the impinging laser light. Highly polished metal surfaces are susceptible to all types of radiation damage, and thus we are currently investigating the effects of the neutrons, x rays, and energetic debris from the fusion microexplosion. The damage caused by this loading has been lessened somewhat by placing the mirrors at a point where the radiation fluxes emanating from the fusion target are more than ten times lower than the first wall fluxes.

An additional problem uncovered by our preliminary optical studies involves damage to the mirrors from the laser light as debris from the fusion chamber accumulates on the mirror surface. A mechanism for removing the debris between shots will have to be devised.

Removing and replacing mirrors will be expensive because extensive handling is required. Replacing the mirrors at the bottom of the reactor also will be difficult without special equipment. The necessity for special designs such as rotating mirrors, gas windows, magnetic field directors, and special remote handling for replacing mirrors will be determined by the lifetime of the mirrors themselves. In this report, we have made no considerations for optical-system design except for layout and basic functional purposes of the laser system surrounding the reactor.

Table 7-11. Laser fusion hybrid design parameters

Optical Transport System

Number of beams	6
Maximum energy flux, J/cm^2	1.5
Beam diameter, m	1.2
Focal length of final mirrors, m	12.0

System Performance

Thermal power, MWt	1400
Fusion thermal power, MWt	200
Gross electrical power, MWe	535
Net electrical power, MWe	400
Recirculating power fraction	0.25
System efficiency, %	29
Average blanket energy multiplication	8.7
Net plutonium production, kg/y	1300
Total tritium production, kg/y	8.0
Laser energy, kJ	100
Laser system efficiency, %	2.0
Power supply energy, MJ	5.0
Pulse repetition rate, s^{-1}	20
Pellet gain, Q	100
Fusion energy gain	2.0

Pellet Apparatus. The pellets of deuterium-tritium will be injected into the reactor at a nominal 20 times per second and must reach an exact location without error. The pellet apparatus will have to be insulated from the reactor (if frozen pellets are used) and must remain correctly aligned with the laser beams during the expansion of the reactor caused by internal heat load. The apparatus also will be subject to thermonuclear blast and the nominal reactor vacuum of 0.1 Torr. However, no apparatus is available currently for this purpose.

First-Wall Considerations. The technological and economic feasibility of the laser-fusion hybrid are critically dependent on the design and performance of the first wall. The radius and lifetime of the first wall determine both the size of the reactor for a given output power and the availability of the power plant. We have performed calculations to determine the radiation-exposure capabilities of several first-wall materials. The results of these calculations are presented in § 7-3. They have led us to choose a 2-cm-thick graphite liner that is supported by stainless steel and cooled with lithium. The

graphite first wall is designed for an operational lifetime of one year with a neutron-wall loading of 1 MW/m² and a repetition rate of 20 Hz.

Design Analysis

System Performance. The overall performance and the more significant design parameters of the laser-fusion hybrid are summarized in Table 7-11. A thermal output of 1400 MW was chosen to emphasize the fact that a laser-fusion-driven hybrid could operate as a relatively small power unit. The fusion targets are irradiated by a six-beam, 100-kJ, 20-Hz laser with an overall efficiency of 2%. The fusion energy gain (i.e., the product of laser system efficiency and pellet gain) for this reactor is 2.0. This yields a plant recirculating-power fraction of 25% and a net system efficiency of 29%. If the fusion energy gain were increased to 4.0, the recirculating power would decrease to 16% and the net system efficiency would increase to 32%.

The performance and the design parameters presented in Table 7-11 can be placed in perspective by comparing the laser fusion hybrid to a typical fast breeder reactor. This comparison is presented in Table 7-12 where both systems have been normalized to a thermal output power of 2500 MW. The fast breeder reactor used in this comparison is an LMFBR with a breeding ratio of 1.2. As shown, the laser-fusion hybrid generates 30% less electrical power because it is being driven by a laser that requires 19% of the gross power. This inferior performance in power generation results from design choices that were influenced by our desire to

emphasize fissile-fuel production at the expense of energy multiplication. The advantages of the laser-fusion hybrid over the LMFBR are readily apparent from Table 7-12. Specifically, the hybrid produces ten times more fissile material, requires no initial fissile-fuel loading, and operates at one-tenth the power density. With no initial fissile inventory, it becomes possible to operate the hybrid in a regime where both criticality accidents and core-disruptive accidents are impossible. Moreover, control rods are not required. The lower power densities make it possible to design a hybrid blanket that provides much more time to recover from a loss-of-coolant accident. In fact, it is technologically feasible and it may be economically feasible to design a hybrid blanket that passively copes with a loss-of-coolant accident.

System Capital and Operating Costs. The capital and operating costs of the laser-fusion hybrid in this conceptual design were estimated by Bechtel Corporation. Their preliminary economic analysis of the reference 1400-MWt design revealed that severe economic penalties resulted from some of the design choices. A survey of the high-cost items indicated that the reactor containment structure and several of the other buildings had been sized much too large for the nominal output power of 400 MWe. In addition, there were several other balance-of-plant items whose costs were relatively independent of output power, thereby implying that a larger plant-output power would be more economical. These results agree with scaling factors for other nuclear power reactors where an electrical power plant is more economical in the 1200-MWe range and, where possible, in twin units.

Table 7-12. Comparison of laser fusion hybrid and fission breeder^a performance

Parameter	Hybrid	Breeder
Thermal power, MWt	2500	2500
Net electrical power, MWe	725	1000
System efficiency, %	29	40
Net fissile production, kg/y	2300	260
Fissile fuel loading units (kg)	0.0	2500
Maximum power density in fuel, W/cm ³	150	1500
Average power density, W/cm ³	30	300

^aThe fission breeder reactor used in this comparison is an LMFBR with a breeding ratio of 1.2.

These results led us to perform our more detailed cost analysis on a hybrid with a larger output power. We scaled our conceptual design to a size with a gross yield of 1300 MWe and a net yield of 950 MWe. This output was obtained from the original design by increasing the laser energy from 100 to 200 kJ, increasing the average pulse repetition rate from 20 to 25 Hz, and increasing the inner radius of the blanket from 3.5 to 6.0 m.

We estimated the capital cost of the laser-fusion hybrid reactor plant from conceptual design and engineering information. A large portion of the power plant consists of conventional technology such as thermal energy transfer, electrical generation, cooling systems; and auxiliary systems; thus,

cost estimating of the components can be based on background experience. Because the fusion reactor and the laser-interface fusion fuel cycle are conceptual, they have been estimated on a first-of-a-kind cost basis. Operating costs are based on the nuclear fuel cycle, equipment replacement costs of the reactor, capital charge rates, and general operating and maintenance costs similar to those of LMFBR reactors.

Capital Costs. The results of the cost analysis are summarized in Table 7-13. For comparative purposes, the costs of the laser fusion hybrid are presented with cost estimates for a typical LWR. All of the cost estimates were made at first-quarter 1976 price and wage levels; we have made no allowance

Table 7-13. Economic analysis of the capital expenses and operating costs of a 950-MWe laser fusion hybrid reactor and a 1200-MWe light water reactor

Item	Cost	
	Hybrid	LWR
Capital Expenses: Direct, Millions of Dollars		
Nuclear steam supply system	78	268
Other mechanical	101	201
Civil and structural	142	158
Piping	77	105
Instrumentation	9	11
Electrical	43	72
Total Direct	450	815
Capital Expenses: Indirect, Millions of Dollars		
Field costs	79	171
Engineering services	80	197
Contingency	91	272
Owners cost at 7%	56	116
Interest during construction at 8%	197 (9 y)	487 (10.5 y)
Total Indirect	503	1243
Total Capital Expenses	953	2058
Cost per kilowatt installed (Dollars)	794	2166
Operating Costs (mills/kWh)		
Capital	19.42	55.77
Fuel	6.3	(-3.17)
Operating and maintenance	1.5	2.40
Total Operating Costs	27.22	55.00

for future escalation. The nuclear steam supply system category for the hybrid primarily includes the reactor vessel with its internals and the primary coolant loop with its associated pumps, motors, heat exchangers, and steam generators. Major items included in the category "other mechanical" are turbine generators, vacuum system, tritium system, and cooling towers. Site improvements, the reactor containment structure, and all the buildings comprise the civil and structural category.

The indirect costs in Table 7-13 were estimated on the basis of a 9-yr construction time for the LWR and a 10.5-yr construction for the more complex laser-fusion hybrid. As a result, the indirect costs for the hybrid account for a larger fraction of the total capital cost. Field costs are those construction items that cannot be ascribed to the direct portions of the facility. They include temporary construction facilities, supply and maintenance of construction equipment and tools, field office operation, and acceptance testing. The engineering services include all engineering costs, home office costs, and fees. Also included in the indirect cost is a contingency allowance for the uncertainty that exists in the conceptual design in quantity, pricing, or productivity.

The total capital cost of the laser-fusion hybrid is estimated to be \$2058 million. Thus, on a cost-per-kilowatt installed basis, the hybrid is 2.7 times more expensive than the LWR. We must note that this cost estimate does not include the laser system or the pellet manufacturing facility. If \$200 million dollars are allowed for these omitted facilities, the laser-fusion hybrid would cost approximately three times more than a typical LWR.

Operating Costs. The cost of electricity has been estimated for both reactors on the basis of a 15% rate of return on the capital invested. The cost of electricity from the hybrid is 55 mills/kWh, or approximately twice from the LWR. The capital portion of the operating cost is by far the dominant expense here.

The fuel cycle cost for the laser-fusion hybrid is negative as a result of revenues obtained from the sale of the plutonium it produces. The cost bases used to estimate the fuel cycle cost for both the LWR and the hybrid are presented in Table 7-14. Also, the fabrication cost for the hybrid is cheaper because the cladding material is stainless steel and the cross sectional area of the fuel pin is much larger. Both the shipping and the reprocessing costs for spent fuel are less for the hybrid because its fuel

is operated at lower average burn-ups (6,000 vs 33,000 MWd/MTU).

However, the major issue concerning a laser-fusion hybrid is not how much it will cost to build nor the price at which it can generate electricity but rather the cost of electricity in a scenario with hybrids providing fissile fuel for existing burner reactors. In Fig. 7-26, the cost of electricity has been plotted as a function of the cost of fissile fuel for an LWR and a laser-fusion hybrid with varying capital costs. The intersections of the curves determine the cost of electricity and fissile fuel in the hybrid-LWR scenario. These curves indicate that the cost of electricity is quite insensitive to the capital cost of the laser-fusion hybrid. Specifically, the cost of electricity increases by only 20 to 40% when the capital cost of the hybrid ranges from 2 to 3 times that of the LWR.

Table 7-14. Comparison of fuel-cycle costs bases for light water reactors and the laser fusion hybrid reactor

Item	Cost
<u>Light Water Reactors^a</u>	
Uranium	\$40/lb U_3O_8
Conversion	\$4.50/kg U
Enrichment	\$100/SWU
Fabrication	\$100/kg U (PWR) (80/kg U (BWR))
Spent fuel shipping	\$20/kg U
Reprocessing	\$225/kg U
Plutonium credit	\$34.25/g Pu_f (PWR) \$26.95/g Pu_f (BWR)
Process losses: conversion	0.2%
fabrication	0.5%
reprocessing	0.5%
<u>Laser Fusion Hybrid Reactor</u>	
Fabrication	\$30/kg U
Spent fuel shipping	\$10/kg U
Reprocessing	\$125/kg U
Plutonium Credit	\$30.00/g Pu_f

^aAssuming a 70% plant capacity factor and a 17.4% working capital charge rate.

Fig. 7-26. Comparison of fissile fuel and electricity costs from a light water reactor and a laser-fusion hybrid reactor.

Evaluations

The production of fissile fuel by a laser-fusion hybrid reactor is a promising step in the development of laser fusion. This study has disclosed a number of advantages resulting from the addition of a depleted-uranium fission blanket to a laser-fusion system. These include:

- The hybrid operates in a regime that requires an order of magnitude less laser/pellet performance than does a pure laser fusion system.
- First-wall requirements and 14-MeV neutron damage are less severe in a laser-fusion system with a fission blanket.
- The laser-fusion hybrid produces a large amount of fissile material — enough to fuel more than six LWRs of equivalent size.
- In a scenario with laser-fusion hybrids producing fuel for existing reactors, the cost of electricity is insensitive to the capital cost of the hybrid.

- The laser-fusion hybrid would extend the total energy available from economically proven LWRs by two orders of magnitude.

The feasibility of the laser-fusion hybrid should be evaluated from three points of view: scientific, technologic, and economic. The scientific feasibility of the laser-fusion hybrid is dependent on achieving pellet gains in the neighborhood of 100 and on developing suitable lasers with overall system efficiencies greater than 1%.

The fission blanket surrounding the fusion chamber was designed with state-of-the-art fission technology to facilitate a straightforward assessment of the technological feasibility of the laser-fusion hybrid. However, a definitive statement regarding the feasibility of fissile fuel production with laser fusion cannot be made without further study. The laser and optical systems must be conceptually designed. The pellet manufacturing and injection systems need to be considered. A more

measure the realism with which a fusion pellet environment can duplicate distant exposure to a nuclear weapon. The energy spectra of the neutrons and x rays emitted by the weapon are important. Soft x rays vaporize the surface of a reentry vehicle, producing impulsive loading, whereas harder x rays penetrate the vehicle skin, damaging internal com-

ponents. Neutrons cause fissions in the vehicle's fissionable components, the number of fissions being dependent on the incident neutron spectrum. The x-ray shine time of the simulator and the spacing of the x-ray and neutron pulses can be significant. The fluence uniformity is also important since a nuclear detonation at a great distance appears as a

Fig. 7-27. Shiva and Shiva Nova configurations. In Shiva the laser beams will be generated and amplified in the long bay on the left side of the top picture, converging on the target in the large room at the right. Shiva Nova I will be an independent facility attached to Shiva. Shiva Nova II will upgrade the Shiva laser and combine the two facilities to illuminate a single target.

detailed analysis of the first-wall design should be conducted. Finally, a safety analysis of the design is required with particular attention being given to system failures that could result in a release of radioactive nuclides to the environment. The most obvious release mechanism is the melting of the fuel in a loss-of-coolant accident.

The economic analysis reveals that the cost of electricity in a hybrid-LWR scenario is insensitive to the capital cost of the hybrid. The laser-fusion hybrid plant is estimated to be three times more expensive than an LWR. The cost of electricity is shown to be only 40% more than the present price. Nevertheless, substantial economic gains would be realized if the cost of the laser-fusion hybrid could be reduced to twice that of an LWR. Possibilities for reducing capital cost which should be explored in future studies include:

- Replacement of the reference coolant and tritium-breeding systems with helium cooling and a solid lithium blanket.
- Investigation of fission blankets that enhance energy multiplication.
- Consideration of blanket geometries that more efficiently utilize the point source from laser fusion.

References

37. *Laser Program Annual Report — 1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975).
38. J. A. Maniscalco, "Fusion-Fission Hybrid Concepts for Laser Induced Fusion," *Nuclear Technology* 28, 98 (1976).
39. A. G. Cook and J. A. Maniscalco, "Uranium-233 Breeding and Neutron Multiplying Blankets for Fusion Reactors," *Nuclear Technology* 30, 5 (1976).
40. J. A. Maniscalco, J. Hovingh, and R. Buntzen, *A Development Scenario for Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-76980 (1976).
41. *Laser Program Annual Report — 1975*, Lawrence Livermore Laboratory, Rept. UCRL-50021-75 (1976).
42. *Laser Fusion Hybrid Reactor Systems Study*, Bechtel Corporation (1976).

Author
J. A. Maniscalco

Major Contributors
L. F. Hansen
J. Hovingh
W. D. Allen (Bechtel)
R. E. Aronstein (Bechtel)
B. Marais (Bechtel)
S. L. Thompson (Bechtel)

7-6 National Security Applications

Early in 1976 we launched a study of potential national security applications of LLL's laser fusion experimental facilities. The study centered on Shiva Nova, the largest projected facility, which is a planned two-phase expansion of the present Shiva system (see Fig. 7-27 and Table 7-15). Several possible applications have been identified:

- Exposure experiments to investigate the effects of nuclear detonations on satellites, missiles, nuclear warheads, and reentry vehicles.
- Experiments to study nuclear-explosive physics.
- Investigations into the physics of nuclear-crater formation.
- Investigations into the effects of nuclear detonations on the atmosphere.
- Experiments to measure the effects of high-power laser beams on reentry vehicles.
- Development and calibration of diagnostic equipment for underground nuclear testing.

We have now initiated a detailed parametric study to evaluate Shiva Nova's potential for exposing reentry vehicles to neutron and x-ray fluences. Strategic planning demands specific knowledge of how much fluence a reentry vehicle can withstand without damage. The best way to determine fluence limits, at present, is through underground nuclear effects testing supplemented by surface experiments using electron beams, pulsed reactors, and surface-loading devices. Such tests are costly. Our study is still under way, but preliminary results indicate that Shiva Nova could add significantly to this nation's nuclear-effects simulation capability.

The two main parameters of interest in exposing reentry vehicles are the available neutron and x-ray fluences and the exposure area. Figure 7-28 shows a cross section of the Shiva Nova II target chamber. The 50 or so laser beams enter the chamber in two conical bundles from opposite sides; the target pellet is suspended from the top of the chamber. The two laser cones converge on the pellet, imploding it to the densities and temperatures required for thermonuclear reactions. These reactions then convert the pellet to neutrons, x rays, alpha particles, gamma rays, and gaseous debris.

Three more parameters — energy spectra, pulse widths and sequence, and fluence uniformity —

Table 7-15. Two-phase development of Shiva Nova

Characteristic	Shiva	Shiva Nova I	Shiva Nova II
Operation period	1977-1982	1981-1982	1983 - ?
Laser chains	20	~20	~50
Laser power (100-ps pulse), TW	20	100	200
Laser energy (3-ns pulse), kJ	20	100	250
Pellet yield, J	2.8×10^2	2.8×10^5	3.2×10^7
Neutron yield	10^{14}	10^{17}	10^{19}
X-Ray yield, cal	400 ^a	1.3×10^4	2.4×10^6

^aFrom a nonfusion target.

plane rather than a point source of radiation. Shiva Nova's projected performance in these three areas is being evaluated.

The diagnostic capabilities of any proposed nuclear-weapon effects simulator are likewise extremely important. The diagnostics developed for evaluating laser fusion target pellet experiments

measure neutron and x-ray yields, neutron and x-ray spectra, and pulse shapes with unprecedented accuracy. Techniques for determining the thermal and mechanical responses of reentry vehicles to underground nuclear detonations can also be applied in Shiva Nova. Measurements of temperature, strain, and impulse will be enhanced by the

Fig. 7-28. Fluences and exposure area of Shiva Nova II.

relatively short diagnostic-cable lengths and by the shorter noise pulses (although measurement of x-ray-induced pressure and stress may be complicated by arrival of the neutron pulse during the measurement). The design of Shiva Nova's target chamber will permit the use of such advanced diagnostic tools as laser interferometry, front-surface observation, and radiography.

As regards safety, reentry-vehicle exposure in Shiva Nova seems practicable. Either the high explosive or the fissionable material will be simulated to preclude nuclear yield. Because Shiva Nova II will accommodate target pellets that incorporate fissionable materials, remote-controlled radioactive disposal systems are already part of the design. Reentry vehicles will produce smaller amounts of radioactive fission products than these pellets, and all such products probably will be completely contained within the vehicle.

Shiva Nova will offer an extremely rapid turnaround time, thus permitting sequential experiments wherein early results are used to modify subsequent experiments. Shiva Nova exposure experiments are expected to cost less than 1% of underground nuclear-effects, but the type of exposures is significantly different. A more detailed estimate of Shiva Nova's utility for effects testing, compared with other simulation and nuclear tests, is being prepared. However, our studies to date indicate that significant military applications are probable and will complement to some extent other simulation and nuclear testing.

Author

J. A. Blink

7-7 Long-Range Planning for Inertial-Confinement Fusion

As the inertial-confinement fusion program approaches a demonstration of scientific feasibility, it becomes increasingly important to generate thoughtful long-range plans. When drafting our

plan, we set several objectives for ourselves. First, we wanted the plan to accommodate several optional technical paths to commercial fusion power. Second, we felt that the plan should provide several options to vary the pace of developing and applying the technology. This would allow management to keep the program in line with changes in technical progress, national needs, and the nation's commitment to inertial-confinement fusion. Third, we desired that the plan establish the goals and milestones required for both commercial feasibility and significant military applications. This would enable us to identify the requirements and tasks in the early (scientific) stages of development, working back from the civilian- and military-application dates. Finally, we wanted a plan that would identify the major issues and decision points. Moreover, the achievement of these objectives completely defines the scope of our long-range plan.

In addition to these objectives, there were a few assumptions and guidelines that significantly influenced the development of the long-range plan for inertial-confinement fusion (ICF):

- The ICF program will be competing with other long-term sources of energy and thus, we must anticipate major decision points in an ERDA-wide time frame.
- Significant military applications will be accomplished before commercial power is achieved.
- Commercialization of ICF will occur through a developing industry that is working in conjunction with government, national laboratories, and utilities.
- The ICF program will proceed through several phases of research and development before commercial power is achieved; key decisions will be required in each phase.
- A broad technology base must be established that will both feed and be fed by the various developments in the program.

The logic used to provide several optional paths to commercial fusion power is diagrammed in Fig. 7-29. This logic is based on the premise that experiments to verify the scientific feasibility of initiating high-gain microexplosions can proceed independent of the development of high-average-power ignition sources.

In addition, solid-state laser technology represents the most highly developed short-pulse, high-peak-power driver technology existing today. Consequently, the series of solid-state laser-fusion

Fig. 7-29. Major milestones and logic followed for the development of power by inertial confinement fusion.

facilities at LLL (from Janus to Shiva Nova) is expected to provide the earliest understanding of the implosion physics and demonstration of the scientific feasibility of ICF.

Once the physics of inertial-confinement fusion is understood and after high-gain microexplosions have been demonstrated, the program can progress to the engineering phases of development, selecting the most promising high-average-power driver for an experimental power reactor. Potential ignition sources for high-average-power operation of the experimental facility include ion beams, gas lasers, and electron beams.

Developmental Phases

A more comprehensive view of the scenario for developing inertial-confinement fusion is presented in Fig. 7-30. This plan assumes that the program will progress through several phases: exploratory development, advanced development, engineering development, and commercial development. The demonstration of technical feasibility has been split between the advanced and engineering phases

because of the prevailing assumption that two experimental power reactors will be needed before a demonstration power reactor can be built. As shown, this long-range plan provides for optional technical paths to commercial fusion. Moreover, the plan is based on the premise that a broad scientific base must be established in the earliest phase of development and must then be allowed to operate through a technical framework which will both feed and be fed by the various developments.

Exploratory Development. Those criteria required to demonstrate the scientific feasibility of inertial-confinement fusion will be met in the exploratory development phase. Scientific feasibility will be demonstrated when a high-gain ($G > 50$) thermonuclear microexplosion is achieved and a suitable high-average-power ignition source is developed. These accomplishments obviously must precede the decision to build an experimental power reactor.

The major program elements in the exploratory phase are separated into three distinct segments: inertial confinement physics, source coupling physics, and source feasibility. Neodymium:glass lasers

operating at 1.06 μm with low-average-power capabilities will be the primary tools in the inertial confinement physics program. Shiva Nova, the largest of the Nd:glass laser facilities, is projected to provide the on-target energies and powers required to drive pellets suitable for commercial power plants on a single-shot basis. The Shiva Nova facility will also be capable of conducting significant national security experiments.

The source-coupling physics program will be con-

cerned primarily with quantifying and maximizing the efficiencies of coupling different-wavelength lasers, ion beams, and electron beams to the fusion target. In the source-feasibility program, several high-average-power sources (gas lasers, ion beams, and electron-beams) will be developed and analyzed.

The facility for pellet development will support work in the exploratory phase by providing 10 pellets per day for Shiva Nova. This facility must

Fig. 7-30. Phases of development in the long-range plan for inertial confinement fusion power.

also develop the technology to produce pellets at the increased rates required by the first experimental power reactor (1000 pellets per day).

The major program elements initiated in this exploratory development phase will continue throughout the development of inertial confinement fusion, thereby forming a foundation of continually expanding technology. The decision to proceed into the next phases (advanced and engineering development) will be based on the successful demonstration of a high-gain microexplosion and on the development of a suitable high-average-power driver.

Advanced Development. The first experimental power reactor based on the inertial-confinement fusion concept, EPR I, will be undertaken in the advanced development phase. This reactor will be the first of a series of major experimental facilities required to verify the physics and engineering principles that are required to commercially develop inertial-confinement fusion. The primary function of EPR I will be to provide information on the integrated engineering performance of a complete ICF system (source, target, and reactor). In addition, EPR I will be expected to demonstrate the capability to produce electric power. An experimental power reactor supporting these objectives will:

- Operate at $\sim 10^3$ pulses/d.
- Generate ≈ 10 MW of thermonuclear power.
- Have limited plant availability $\approx 20\%$.
- Obtain a fusion-energy gain ≥ 3 .*
- Achieve high-temperature operation.
- Cost approximately \$500 million.

In the advanced development phase, pellet technology will consist primarily of producing 1000 pellets per day for EPR I. The capability to produce pellets even more rapidly (10^5 pellets/day) will have to be developed to meet the requirements of the next experimental power reactor.

A test and engineering facility also will be built and operated to investigate the effects of the thermonuclear environment on the final focusing elements, the first wall, and the blanket structure. This facility will not have a high-average-power capability and therefore will be used to investigate

single-pulse phenomena (< 10 pulses/day). These test and engineering requirements could be met most economically by utilizing the present Shiva Nova laser-fusion facility.

For military applications side, this phase of the program will not be purely developmental; major military goals already will have been accomplished. For example, Shiva Nova will be driving experiments to study nuclear-weapon effects offering significant advantages over underground testing — reduced cost, better diagnostics, and an increased number of experiments per year. However, it may not be practical for the laser-fusion program to continue the military applications of Shiva Nova in this phase (e.g., if Shiva Nova were being used for pellet development and test and engineering). Therefore, a decision must be made before this phase concerning the future weapon-effects-simulation capability of this nation. There appear to be three options:

- 1) Abandon laser fusion and exploit underground-effects testing.
- 2) Designate Shiva Nova as a permanent, full-time, weapon-effects-simulation facility.
- 3) Build a new laser-fusion weapon-effects simulator.

A new facility could considerably improve Shiva Nova's weapon-simulation capabilities. For example, a very large target chamber could be incorporated allowing higher yields, increased tailoring of the radiation, and better fluence uniformity. In addition to these technical reasons, economics may favor a new facility; the cost of upgrading Shiva Nova and building a large target chamber may be greater than the expense of constructing a new facility.

Engineering Development. This third phase of the program will focus primarily on the major technical problems associated with an ICF power plant. These include the development of:

- A high-average-power driver with the required efficiency ($> 1\%$) and reliability ($> 70\%$).
- A first wall able to withstand the effects of x rays, debris, and neutrons from the microexplosion.
- Structural materials that can withstand the cumulative-damage effects of high-energy neutrons and cyclical stresses.
- Final-focusing elements that can be placed far enough away from the microexplosion so that they can last a reasonable length of time.
- The technology to mass-produce fusion targets cheaply.

*Fusion-energy gain is defined as the product of pellet gain and laser-system efficiency. As such, it represents the ratio of thermonuclear-energy output to electrical-energy input.

The second experimental power reactor, EPR II, will be built to demonstrate limited steady-state electrical generation in a smaller and less-costly mode than is available with a demonstration power reactor. The experimental power reactor that can accomplish this objective will be able to:

- Operate at 10^5 pulses per day.
- Generate considerable thermonuclear power (>100 MWt and tens of MWe).
- Increase plant availability to >40%.
- Achieve fusion-energy gain >6 .
- Demonstrate tritium regeneration and recovery.
- Cost approximately \$1 billion.

In addition, a test and engineering facility will be begun in this phase to qualify materials for commercial power-plant operation. This facility must be able to:

- Generate ≈ 10 MW of thermonuclear power.
- Consume ≤ 100 MW of electrical power off-line.

- Achieve fusion-energy gain >0.1 .
- Extend plant availability to $\approx 70\%$.
- Test materials for commercial operation to 10^{23} neutrons/cm².
- Cost approximately \$500 million.

Long lead times are generally required to develop and test new materials. Therefore, it would be desirable to develop this high-average-power test facility much earlier in the program. Unfortunately, it is difficult to project a more rapid development of the technology that is required to operate at 70% plant availability.

The pellet production facilities in this phase will have to provide 10^5 targets per day both for the EPR II and for the materials test facility. At this stage, we must develop the technology for fuel factory to mass-produce targets cheaply enough to allow economical power production.

Nonelectric applications of inertial-confinement fusion also have been identified, including propulsion, fissile-fuel production, high-temperature

Fig. 7-31. Three planning options for engineering facilities required for inertial confinement fusion power.

process heat, burn-up of radioactive fission waste, and synthetic-gas production. The technical feasibility and economic incentives for developing these alternative applications will be evaluated during this phase. The decision to pursue any of the alternative applications in conjunction with the production of commercial electricity must be made by weighing the recognized benefits against the additional costs for development.

Commercial Development. The major efforts in this final phase of development will be associated with planning, constructing, and operating a demonstration power reactor. This facility will be required to demonstrate the potential for economically produced ICF electricity over alternate long-range sources of energy by operating in a safe, reliable, and environmentally acceptable manner. In short, the demonstration power reactor will:

- Generate 500 to 1000 MW (several 100 MWe) of thermonuclear power.
- Reach a plant availability $\approx 70\%$.

- Breed tritium.
- Be fully licensed as a power reactor.
- Consume less than 25% of generated power as recirculating power.
- Achieve a fusion-energy gain >10 .
- Cost less than \$2 billion.

Time Schedules and Options

For planning purposes, alternate time schedules for major engineering facilities are projected in Fig. 7-31. The three planning options are designated as cautious, aggressive (midrange), and accelerated.

In the cautious plan, the decision to begin the *design* of a major engineering facility is made only after the preceding facility has achieved the milestones required for scientific justification. For example, the planning and design phase of the EPR II would not begin until EPR I had operated and achieved its objectives. In this plan, technical

Fig. 7-32. Time schedule for scientific and engineering facilities following the aggressive planning option.

progress is limited by the availability of funds and the demonstration power plant would not operate until after the turn of the century.

In the aggressive plan, the decision to begin *construction* of a major engineering facility would not be made until the preceding facility had achieved the milestones required for scientific justification. With this logic, construction of EPR II would not begin until EPR I had achieved its objectives. Funding is adequate and new projects are undertaken when their success is reasonably assured. A demonstration plant would operate at the turn of the century.

In the accelerated plan, the need for a new energy source is extremely urgent. Major engineering facilities are addressed in parallel and new facilities are begun as soon as their *need* is defined. Thus, planning for EPR I would begin in 1983, before the scientific feasibility of such a plant has been demonstrated. Reasonable scientific justification would be obtained by extrapolating results from previous facilities. Funding is available and adequate for the construction of major facilities in parallel. Following this plan, a demonstration plant would operate in the mid-1990's.

Comparing these three plans, we note that from the slowest to fastest option, there is a difference of 11 yr in the operational date of the demonstration power reactor. However, in the accelerated plan, the decrease in time to the DPR is gained at the expense

of parallel development of major facilities. This high-risk strategy would seriously impact the rate of spending in the program as well as the rate of employing the technology base of manpower and production capabilities.

In Fig. 7-32, the time schedule for the engineering facilities in the aggressive (midrange) plan is presented, together with the time schedule for the development and operation of the required scientific facilities. Here we see that the decision to begin EPR I is made after Shiva Nova has been operating long enough to demonstrate a high-gain microexplosion and after all of the potential high-average-power sources have been operating long enough to be adequately evaluated. Pellet development is the only major engineering technology that strongly overlaps the design and construction of the scientific facilities. From this, it is evident that we must begin to develop the technology to mass-produce targets immediately so that it will be available when the decision to build EPR I is made. We have estimated the timing for all of the pellet-development facilities not on present engineering knowledge but rather on the assumption that current pellet technology can be developed rapidly enough to prevent pellet availability from becoming a pacing element in the program.

Author
J. A. Maniscalco

SYSTEM STUDIES

James Maniscalco - Group Leader - Reactor Design, neutronics

Audrey Heine - Secretary

Jack Hovingh - Reactor cavity/first wall studies

Wayne Meier - Reactor design, Lithium fall, blanket studies

James Blink - Military applications

Luisa Hansen - Neutronics

Section 8

LASER ISOTOPE SEPARATION PROGRAM

Contents

Section 8 — LASER ISOTOPE	
SEPARATION PROGRAM	8-3
8-1 Overview	8-3
Process Description	8-3
Process Research and Development	8-5
Economic Analysis	8-6
Other Isotopes and Laser	
Photochemistry	8-9
8-2 Atomic Uranium Laser Spectroscopy	8-9
Spectroscopic Technique	8-11
High-Lying and Rydberg States	8-13
Excitation and Ionization Cross	
Sections	8-17
Related Studies	8-13
8-3 Photon Dynamics	8-20
Uranium-Vapor Isotope Separation	8-20
Coherent Excitation Model	8-22
Analytic Solutions	8-23
N-Level Chains	8-23
Three-Level Ladder	8-25
Doppler Access	8-25
Lambda System	8-29
Summary	8-29
8-4 SPP-II Test-Bed Facility	8-29
8-5 Copper-Vapor Lasers	8-33
8-6 Dye Amplifiers	8-36

Section 8

LASER ISOTOPE SEPARATION PROGRAM

8-1 Overview

The major goal of LLL's Laser Isotope Separation (LIS) Program is to develop economically viable laser processes for the large-scale enrichment of uranium for light-water reactor fuel.

LIS technology centers around the use of very monochromatic radiation to isolate ^{235}U atoms or molecules from the corresponding ^{238}U species. The isotopic differences important for LIS are manifest in the electronic and vibrational spectra and appear as slight shifts in the absorption spectra of one isotope relative to another in the feed atoms or molecules. Since the spectroscopic selectivity is relatively independent of fractional mass differences in the isotopes, the LIS process intrinsically has a much higher separation factor than either the gaseous diffusion or centrifuge methods. Consequently LIS plants can be much smaller and relatively inexpensive. Current LLL estimates give less than \$1 billion for an LIS plant as compared to \$3 billion to \$4 billion for a gaseous diffusion plant of equal capacity (the standard plant capacity assumed for such economic comparisons is 9 million separative work units (SWU) per year). On the basis of current projections for new enrichment capacity over the next 20 years, it appears that present-value savings of billions of dollars could be achieved using LIS. A comparison of the savings a full-scale LIS plant could produce as opposed to the estimated cost of the research and development required to develop such a plant shows a very favorable benefit-to-cost ratio in excess of 15.

The principal near-term objectives of the Laser Isotope Separation Program are: (1) to perform the necessary research to evaluate the physics and chemistry of new laser-induced processes, and (2) to develop the components and carry out the necessary integration to establish the technical feasibility of these processes for further development into prototype hardware. An important aspect of the

program is the development of a broad technical data base to evaluate photoseparation processes in general, particularly in relation to a quantitative understanding of the scaling factors associated with each concept.

The research and development expenditures required to establish technical feasibility of LIS enrichment of uranium can strongly impact the burgeoning technology base required for other laser applications, both isotopic and nonisotopic in nature. Unique quantum characteristics can be used to selectively activate, separate, and modify atoms and molecules in laser-driven processes with application to waste cleanup, photosynthesis, industrial catalysis, and biology. The technological spin-offs from early LIS research and development are expected to be considerable. Although at this time the program is largely devoted to uranium LIS, in the longer term it will provide the experimental expertise for continuing research and development in other large-scale applications of "quantum engineering."

Process Description

A number of separation methods, based on both atomic and molecular feeds, are being pursued at LLL. Selective ionization of atomic vapor is best understood and is currently receiving the most attention. The general optimism attached to this generic technique is based on a number of factors including the results of various feasibility experiments in the early stages of the LIS program, detailed spectroscopic investigations since then, and the identification of visible-wavelength laser technologies that appear to be scalable with low-to-moderate risk in the critical time frame. For uranium atomic vapor, spectroscopic feasibility¹ was demonstrated in 1974, and macroscopic quantities of light-water-reactor grade assay were

separated² in 1975 (Fig. 8-1). There was no attempt in either of these scientific experiments to develop new hardware. Rather, readily available commercial cw ion and tunable dye lasers were employed.

Figure 8-2 summarizes a number of laser photoionization processes that are being investigated and also indicates the probable types of lasers that would be used. The first excitation

scheme shown at the very left of the figure would use a three-photon process, the photons being generated by pumping tunable dye lasers with either copper vapor or frequency-doubled Nd:YAG lasers. This process uses direct autoionization, and therefore a significant effort within the program is devoted to exploring the autoionizing spectrum or atomic uranium vapor. The second process would

1974-1975 Project Morehouse: Scientific Feasibility

- Produced milligram quantities of 2.5% enriched material
- Evaluated atomic vapor source
- Evaluated electrostatic ion extraction
- Developed technique for protecting optical windows
- Evaluated cw-laser, two-photon approach

Fig. 8-1. Project Morehouse in 1975 demonstrated enrichment of macroscopic quantities of uranium to 2.5% in the ^{235}U isotope by use of a xenon ion laser to selectively excite the ^{235}U atoms.

Fig. 8-2. Various photoionization processes for atomic uranium vapor are being investigated in the LIS Program.

use the same pump lasers, but ionization would not be achieved through an autoionization process. Instead, ionization would be accomplished through either collisional or plasma effects that occur in the vapor stream or through the utilization of an external microwave or pulsed electric field. The next four processes are completely analogous to the first two but use either two-step or one-step photoionization. The shorter wavelength lasers used in these cases are based on more advanced technology and require considerable research and development to be brought to the commercial stage.

Process Research and Development

The system elements entering into the definition of a total laser-isotope-separation process, as illustrated in Fig. 8-3, specify the major program activities. During 1976 significant progress was achieved in the development of a number of the major subsystems in addition to the acquisition of a

broad spectroscopic data base for the atomic vapor process. A small test bed facility for the experimental evaluation of process options under conditions representative of an operating LIS system was completed and became operational in the latter portion of the year.

Table 8-1 summarizes the atomic-vapor data base required to assess the processes shown in Fig. 8-2. A new spectroscopic technique was employed in evaluating much of the critical spectroscopy for this extremely complex atom. New methods were successfully developed for higher precision measurements of absolute absorption cross sections and the spectroscopic differentiation of very densely packed energy levels, and in addition various field-induced phenomena on the ionization and autoionization spectra were clarified. These parameters define, for example, laser wavelength and saturation flux requirements, and the overall photon utilization efficiency for a particular point design. Parallel theoretical efforts employed these data to construct

Fig. 8-3. The key elements of an LIS system shown here dictate the major program activities.

general computer codes to predict process performance. In order to establish the necessary collision-physics data base, a crossed-molecular-beam apparatus was constructed. A top-view schematic of this highly versatile apparatus is shown in Fig. 8-4.

Table 8-1. Data base requirements for atomic vapor LIS

- Isotope shifts and hyperfine splittings
- Level identification/assignment (bound and nonbound)
- Intermediate-excitation and autoionization cross sections
- Radiative lifetimes and branching ratios
- Field-induced phenomena, including ionization/autoionization
- Electron-impact cross sections (Rydberg levels)
- Excited-state reaction and quenching cross sections
- Charge-exchange and momentum-transfer cross sections

Good progress was achieved in the development of pulsed visible-wavelength laser systems. Pump-to-dye conversion efficiencies in excess of the baseline case value were achieved. In addition, pump powers above that projected in early 1976 were obtained, as seen in Fig. 8-5. Currently the LIS Program is in the process of constructing a pre-prototype laser in the 100-watt pump-power range from which a small-scale prototype will be constructed with single-aperture powers in the range of actual plant requirements.

The test bed facility is described in a following article. In addition to enabling the evaluation of atomic vapor process options, it will allow us to test components and to address integration issues in environments similar to those of an actual LIS enrichment system. Numerous diagnostic devices are employed in the separation chamber, to obtain precise data that can be used in the scaling relations so as to permit economic projections and model verification.

Economic Analysis

An essential element in the LLL Laser Isotope Separation Program is economic modeling which

Fig. 8-4. Plan view of mass spectrometer sampler, built to establish the collision-physics data base needed for uranium LIS development. Main chamber and detector of the crossed-molecular-beam apparatus are shown.

Fig. 8-5. Projected development of pump lasers for the uranium LIS process. Performance already achieved is indicated by x's.

Fig. 8-6. Some results of the joint economic studies done by LLL and Battelle-Columbus, showing sensitivity of uranium LIS production costs to various parameters.

Fig. 8-7. Breakdowns of production costs and capital costs as estimated for a 9-million-SWU/year plant for LIS enrichment of uranium.

draws upon results from system modeling and employs plant-related factors to determine the total LIS process costs. Figure 8-6 summarizes certain results of the economic studies carried out in a joint effort with Battelle-Columbus. The sensitivity plot gives the production cost in dollars per separative work unit cost as a function of certain key laser-related parameters. The modulator lifetime refers to the total power-conditioning system but is largely controlled by certain specific components within that system. A significant reduction in this lifetime, to levels typical of actual equipment, would not have a dramatic impact on the production cost. Similarly the laser lifetime, though showing a much greater sensitivity, is not expected to be a major problem. The assumed lifetimes are based on lasers similar to those being developed for LIS. As indicated previously, conversion efficiencies (pump to dye) greater than the base case assumption have been demonstrated, allowing significant reductions in the overall production costs—to less than \$40/SWU. Finally, the available population refers to the ^{235}U population that is actually available for laser excitation. At present, populations in excess of the base case have not been demonstrated.

Figure 8-7 shows the distribution of the production costs for a 9-million-SWU/year plant and a breakdown of the plant capital cost, which is the major cost involved. The capital cost estimate is \$1 billion or less for the baseline case assumptions. Advanced technology investigations at LLL indicate that a cost well below \$1 billion is possible.

Other Isotopes and Laser Photochemistry

Laser isotope separation technology is generally applicable to all elements. As indicated previously the LLL experimental efforts have been directed almost entirely toward uranium separation because of the obvious economic potential. However, during this past year extensive market studies were carried out to evaluate the potential impact that production of isotopes at substantially lower cost would have on a wide spectrum of alternate applications. These results are summarized in an article in the following section.

The technology being developed for LIS also has potential large-scale applications to the general

chemical industry, although the specific applications are not nearly as well defined at this time.

References

1. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), pp. 491-494.
2. S. A. Tuccio, R. J. Foley, J. W. Dubrin, and O. Krikorian, *IEEE J. Quant. Electron.* **11**, 1010 (1975).

Authors

J. Davis

R. Davis

8-2 Atomic Uranium Laser Spectroscopy

Supporting our LIS missions is a broad spectrum of experimental chemical-physics activities including atomic and molecular spectroscopy, chemical kinetics, photochemistry, and basic atomic and molecular collision physics. This article describes our recent work in uranium atomic-vapor spectroscopy. Much spectroscopic information on the complex uranium atom has been gained during the past year by a relatively new technique that enables routine measurement of radiative lifetimes, absorption cross sections, branching ratios, and hyperfine splittings, with identification and assignment of new levels.³⁻⁶

Traditionally, studies of heavy elements have been based on emission spectra from low-excitation-potential discharge lamps. For many reasons this technique usually allows assignments of only the lower portions of the spectrum. For elements such as uranium, with a ground-state valence configuration of f^3d^2 , some 92 000 emission lines have been catalogued; only a small fraction have been assigned, mainly by workers at Los Alamos Scientific Laboratory and the University of Paris, Orsay (France).

Figure 8-8 summarizes available spectroscopic data as of a few years ago. At that time, the ionization potential was only approximately known, only a few levels of intermediate energy (25 000 to 35 000 cm^{-1}) and odd parity had been tabulated, and essentially nothing was known about the very-high-lying levels and level structure above the ionization limit.

Fig. 8-8. Energy-level diagram for atomic uranium vapor.

Fig. 8-9. Multistep, photoionization-spectroscopy method, variation of uranium-ion current with wavelength (λ), laser power, and delay time between laser pulses allows identification of new levels and measurement of spectroscopic parameters.

Cross-section, radiative-lifetime, and branching-ratio data were scarce and, in many instances, the cited values were limits. Available, however, was a fair amount of data on isotopic shifts (^{235}U - ^{238}U). In the visible portion of the spectrum, these shifts are typically 0.1 to 0.3 cm^{-1} . Because of uranium's low volatility, temperatures exceeding 1900 K are needed to achieve the vapor densities required for the measurements described below. At this temperature, a significant fraction of the uranium atoms reside in the low-lying metastable (odd-parity) states listed on the right side of Fig. 8-8.

Spectroscopic Technique

The LLL scheme is a molecular-beam technique known as sequential, multistep, laser-ionization spectroscopy (see Fig. 8-9). This is a refinement and extension of the methods of Janes,⁷ Stebbings,⁸ and others. It allows an atomic beam of uranium to be

used with a number-density/path-length product roughly a billion times smaller than in conventional spectroscopy. In addition to being extremely versatile, the technique is also extraordinarily sensitive.

A beam of uranium atoms ($<10^{-5}$ torr) is partly ionized by sequential pumping with two to four pulsed lasers. By observing the variation in uranium-ion current with wavelength, the delay time between laser pulses, and the laser power density, one can measure essentially all the spectroscopic parameters of interest.

To illustrate, visible laser photons excite the uranium atoms to an intermediate, even-parity level. Following a short delay (about 20 ns) to avoid ambiguities, λ_2 photons are introduced. If there is an odd intermediate level at an energy corresponding to $\lambda_1 + \lambda_2$, this level will be populated and subsequently ionized by the λ_2 photons or by an additional λ_3 photon. Thus, by scanning laser 2 in wavelength, we can quickly identify the

Fig. 8-10. Experimental apparatus arrangement for multiwavelength stepwise ionization.

position of intermediate odd levels. By measuring the ion current as a function of time delay between the lasers, we get the resulting ion-current variation, establishing the radiative lifetime of the excited level.

Ionization of high-lying levels is achieved with infrared photons (λ_1) or by field ionization. Because we are detecting ions, the signal-to-noise ratios associated with this method are very favorable. Moreover, it is unnecessary to know the absolute neutral-beam flux or the ion-detection efficiency. Finally, it is clear there are several properties that still cannot be obtained easily by conventional methods.

A diagram of the photoionization spectroscopy apparatus is shown in Fig. 8-10. Nitrogen-pumped dye lasers ($\leq 0.5\text{-cm}^{-1}$ in width) and a medium power CO_2 laser excite and ionize the atom. One of

Fig. 8-12. Methodology for J quantum-number assignments.

Fig. 8-11. Laser (λ_2) scan for intermediate-level identification where $\lambda_1 = 6056 \text{ \AA}$.

the lasers in these studies is a high-resolution ($\sim 75\text{-MHz}$ FWHM), pressure-scanned dye laser which, in the cross-beam configuration, enables sub-Doppler width studies with a resolution approaching 0.1 ppm in the optical regime.

The uranium beam is formed by heating an alloy of uranium (uranium dirhenide) to a temperature of about 2000 K in a tungsten effusion cell. Thermal ions and electrons are removed electrostatically, and the neutral beam enters a collision cell where it is photo- or field-ionized. The ions are then directed into a quadrupole mass spectrometer that filters out all other ions. The uranium ions reaching the multiplier are integrated. Real-time wavelength calibration is achieved by monitoring known lines from a microwave-powered uranium-atom lamp. A common master oscillator delivers a 2500-V pulse to the grid of the thyatron in each nitrogen laser, providing precise temporal control of the dye lasers. The measured jitter is less than 5 ns . Output delays between any two lasers are achieved by sending the high-voltage trigger through an appropriate length

Fig. 8-13. Delay technique for preferential detection of Rydberg sequences.

of cable. In addition, switchable preprogrammed delays of up to 300 ns are designed into the master oscillator. In most of the measurements, the unpolarized outputs of the dye lasers are 10-ns pulses of 20-kW peak power with 0.5-cm^{-1} linewidth.

Figure 8-11 shows uranium ion current vs λ_2 . Each ion peak corresponds to an odd intermediate level with a J value of either 5, 6, or 7 because the level populated by the 6056-Å laser has a $J = 6$. The heights of these peaks are a relative measure of the photoionization cross section and not of the intermediate-excitation cross section. The latter has a value comparable to 10^{-14} cm^2 and is saturated; however, the ionization step is not saturated.

Employing this new general method, over a 100 new odd levels in the $32\,000$ to $35\,000\text{-cm}^{-1}$ interval

have been identified. In many instances, we have been able to assign quantum numbers to these transitions by exciting, in separate experiments, a number of low-lying levels of different but known J values. (This methodology is illustrated in Fig. 8-12.) The second laser (λ_2) is scanned in each case and the presence or absence of commonly excited intermediate levels is noted. Employing the dipole-selection rules, we can then assign the upper-level J values. Table 8-2 is a tabulation of some of the levels assigned using this approach.

High-Lying and Rydberg States

At LLL, very high-lying valence and Rydberg (hydrogenic) levels in atomic uranium have been

Table 8-2. Assignment of excited odd parity states in uranium

Level energy	J=4, 17448.2 cm ⁻¹	J=5, 16929.7 cm ⁻¹	J=6, 17070.5 cm ⁻¹	J=6, 16585.8 cm ⁻¹	J=7, 15631.8 cm ⁻¹	J assignment
33442.8	33442.8	33442.8	33442.8	33442.7	—	5
33500.3	33499.8	33500.5	—	33500.6	—	5
33624.2	—	33624.2	—	—	33624.2	6
33720.5	33720.5	—	33720.8	33720.4	—	5
33742.7	33742.8	33742.7	33742.6	33742.6	—	5
33833.2	—	33833.2	—	—	33833.1	6
33914.4	33914.3	33914.2	33914.7	—	—	5
34003.1	34003.1	—	34003.2	—	—	5
34024.6	34024.6	34024.6	34024.7	—	—	5
34070.5	34070.8	34070.3	34070.5	—	—	5

identified and characterized. Levels lying very close to the ionization limit had not been observed in emission studies. There is an enormous density of levels above 49 000 cm⁻¹, nearly one level per wave

number in certain regions. To distinguish between high-lying valence and Rydberg levels, a delay technique shown in Fig. 8-13 is used. The valence levels have lifetimes comparable to 100 ns while the Rydberg level lifetimes are, of course, much longer. Thus, by delaying the CO₂ laser-ionizing pulse a couple microseconds, most of the valence levels will have decayed away, leaving only the Rydberg levels to be ionized. Figure 8-14 illustrates the enormous simplification in the spectrum achieved using temporal discrimination. A high-resolution (<0.1 cm⁻¹) scan of a Rydberg progression is given in Fig. 8-15. Effective principal quantum-number assignments have been made and the two series are assigned to the {5f³7s²}[n]p and {5f³7s²}[n]f configurations. The Rydberg-progression data (Fig. 8-16) provide an accurate value for the ionization potential: 6.1941 ± 0.0005 eV (49 958 ± 4 cm⁻¹).

These Rydberg levels are also ionized by an electric field as demonstrated by several investigators

Fig. 8-14. Preferential observation of Rydberg states in uranium populated from the 32 899.3-cm⁻¹ odd level: (a) CO₂ ionization-pulse delay ~40 ns; (b) ~2 μs.

Fig. 8-15. High-resolution scan of doublet Rydberg progression populated from the $32\,899.79\text{-cm}^{-1}$ level.

Fig. 8-16. Quantum defect vs principal quantum number for $[f^3 s^2]np$ series assessed from the $32\,899.790\text{-cm}^{-1}$ level. Numbers at the end of the three lines are the limit values (cm^{-1}).

on other much simpler atoms.^{9,10} As seen in Fig. 8-17, the electric field plus Coulomb potentials yield an effective potential having a maximum. Depending on the Rydberg-level energy and on the field strength, ionization can occur either classically, as shown, or by tunneling. Field-ionization measurements on these levels have been

Fig. 8-17. Coulomb potential in an applied electric field.

Fig. 8-18. Ionization signal as a function of pulsed, ionizing electric field. The asterisk denotes the point at which the apparatus collection efficiency drops to 98% with a 1-ms pulse.

conducted in the same apparatus but with a slightly different collision-cell configuration. A well-defined electric field up to 15 kV/cm is established by placing a dc potential on two parallel plates following the optical excitation to the Rydberg level under examination.

Figure 8-18 indicates that at a field strength of approximately 160 V/cm, Rydberg atoms with an effective quantum number of $n^* = 39.18$ are completely ionized. Critical electric fields have been established for a number of Rydberg levels and the results are in excellent agreement with Ducas *et al.*⁹ There is also good agreement with the simple theoretical model shown in Fig. 8-19. Conventional Stark spectroscopy measurements have also been carried out on the high-lying Rydberg and valence levels using the photoionization method. In addition, in an external dc electric field, lifetime lengthening resulting from angular-momentum-mixing effects has been observed.

Figure 8-20 shows a laser scan probing the ionization region. The ionization onset is 6.191 ± 0.002 eV, in good agreement with the Rydberg-convergence method. There is a very high density of

Fig. 8-19. Critical ionization field vs effective principal quantum number for high-Rydberg states. Solid circles are for uranium;⁵ open circles are for sodium.⁹

Fig. 8-20. Partial autoionization spectra of uranium from the odd-parity level at $33\,082.7\text{ cm}^{-1}$.

autoionizing levels with peak cross sections at least two orders of magnitude greater than those for direct ionization. Very narrow autoionizing lines ($\leq 0.5\text{ cm}^{-1}$) have been found to be common for uranium, in comparison with the usual very broad linewidths reported for the lighter elements.

We have measured large numbers of radiative lifetimes for both Rydberg and valence levels; the former values are in good accord with theoretical predictions. A typical result is shown in Fig. 8-21. Here, the level is populated from a low-lying metastable level. The measured lifetimes of the valence levels vary from 40 to 760 ns but in general are greater than 300 ns.

Excitation and Ionization Cross Sections

Two techniques have been employed to measure the excitation and ionization cross sections. A saturation approach involves measuring ion current as a function of laser intensity followed by a straight-forward analysis. More recently, a new and very powerful method for the measurement of branching ratios (Fig. 8-22) has been developed at LLL,⁶ enabling a more accurate determination of cross sections. (The branching ratio, itself, is also an important parameter.)

The transition of interest is saturated by a pump laser using λ_p photons. Following the pump pulse, a fraction of the atoms will decay radiatively to the initial state (branching ratio); the remaining atoms fall into metastable levels. The initial level population is then monitored as a function of time by the photoionization probe-laser sequence. After about $1\text{ }\mu\text{s}$, the dipole-allowed decay back to the initial level is essentially complete. The branching ratio is established by ratioing the appropriate signals (Fig. 8-23). Together with the experimentally measured upper-state lifetime, the cross section is then computed using the Einstein relationship. Over this past year, we have obtained a large number of excitation cross sections for uranium, and where comparisons with conventional methods are possible, the agreement has generally been good.

The uranium-atom properties described to this point are essentially independent of the specific isotope. However, because of its nuclear spin, ^{235}U exhibits hyperfine splitting which can be significant when compared to the Doppler broadening. In the

Fig. 8-21. Lifetime (radiative) determination of state reached by $3781\text{-}\text{\AA}$ transition from the 620-cm^{-1} metastable level.

past, hyperfine measurements have proven to be particularly difficult. Employing a pressure-tuned, narrowband, pulsed-dye laser, hyperfine measurements have been made with the multistep laser-photoionization method on an atomic beam enriched in ^{235}U . Figure 8-24 shows a typical high-resolution hyperfine scan for the $16\,900.4\text{-cm}^{-1}$ transition originating from the ground state. Obviously, the technique also provides very accurate isotope-shift values for the investigated transitions.

Fig. 8-22. Branching ratio methodology.

Fig. 8-23. Branching ratio measurement for the even parity $22\,918.55\text{-cm}^{-1}$ ($J = 7$) state.

Related Studies

Clearly, the methods we have described can be used to study the relevant behavior of any heavy atom and, with the lasers presently available, a major fraction of the elements in the periodic table can also be examined. Table 8-3 summarizes some of the recent LLL measurements of ionization limits of the lanthanides, both from the onset of photoionization and from Rydberg-convergence data. Several striking correlations are noted. For example, the change in the ionization potential with atomic number is very regular as one proceeds across the lanthanide row. It is well fit by two straight lines for $f^n s^2 \rightarrow f^n$ ionization processes. This behaviour can be explained simply in terms of the Pauli exclusion principle and Hund's rule.¹⁴ We have also correlated these results to the actinides and find excellent agreement with the spectroscopic extrapolations of Sugar.^{15,16} The fit of the experimental data to the theoretically predicted lines provides measurement of various Slater exchange parameters and one-electron binding energies in these heavy atoms.

References

3. R. W. Solarz, C. A. May, L. R. Carlson, E. F. Worden, S. A. Johnson, and J. A. Paisner, *Phys. Rev. A* **14**, 1129 (1976).
4. L. R. Carlson, J. A. Paisner, E. F. Worden, S. A. Johnson, and R. W. Solarz, *J. Opt. Soc. Am.* **66**, 846 (1976).

Fig. 8-24. Hyperfine structure determination.

Table 8-3. First-ionization potentials of the lanthanides

Element	Surface ionization (Ref. 11)	Electron impact (Ref. 12) (Ref. 13)		Spectroscopic extrapolation (Ref. 14 & 15)	Laser-photoion onset (this work)	Rydberg convergence (this work)
Ce	5.54	—	5.44	5.47 ± 0.05	5.537 ± 0.004	5.5387 ± 0.0004
Pr	5.40	—	5.37	5.42 ± 0.03	5.464 ± 0.006	—
Nd	5.49	—	5.49	5.489 ± 0.20	5.523 ± 0.003	5.5250 ± 0.0006
Sm	5.61	5.56	5.58	5.63 ± 0.03	5.639 ± 0.003	5.6433 ± 0.0010
Eu	5.64	5.61	5.68	5.67 ± 0.01	5.666 ± 0.003	5.6704 ± 0.0003
Gd	6.16	5.98	6.24	6.14 ± 0.05	—	6.1502 ± 0.0006
Tb	5.89	—	5.84	5.85 ± 0.03	—	5.8639 ± 0.0006
Dy	5.82	5.8	5.90	5.93 ± 0.05	5.936 ± 0.003	5.9391 ± 0.0006
Ho	5.89	5.85	5.99	6.02 ± 0.05	6.017 ± 0.003	6.0216 ± 0.0006
Er	5.95	6.11	5.93	6.10 ± 0.08	6.104 ± 0.003	6.1077 ± 0.0006
Tm	6.03	5.87	6.11	6.18 ± 0.08	—	6.1842 ± 0.02^a
Yb	6.04	5.90	6.21	6.25 ± 0.10	—	6.2540 ± 0.02^a

^aRef. 17.

5. J. A. Paisner, C. A. May, L. R. Carlson, E. F. Worden, S. A. Johnson, and R. W. Solarz, "Hyperfine Structure Measurements in ^{235}U , Lawrence Livermore Laboratory, Rept. UCRL-78736 (1976).
6. L. R. Carlson, S. A. Johnson, E. F. Worden, C. A. May, R. W. Solarz, and J. A. Paisner, *Determination of Absolute Atomic Transition Probabilities Using Time-Resolved Optical Pumping*, Lawrence Livermore Laboratory, Rept. UCRL-78662 (1976).
7. G. S. Junes, I. Itzkan, C. T. Pike, R. H. Levy, and L. Levin, *IEEE J. Quant. Electron.* QE-11, 101D (1975).
8. F. B. Dunning and R. F. Stebbings, *Phys. Rev.* A9, 2378 (1974); R. D. Rundel, F. B. Dunning, H. C. Goldwire, Jr., and R. F. Stebbings, *J. Opt. Soc. Am.* 65 628 (1975).
9. T. W. Ducas, M. G. Littman, R. B. Freeman, and D. Kleppner, *Phys. Rev. Lett.* 35, 366 (1975) and references therein.
10. T. F. Gallagher, L. M. Humphrey, R. M. Hill, and S. A. Edelstein, *Phys. Rev. Lett.* 37, 1465 (1976).
11. G. R. Hertel, *J. Chem. Phys.* 48, 2053 (1968).
12. K. R. Zmbov and J. L. Margrave, *J. Phys. Chem.* 70, 3014 (1966).
13. R. J. Ackermann, E. G. Rauh, and R. J. Thorn, *J. Phys. Chem.* 65, 1027 (1976).
14. E. F. Worden, J. A. Paisner, J. G. Conway, and R. W. Solarz, submitted to *J. Opt. Soc. Am.*
15. W. C. Martin, L. Hagan, J. Reader, and J. Sugar, *J. Phys. Chem. Ref. Data* 3, 771 (1974).
16. J. Reader and J. Sugar, *J. Opt. Soc. Am.* 56, 1189 (1966).
17. P. Camus, *The Absorption Spectra of Ytterbium, Lutetium, and Thulium in the Region 2700 Å to 1900 Å*, Ph.D. thesis, University of Paris, Orsay, France (1971); P. Camus and F. S. Tomkins, *J. Phys.* 30, 545 (1969).

Authors

J. Dubrin
R. Solarz
J. Paisner

Major Contributors

L. Carlson
S. Johnson
E. Worden

8-3 Photon Dynamics

Our theoretical effort aimed toward applying laser-induced excitation and ionization to isotope separation has four general objectives:

- To identify a particular excitation scheme and extract from the actual physical milieu a mathematical model expressing the basic processes.
- To identify the key physical parameters of the equations and learn their effects on the solutions to the equations.
- To validate the solutions by comparison with experiment, identify possible bottlenecks and critical dependence of results on possibly uncertain assumptions, and determine possible conflicts in results of different models.

• To determine values of the physical parameters that optimize the solutions — say, the values giving maximum ion yield for least laser power.

The resulting mathematical models are similar whether one deals with excitation-ionization of atoms, with molecular excitation and dissociation, or with laser-induced photochemical reactions.

During this year we have made significant progress toward each of these objectives. From the complexities of atomic-vapor excitation by lasers, we have extracted a simple mathematical model. Analytic and numerical techniques have been developed for solving the model equations. We have elucidated the relationship between physical parameters and dynamical behavior and, under various constraints, have found conditions on the physical parameters which produce maximum ionization. The following examples illustrate portions of our advance in understanding the basic dynamics of photon excitation.

Uranium-Vapor Isotope Separation

Isotope separation by selective laser-induced excitation, reviewed recently by Zare,¹⁸ is deceptively simple in concept. Taking advantage of the small frequency shift of spectral lines between different isotopes, one can tune a laser to selectively excite a particular isotope, leaving the other isotopes unaffected. Then further excitation, followed by ionization, produces an electrical differentiation between isotopes, permitting simple physical separation.

For practical application of this elementary concept, one must overcome many engineering problems as well as some basic physics problems centered on the question: how does one adjust the laser parameters (number of lasers, frequencies, intensities, and bandwidths) and the atomic conditions to achieve the greatest isotopically selective yield of ions for the least expenditure of laser power?

Atomic vapor sources have a distribution of thermal velocities, resulting in a distribution of Doppler shifts for the laser irradiation. (At 2700 K the Doppler distribution for 600-nm-wavelength radiation has an FWHM of 1.2 GHz; the ^{235}U - ^{238}U isotope shift is about 6 GHz.) Individual atomic transitions in ^{235}U are split into hyperfine components typically spread over about 2 GHz (see Fig. 8-25).

Fig. 8-25. Transition in uranium showing relative size of the 5.7-GHz isotope shift, the 1.7-GHz hyperfine splitting, and the 2700 K Doppler FWHM of 1.2 GHz.

Furthermore, the atomic angular-momentum state J has $2J + 1$ discrete quantized orientations in a laser-fixed reference frame (for the ground state of uranium, $J = 6$). To treat these effects exactly, one must average an ensemble of particular cases, although for many purposes it suffices to consider a hypothetical average atom.

In the elementary description of radiative excitation (by incoherent light), atomic excitation by radiative absorption is offset by stimulated emission and spontaneous decay. Although many decays merely reemit the initial frequency, a significant portion emit shorter wavelengths, resulting in a metastable state that is immune to excitation. To avoid such losses, it is desirable that stimulated rates dominate spontaneous rates (a relationship often quantified by the saturation parameter, which is

the ratio of absorption to spontaneous emission rates), and that the excitation-ionization process be completed before significant decay occurs (typically radiative lifetimes are hundreds of nanoseconds). Laser fields sufficient for these objectives (intensities of tens of kW/cm^2) are weak compared with the electrostatic fields that bind electrons in an atom.

Following the stages of selective excitation, ionization can be caused in several ways: by photoionization of an excited state, by excitation to an autoionizing state (i.e., a resonance in photoionization), by collision-induced ionization, or by static-field-induced ionization. One must avoid uranium-vapor densities so high that charge-exchanging collisions destroy the isotope selectivity before the ions can be extracted.

Coherent Excitation Model

The foregoing considerations suggest that a significant physical regime is in effect when stimulated radiation processes completely dominate all other perturbations of atomic dynamics: spontaneous emission, collisional quenching (but not ionization), and other incoherent processes are negligible compared with the effects of stimulated emission and absorption, which in turn are minor perturbations upon the behavior of free atoms. These conditions suggest an elementary model which we have studied extensively: an isolated, multilevel atom simultaneously irradiated by one or more nearly monochromatic classical light sources, each tuned close to a Bohr resonance frequency, while continuously subject to an ionization mechanism.

We describe the radiation as a coherent superposition of laser-generated electric fields. The total radiation field is

$$\vec{E}(t) = \sum_{\lambda} \sqrt{\frac{8\pi I_{\lambda}}{c}} \operatorname{Re}[\vec{\epsilon}_{\lambda} \exp(i\omega_{\lambda} t)] \quad (1)$$

where I_{λ} is the intensity, ω_{λ} the angular frequency, and $\vec{\epsilon}_{\lambda}$ the unit polarization vector for the λ th laser. The behavior in time of the irradiated atom is described by the time-dependent Schrödinger equation. Limiting consideration to a succession of N levels, we express the Schrödinger amplitude as

$$\Psi(t) = \sum_{n=1}^N C_n(t) \psi_n \exp(i\phi_n t) \quad (2)$$

where ψ_n are field-free atomic basis sets and ϕ_n are arbitrary phases. In the conventional Schrödinger picture, the phases are set to zero; in the Dirac or interaction picture, phase differences are equated to atomic Bohr frequencies; we adopt the rotating wave picture wherein phase differences are equated to laser frequencies. Because we deal with only a finite number of levels, rather than a complete configuration space (which would include a continuum as well as discrete levels), the effective Hamiltonian is complex; the negative imaginary diagonal matrix elements represent half the rate of probability loss

into states outside our N -level basis. Assuming that such losses are due to ionization, we obtain the fraction of ionized atoms as an integral over the Doppler distribution of velocities $f_{\text{Dopp}}(\nu)$ and an average over other atomic parameters (such as orientation) denoted by a :

$$\bar{P}_{\text{ion}}(t) = \int d\nu f_{\text{Dopp}}(\nu) \times \sum_a \left[1 - \sum_{n=1}^N |C_n(t)|^2 \right] / \sum_a 1 \quad (3)$$

To determine the amplitudes $C_n(t)$ and hence the ionization probability, we solve the linear, first-order, time-dependent Schrödinger equation,

$$i \frac{d}{dt} C_n(t) = \sum_m W_{nm} C_m(t) \quad (4)$$

For ladderlike excitation schemes in which radiative transitions link only adjacent energy levels, the matrix W is tridiagonal: only elements of the form W_{nn} and $W_{n,n\pm 1}$ can be nonzero. Our choice of phases has removed a primary time dependence of the matrix W , leaving time variation in terms which oscillate at sum and difference frequencies $\omega_{\lambda} + \omega_{\lambda'}$ and $\omega_{\lambda} - \omega_{\lambda'}$. Both types of periods can be seen to be much shorter than the time period over which appreciable variations occur in populations, and hence such oscillatory terms can be replaced by their null-time averages without incurring serious error. In the resulting rotating wave approximation (RWA),¹⁹ the matrix W has complex-valued diagonal elements

$$W_{nn} = D_n - \frac{i}{2} \gamma_n \quad (5)$$

where γ_n is the probability loss rate out of level n and D_n is the cumulative detuning of $(n-1)$ laser excitations away from the Bohr frequency for transition from level 1 to level n :

$$D_n = (E_n - E_1)/\hbar - (\omega_1 + \omega_2 + \dots + \omega_{n-1}) \quad (6)$$

That is, only the detuning, not the individual laser frequencies, affects the dynamics in the RWA.

The off-diagonal elements, expressing in frequency units the energy of interaction $\underline{d} \cdot \underline{E}$ between the dipole transition moments and the electric vector of the lasers, provide the definition of the Rabi frequency Ω_n :

$$2W_{n,n+1} \equiv \Omega_n = \langle n | \underline{d} \cdot \underline{E}_n | n+1 \rangle \times \sqrt{8\pi I_n / ch^2} \quad (7)$$

Although Ω_n depends upon atomic orientation, through the angle $\underline{d} \cdot \underline{E}_n$ between atomic dipole and polarization, a rough estimate may be obtained from the rule of thumb $\Omega = 10^{14} \sqrt{\sigma I}$ with Ω in rad/s, intensity I in W/cm², and peak cross section σ (for Doppler-broadened uranium at 2700 K) in cm²; typical transitions require 10 kW/cm² for a Rabi frequency of 10^9 rad/s.

Because the matrix W is constant, one can readily solve the RWA equations for any time by constructing the matrix exponential $\exp(-iWt)$. This construction is obtained from the eigenvalues Z_k and eigenvectors $\langle \psi_n | k \rangle$ of W ; these are the dressed-atom states. Assuming initial ($t = 0$) ground state certainty, one finds that

$$C_n(t) = \sum_k \langle \psi_n | k \rangle \exp(-iZ_k t) \langle k | \psi_1 \rangle \quad (8)$$

Although the foregoing description deals only with the elementary RWA Schrödinger equation, we have generalized the treatment to include slowly varying field amplitudes (as in pulse shapes and modulation) and to permit the treatment of relaxation processes by dealing with Bloch equations rather than Schrödinger equations.²⁰

Analytic Solutions

The RWA equations have exact analytic solutions in several special cases; these provide valuable checkpoints for numerical solutions. The infinite-level lossless harmonic oscillator ($\Omega_r = \sqrt{n} \Omega_1$ and $D_n = (n-1)(\omega_{osc} - \omega)$ with ω_{osc} the oscillator frequency) maintains a Poisson population distribution $|C_n(t)|^2 = X^n \exp(-X) / (n-1)!$ at all times. For resonant excitation, $\omega = \omega_{osc}$, the average ex-

citation X grows without bound quadratically in time, $X = (1/4)(\Omega t)^2$; for a nonresonant driving force, average excitation X tends after a long time to the value $(1/2)[\Omega/(\omega - \omega_{osc})]^2$.

Other soluble situations include (1) the truncated N -level, lossless, resonantly driven harmonic oscillator, and (2) the N -level (including $N = \infty$) uniform Rabi frequency sequence ($\Omega_n = \Omega_1$).²¹ Studies of such models provide insight into the way molecules are excited by radiation.

The two-level system (and likewise the three-level system) is soluble for arbitrary values of the basic parameters — detuning, loss, and Rabi frequency.²² In a two-level atom, the population flows periodically between the two levels while decaying (if ionization loss is present). The frequency of population oscillation, when driven resonantly without loss, is the Rabi frequency Ω_1 . When loss rate exceeds a critical value ($\gamma > 2\Omega_1$ for resonant excitation), the Rabi oscillations are critically damped; further increase in γ actually causes ionization to proceed more slowly.

N-Level Chains

Systems having a chain (or ladder) of adjacent-linkage transitions $1 \rightarrow 2 \rightarrow 3 \rightarrow \dots \rightarrow N$ represent the most fundamental model of coherent photon excitation.

The behavior of two- and three-level systems is marked by exactly periodic population pulsations. This precise regularity is generally absent for larger systems as seen in Fig. 8-26(a) which shows populations of resonantly excited lossless systems having equal Rabi frequencies. This behavior finds explanation in terms of incommensurate dressed-atom frequencies Z_k .

Near periodicity does occur for the resonantly driven, truncated (N -level) harmonic oscillator, as illustrated in Fig. 8-26(b). We have found^{4,6} analytic expressions for many of the regularities we have observed in such N -level systems (e.g., the regular flow of probability during the initial burst, the regular "sloshing" of probability in the truncated harmonic oscillator, the long-time distribution of population). These findings provide a foundation for understanding more complicated realistic models.

For single-frequency excitation at the fundamental frequency, anharmonicity in energy level spacing prevents excitation flow into highly excited states; there is very little likelihood of finding population

Fig. 8-26. Excitation probabilities $P_n(t) = |C_n(t)|^2$ of levels $n=1, 2, \dots, N$ as a function of normalized time interval $\Omega_1 t$ for $N=3$, 4-, and 5-level atoms. (a) All Rabi frequencies are equal, $\Omega_n = \Omega_1$; (b) Rabi frequencies increase like harmonic oscillator, $\Omega_n = \sqrt{n} \Omega_1$.

in a level for which the cumulative anharmonic detuning exceeds the Rabi frequency into the level.²³ Multiphoton excitation at sharply defined frequencies can enhance long-time excitation.

Three-Level Ladder²⁴

The interplay of parameters D_n , Ω_n , and γ_n regulates the behavior of solutions to the RWA. For any given time interval it is possible to find values of the parameters which maximize ion production. This is easy to demonstrate in the three-level, two-transition system with ionization loss γ , only from the third and uppermost level. Figure 8-27 shows, for lasers tuned to the field-free resonance frequencies, the effect of altering the relative values of the two Rabi frequencies. The two frames illustrate two choices of ionization loss rate, and the successive curves are for successively later times. For any given time and any loss rate, the maximum ionization yield occurs when the two Rabi frequencies are approximately equal (or better still, successively increasing by about 25%).

Similarly, Fig. 8-28 shows the effect of varying

the loss rate, while resonantly tuned, for three choices of relative Rabi frequency; as before, successive curves refer to successive times. In all cases, the maximum yield occurs when ionization rate approximately equals the largest Rabi frequency. (For smaller γ , the small rate coefficient limits ion production; for larger γ , the overdamping diminishes ionization, just as in the two-level system or as with the reduction of peak cross section by power broadening.)

Doppler Access

Much interest at LLL has centered on four-level excitation sequences, with ionization from level 4. For resonantly tuned lasers, the preceding optimization results suggest the desirability of matching Rabi frequencies and ionization rate. However, the Doppler distribution of laser-frequency shifts appears as a distribution of detunings. For pulsed collinear lasers, the cumulative detuning D_n is the sum of $n - 1$ very nearly equal Doppler shifts. Figure 8-29 illustrates the effect of this Doppler detuning upon the four-level dynamics of a system having

Fig. 8-27. Ionization probability $P_{\text{ion}}(t) = 1 - \sum_{n=1}^3 |C_n(t)|^2$ for a three-level, ladderlike excitation sequence as a function of the Rabi frequency ratio Ω_2/Ω_1 . Successive curves refer to successively later times in increments of $1/\gamma$. (a) Ionization loss rate from level 3 is $\gamma = 0.1\Omega_1$; (b) Loss rate is $\gamma = \Omega_1$.

Fig. 8-28. Ionization probability for the system of Fig. 8-27 as a function of ionization rate γ . Successive curves refer to successively larger values of Ω_2 : (a) First transition stronger, $\Omega_2 = 0.3\Omega_1$; (b) Equal Rabi frequencies, $\Omega_2 = \Omega_1$; (c) Second transition stronger, $\Omega_2 = 1$.

Fig. 8-29. Excitation probabilities $P_n(t)$ and ionization probability $P_{\text{ion}}(t)$ as a function of time t (ns) and of Doppler detuning D (rad/ns) for four-level excitation sequence having $\Omega_s = 2$ (rad/ns) and ionization rate $\gamma = 1$ (rad/ns).

four equal Rabi frequencies. Successive frames show fractional population $|C_n(t)|^2$ in levels 1 through 4, as well as the ion fraction

$$P_{\text{ion}}(t) = 1 - \sum_{n=1}^4 |C_n(t)|^2. \quad (9)$$

In each frame, we see population as a function of time (actually of the variable $\Omega_1 t$) and as a function of the single-laser Doppler detuning $\Delta = (E_2 - E_1)/\hbar - \omega_1$, where ω_1 is the atom-frame (Doppler-shifted) laser frequency. The central section paralleling the time axis corresponds to exact resonance. With increasing detuning the population

Fig. 8-30. Doppler-averaged probability for remaining un-ionized for the system of Fig. 8-29 and a temperature of 2700 K. Left-hand frame shows probability as a function of time and detuning; right-hand frame shows end view: the effective absorption coefficient. (a) Rabi frequencies $\Omega_a = 2$ (rad/ns) as in Fig. 8-29; (b) Rabi frequencies $\Omega_a = 4$ (rad/ns).

oscillations grow more rapid and smaller in amplitude, just as in the two-level atom. We can follow the excitation probability as it flows out of level 1, through levels 2, 3, and 4, to emerge as a burst of ionization.

Folding these curves into a Doppler profile, we obtain the curves of Fig. 8-30(a). With the chosen parameters, only 22% of the atoms are ionized. We can improve this result by using more intense lasers.

Figure 8-30(b) illustrates the effect of doubling all Rabi frequencies (a fourfold intensity increase). By so doing, we nearly double the ionized fraction. Further increase in laser intensity produces only slow improvement in ionization, a saturation effect evident in the figure.

We are examining several alternative schemes for more complete ionization of the Doppler profile, including pulse modulation and frequency sweeping.

Fig. 8-31. Excitation probability $P_n(t)$ and ionization probability $P_{\text{ion}}(t)$ for the three-level "lambda" system $1 \leftrightarrow 2 \leftrightarrow 3$ with loss from middle level 2, with Rabi frequencies $\Omega_1 = \Omega_2$ and loss $\gamma = 2\Omega_1$. Left-hand frame shows time dependence without Doppler shift, right-hand frame shows $P_{\text{ion}}(t)$ as a function of Doppler detuning (in units of Ω_1). (a) Both lasers tuned to respective zero-field Bohr frequencies; (b) Lasers detuned (one to red, the other to blue) by Ω_1 .

An interesting alternative possibility is to employ counterpropagating lasers, so that the succession of excitation frequencies are alternately red-shifted and blue-shifted. A two-photon sequence can be exactly resonant, thereby achieving Doppler-free absorption. With a three-photon sequence, the improvement is less dramatic.

Averaging over the Doppler distribution of frequency shifts tends to dampen the population oscillations that characterize coherent excitation. Nevertheless, remnants of coherence are often quite apparent. We have also examined the effect of relaxation processes, as modeled by the multilevel Bloch equations.²⁰

Lambda System

Ionization bottlenecks can occur with coherent excitation whenever two levels feed a common ionizing level, e.g., when the loss occurs from level 2 of a three-level ladderlike excitation sequence, $1 \longleftrightarrow 2 \longleftrightarrow 3$. With either single transition alone, complete ionization occurs eventually. With simultaneous resonant excitation, a portion of the population (the fraction depends on relative Rabi frequencies and can be as large as $1/2$) remains forever un-ionized, locked into a coherent superposition of states 1 and 3 from which no transition occurs to level 2. Figure 8-31(a) illustrates the time dependence of populations in this system, termed the "lambda system" by Whitley and Stroud²⁵ because of the schematic appearance of the connected energy levels. The bottleneck persists in the presence of Doppler detuning, as Fig. 8-31(a) shows, but can be eliminated by detuning the rest-frame laser frequencies away from resonance. Figure 8-31(b) shows the dynamics when the first laser is red-shifted by one Rabi frequency and the second is blue-shifted the same amount; the detuning has eliminated the bottleneck.

Summary

The preceding examples illustrate a portion of the physics of laser-induced excitation being studied at LLL and by others through contract and consultation with LLL. The realm of coherent excitation is relatively new; from our effort has come a better understanding of the interplay of the basic physical parameters—the detunings, Rabi frequencies, and loss rates—upon the dynamics of photon excitation.

References

18. R. N. Zare, "Laser Separation of Isotopes," *Sci. Amer.* **236**(2), 86 (Feb. 1977).
19. T. H. Einwöhrner, J. Wong, and J. C. Garrison, *Analytical Solutions for Laser Excitation of Multilevel Systems in the Rotating Wave Approximation*, Lawrence Livermore Laboratory, Rept. UCRL-78052 (1976).
20. J. Ackerhalt and B. W. Shore, *Rate Equations Versus Bloch Equations in Multi-Photon Ionization*, Lawrence Livermore Laboratory, Rept. UCRL-79204 (1977).
21. Z. Bialynicka-Birula, I. Bialynicki-Birula, J. H. Eberly, and B. W. Shore, *Coherent Dynamics of N-Level Atoms and Molecules*, Lawrence Livermore Laboratory, Rept. UCRL-79139 Pt. 2 (1977) [*Phys. Rev. A* (in press)].
22. L. Allen and J. H. Eberly, *Optical Resonance and Two-Level Atoms* (John Wiley and Sons, New York, 1975).
23. J. H. Eberly, B. W. Shore, Z. Bialynicka-Birula, I. Bialynicki-Birula, *Coherent Dynamics of N-Level Atoms and Molecules: I. Numerical Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-79139 Pt. 1 (1977) [*Phys. Rev. A* (in press)].
24. B. W. Shore and J. Ackerhalt, "Dynamics of Multi-Level Laser Excitation: Three-Level Atoms," *Phys. Rev. A* (April 1977).
25. R. Whitley, Ph.D. thesis, Univ. of Rochester (1977), privately communicated by C. Stroud.

Author

B. W. Shore

8-4 SPP-II Test Bed Facility

Our selective photoionization pulsed test-bed facility (SPP-II), shown schematically in Fig. 8-32, evolved from the second of two concepts we advanced for a facility to evaluate uranium enrichment technologies. Its purpose is twofold: to study promising techniques for laser-driven isotopic separation of atomic uranium, and to test potentially economic and scalable component systems and subsystems under practical working conditions. The design emphases are flexibility and provision of an actual separation environment where issues of compatibility and integration must be addressed.

In experiments we expect to complete during the first year on the test-bed system, the desired isotope will be prepared for extraction by photoionization. Laser irradiation will provide both initial selective excitation and further excitation of the desired species to a level from which ionization can

proceed. The crossing into the continuum can be photon-driven by the output from a visible laser, or it may occur as a result of physical processes such as collisional or field ionization.

Natural uranium will be obtained in the vapor state from a high-temperature oven in which liquid uranium is in equilibrium with its vapor. A joule-heated tungsten shell surrounds an internal tungsten boat containing the liquid uranium. Sources of this type have been used in LLL experiments for about a year and are well understood.

Multistep excitation of the vaporized atoms to a level just below or just above the ionization energy will also be possible with the combined beams from a set of three (or four, if the 620-cm^{-1} level of uranium is accessed) tunable-dye lasers that are coherently pumped by a set of eight copper-vapor lasers.

The copper-vapor lasers were developed for this facility by General Electric in Valley Forge, Pennsylvania. The dye-laser master oscillators are a

modified version of the Molelectron DL 300 and the dye-laser amplifiers were developed at LLL. All the lasers operate at a nominal repetition rate of 6 kHz; however, there is nothing fundamental prohibiting their operation at any repetition rate between 1 and 10 kHz. Pulse widths are typically 25 to 30 ns. The average output power from each copper-vapor laser is approximately 5 W; there is roughly a 75/25 split between the two output wavelengths at 510.6 and 578.2 nm.

Although we have experienced a large number of electronic and reliability problems in establishing the performance of all eight lasers simultaneously, most of these problems have been solved. We can now, with fair reliability, operate all eight lasers simultaneously. The beam divergence from the copper-vapor lasers is typically between 5 and 10 times diffraction-limited. This good beam quality is available only with an unstable resonator in the oscillator.

Fig. 8-32. SPP-II test-bed facility.

Fig. 8-33. Schematic diagram of the dye laser.

A typical configuration for the operation of the dye laser is shown in Fig. 8-33. The Hansch-style modified Molelectron laser with piezo controls on both the front flat and the tilted etalon is used to provide input for one or more sequential linear dye-amplifiers. In a separate set of dye-amplifier experiments, we obtained very significant linear dye-amplifier conversion efficiencies. With the standard 3-mm etalon in place in the Molelectron cavity, the output spectral bandwidth is about 1.5 GHz FWHM. In this configuration, the bandwidth is not spectrally full and consists of a series of three to seven axial-cavity modes, each of which has an intensity that varies from shot-to-shot in a moderately random fashion.

The dye-amplifier cells have been designed with convergent flow to minimize the dimensions of the boundary layers in the region of pump-laser irradiation. When we designed these Brewster-angle, linear-amplifier cells (see Fig. 8-34), care was taken to avoid any parallel surfaces so as to reduce the likelihood of a gain limitation resulting from a parasitic oscillation.

With the copper-vapor pumped dye-lasers, efficient laser operation is possible from 570 to 680

nm with the use of only three dyes: Rhodamine 6G, Kiton Red S, and DCM. With this laser combination, a uranium atom must absorb three successive red photons to attain the energy required to reach its continuum.

Fig. 8-34. Dye-amplifier cell.

Fig. 8-35. Electrostatic accel-decel extractor.

After each individual dye-laser beam has passed through its last amplifier stage, it enters the beam-combination table. Here, all the individual beams are combined in a collinear fashion, either with an inverted grating or a set of multilayer, dielectric beam splitters. Just before beam combination, a small fraction of each beam is split off and routed to the laser-stabilization table.

Extraction of the selectively ionized ^{235}U atoms from the neutral-gas background can be completed in the SPP-II process chamber with an electrostatic accel-decel extractor. With this approach, an electric field is used to accelerate the ions out of the plasma and form an ion beam that is focused onto the product collector. To minimize the sputtering of material already present on the product collector, the ions are decelerated prior to their impact.

The electrodes essential to the accel-decel ap-

proach are shown in Fig. 8-35. Vapor continuously flows from the oven but is irradiated by a pulsed laser beam. Because of the relatively small diameter of the laser beam and the laser-repetition rate of 6 kHz, only a small portion of the uranium atoms that exit the oven are actually laser-irradiated. The accel electrodes are biased highly negative with respect to ground. They accelerate the photo-produced ions to the product collector along the illustrated trajectories. With reasonable voltages, the plasma can be dissipated and the ions can be collected in a time that is short when compared with the charge-exchange time.

Most of the mechanical and electrical components for the test-bed system were installed in the laboratory in October 1976 (see Figs. 8-36 and 8-37). Much of the initial integration was completed during November; some preliminary experiments

Fig. 8-36. Master control console.

Fig. 8-37. Operating test bed lasers.

were run in December, and we have been involved continuously in attempts to increase the overall system reliability. We are now completing experiments designed to help specify the optimum photoionization spectroscopy and laser bandwidth requirements.

Author
M. Spaeth

8-5 Copper-Vapor Lasers

Recent developments²⁶⁻²⁸ in copper-vapor laser technology have demonstrated this system to be an efficient ($\sim 1\%$) and moderately high-power (~ 20 W) source of visible radiation. These lasers are characterized by high, small signal gain coefficients ($> 0.1 \text{ cm}^{-1}$), short inversion times ($\sim 30 \text{ ns}$), and large Fresnel number optics ($N > 100$). Their ultimate utility in applications such as dye-laser pumping depends on the ability to achieve both mode control and oscillator-amplifier staging techniques. We have performed experiments with unstable resonator oscillators and oscillator-amplifier configurations which have demonstrated near-diffraction limited beams and efficient amplifier-power extraction.

The lasers used in these experiments were self-heated metal-vapor devices²⁸ with nominal discharge-tube diameters of 2 cm, and an active length of 40 cm. They have a nominal 5 W of average output power in both the 5106-Å and 5782-Å transitions (nominal power ratio of green-to-yellow of about 3 to 1) when operated at a pulse-repetition frequency of 6 kHz. The lasers were also equipped with a stable optical resonator consisting of a 5-m radius of curvature-total reflector and an uncoated flat-Fresnel reflection output coupler separated by 1 m.

The time-averaged beam divergence of such lasers was measured at constant laser-excitation conditions as a function of the cavity Fresnel number, $N = a^2/\lambda L$. Over the range of N values from 60 to 200, the beam divergence scales approximately linearly with N or as the square of the beam diameter (Fig. 8-38), reaching a value 130 times the Gaussian dif-

Fig. 8-38. Beam divergence vs laser aperture for a 5-W, stable resonator copper-vapor laser.

Fig. 8-39. Unstable-resonator oscillator copper-vapor laser; magnification = 7.5, output coupling = 96.5%, scraper-hole size = 2.5 mm, beam diameter = 1.9 cm.

fraction limit at the full 2-cm aperture. This large beam divergence is undesirable for applications such as dye-laser pumping that require good propagation characteristics and tight focusing.

We investigated unstable resonators as a means to obtain a lower divergence beam. For this purpose, a positive-branch confocal unstable resonator

Fig. 8-40. Streak-camera data of time-resolved, unstable-resonator beam divergence.

Fig. 8-41. Time response of the unstable resonator at varying magnifications: $\tau = (2L/C) \{ \ln[a^2(m-1)/\lambda L_{\text{eff}}] / \ln(m) \}$ where $\lambda = 5106 \text{ \AA}$ and $a = 0.5 \text{ cm}$.

with a magnification of $M = 7.5$ (corresponding to an output coupling of 96.5% obtained at a flat-scraper output mirror located near the convex element) was fabricated and tested (see Fig. 8-39). At the full 2-cm aperture, the unstable resonator achieved a time-averaged beam divergence of six times the Gaussian limit which corresponds to a 26-fold reduction of the beam divergence when compared with the stable cavity without any degradation in output power.

A time-resolved measurement with a streak camera of the unstable-resonator beam profile revealed a dynamic decrease in the instantaneous beam divergence of the unstable-resonator output during the 30-ns pulse (Fig. 8-40). This phenomenon represents the build-up of the unstable-resonator mode and its evolution toward diffraction-limited conditions with successive passes of the radiation field in the resonator.²⁹ The instantaneous beam divergence decreased from approximately ten times the diffraction limit at the beginning of the 30-ns pulse to one to two times the diffraction limit at end of the pulse.

Figure 8-41 is a plot of the response time of an unstable-resonator cavity; response time is defined as the time required for a plane-wave input to demagnify to the diffraction limit and then to reflect

back out of the resonator. To obtain diffraction-limited operation with transient inversion systems like copper, the resonator-response time should be a small fraction of the effective laser-pulse width. This condition can be achieved with a shorter cavity length and higher magnification systems.

The amplifier-extraction characteristics of the copper vapor medium were studied with two devices, an unstable-resonator laser as the oscillator driver and an identical unit as a single-pass amplifier. Both devices were excited at a 6-kHz pulsing rate and were suitably electronically delayed to provide nanosecond synchronization of the optical pulses. The unique feature of the unstable-resonator oscillator in these experiments was to provide a low-divergence probe beam to allow the effective dis-

crimination between the amplifier-output signal and the highly divergent, amplifier single-pass fluorescence. This capability, in turn, allows the measurement of single-pass small-signal gains as high as 2×10^4 .

The saturation characteristics of both the 5106-Å and 5782-Å transitions were investigated as a function of the copper-vapor number density. Over the range of conditions studied, the saturation characteristics of both laser transitions can be accurately described by the steady state formalism $\ln(I_t/I_i) + (I_t - I_i)/I_i = \alpha \ell$. The small signal gain, $\alpha \ell$, the saturation power, I_s , and the total stored optical power, αI_s , in the 5106-Å transition are plotted in Fig. 8-42 as a function of the copper-number density. Figure 8-42(c) also includes a plot of the total

Fig. 8-42. Plots of (a) small signal gain, $\alpha \ell$; (b) saturation power, I_s , and (c) total stored optical power, αI_s , in the 5106-Å transition vs copper-number density for a S-W copper-vapor laser. Total input electrical energy per pulse into the discharge plasma is also presented in (c).

input electrical energy per pulse into the discharge plasma.

The data are presently being compared to a laser-kinetics model. These experiments also demonstrate that the high copper-vapor medium gains can be controlled in amplifier configurations by proper time-synchronized injection of oscillator flux. This results in more efficient power extraction from the copper-vapor medium when operated as an amplifier rather than as an oscillator. Staging of successive amplifier modules is therefore possible and efficient.

References

26. A. A. Isaev, M. A. Kazaryan and G. G. Petrash, *JETP Lett.* **16**, 27 (1972).
27. C. J. Chen and G. R. Russell, *Appl. Phys. Lett.* **26**, 504 (1975).
28. Final Report, ERDA Contract P. O. 1540403, General Electric Company, Space Sciences Laboratory, Valley Forge, Pennsylvania; the laser-discharged tubes used in our experiments were developed by General Electric under this contract.
29. K. I. Zemskov, A. A. Isaev, M. A. Kazaryan, G. G. Petrash, and S. G. Rautian, *Sov. J. Quant. Electron.* **4**, 474 (1974).

Authors

T. Kan
R. S. Hargrove
R. Grove

Major Contributors

G. S. Dzakowic
D. G. Ball
D. O. Kippenhan
M. Pearson
C. Riley
T. Kuklo

8-6 Dye Amplifiers

Copper-vapor lasers are an attractive pump source for dye oscillator-amplifier systems that lase in the 560- to 700-nm wavelength region. We have conducted an extensive program to develop efficient, high-average-power coherently pumped dye oscillators and amplifiers. We discuss the results of a detailed experimental and analytical characterization of dye amplifiers pumped by copper-vapor lasers.

The copper laser and dye amplifier facility is shown in Fig. 8-43. One copper-vapor laser is used

to pump the amplifier and the other pumps the input oscillator. The input signal, pump beam, and dye-flow directions are mutually orthogonal (Fig. 8-44). The copper-vapor laser beam is divided to pump both sides of the area of the flow channel. Double-sided pumping precisely defines the geometry while increasing the gain and output-beam uniformity. The flow velocity is sufficient to exchange the dye more than ten times between pump pulses at a typical pulse-repetition frequency (PRF) of 6.0 kHz. This flow rate prevents thermal distortion of the medium and the subsequent reduction of beam quality. The amplifier input signal is generated in a Hänsch-type dye oscillator³⁰ pumped by another copper laser. This input signal is precisely synchronized with the amplifier pump by an active servo control that maintains the optimum time delay between the two light pulses. The input-oscillator signal is focused into the amplifier with a beam diameter that closely matches the gain volume. Polarization of the amplifier input and pump beams are both perpendicular to their plane of intersection. This orientation maximizes the gain of the amplifier for dyes similar to Rhodamine 6G.³¹

The copper-vapor lasers used in the experiment are self-heated devices,³² capable of 5-W average power on both transitions (5106 and 5783 Å) at a 6.0-kHz PRF. An essential feature of the laser is the unstable resonator which we designed to improve the poor beam quality obtained from high-Fresnel-number stable resonators. Our unstable resonator has an output beam that is a few times diffraction limited and efficiently pumps the small amplifier gain region. To avoid an intrapulse variation of the focused far-field spot size, resulting from the dynamics of mode development within the unstable resonator, the focusing optics were adjusted to image the near-field distribution of the pump onto the dye cell.

We collected experimental data on amplifier gain (output/input power) as a function of pump power, input power, dye concentration, and wavelength for the four dye-solvent systems listed in Table 8-4. This table also presents a summary of the optimum experimental results obtained simultaneously for each dye. The high conversion efficiencies obtained (20 to 30%) at relatively high average output powers (0.41 to 0.76 W) are of particular interest. These output powers and efficiencies were limited only by the available pump power.

Fig. 8-43. Dye amplifier and copper-vapor laser facility. One copper laser (green beam) is used to pump the input oscillator for the dye amplifier (right background). The other copper laser pumps both sides of the dye amplifier (left foreground). An amplified beam (red beam) is emerging from the amplifier (out of the picture at left).

The dye concentrations chosen for these experiments are also given in Table 8-4 and are close to the optimum values. At low dye concentrations, the pump intensity is relatively uniform throughout the cell volume and the amplifier-output power increases with increasing concentration. As the concentration is increased beyond optimum values, most of the pump energy is deposited near the cell wall; strong fluorescence loss is also observed and the amplifier output (excluding fluorescence) decreases. The concentrations used in these experiments correspond to small signal absorption depths about one-third of the cell thickness for all four dyes. This concentration is smaller than the optimum value, but, in all cases, the output power was greater than 90% of the power obtained at optimum concentration. Operation at slightly lower-than-

optimum concentration results in a tradeoff of a small reduction in output for lower fluorescence and greater spatial uniformity.

Fig. 8-44. Dye amplifier cell.

Table 8-4. Dye-amplifier performance

Parameter	Rhodamine 6G chloride/ ethanol	Rhodamine B trifluoroethanol +0.01 N NaOH	Kiton red S/ trifluoro- ethanol	4-dicyanomethylene-2-methyl-6-p- dimethylaminostyryl 4-Hpyran/dimethyl sulfoxide
Wavelength (nm)	572	591	617	649
Output power (W)	0.65	0.41	0.76	0.43
Efficiency (%)	29.7	20.7	18.2 ^a	18.7
Amplifier pulse width FWHM (ns)	22	22	31	27
Input power (mW)	31	16	28	28
Concentration (10 ⁻³ M)	1.0	1.3	1.7	2.6
Tuning range FWHM (nm)	564 to 600	582 to 613	595 to 639	625 to 688
Pump power at 5105 Å (W)	2.10	1.91	4.03 ^a	2.15
Pump pulse width FWHM (ns)	32	32	32	32
PRF (kHz)	6.0	6.0	6.0	6.0

^aThese values are for both copper-laser wavelengths present in the pump beam (70% at 5105 Å and 30% at 5782 Å.)

The amplifier output vs wavelength is shown in Fig. 8-45. For the dye systems chosen, continuous tuning is possible from 5640 to 6880 Å at average output powers between 200 and 700 mW. It is interesting to note that the tuning ranges (FWHM) are 20 to 30% greater than those of the input oscillator. This is a consequence of amplifier power broadening.

Amplifier power gains were measured as a function of input-oscillator power and pump power. Experimental data for Rhodamine 6G in ethanol are shown in Fig. 8-46. The dependence of amplifier gain on the pump and oscillator-input power are similar for all four dye-solvent mixtures. In all cases, the amplifier-extraction efficiency increases with increasing pump or input power. The dependence of amplifier gain on pump power is much stronger than its dependence on input power. All experimental data indicate that, at constant PRF, higher pump power will yield a higher output power

and efficiency. All of these qualitative features can be quantified with the aid of an analytical model which we discuss below.

In addition, it has been experimentally verified that the amplifier precisely duplicates the spatial and spectral distributions of the input-oscillator signal. However, the temporal distribution is distorted to resemble the pump pulse. Far-field intensity distributions of the oscillator output were measured before and after amplification. These spatial distributions were measured at the focal plane of a lens with a photodiode and pinhole aperture. The amplified distribution was essentially the same as the input distribution (2.9 times the gaussian diffraction limit). Similarly, the spectral distributions were determined with a Fabry-Perot interferometer. A streak camera was used to photograph the interferometer fringes to obtain pulse-to-pulse temporal resolution of the spectrum. As expected, the amplifier did not distort the input-spectral distribution because the dye-solvent medium is homogeneous.

Fig. 8-45. Comparison of dye amplifier output power (solid lines) and oscillator input power (broken lines) for four dye-solvent mixtures at various wavelengths. Pump laser conditions correspond to the values in Table 8-4.

Fig. 8-46. Dye amplifier gain (output/input power) is a strong function of pump power. Theoretical (broken lines) and experimental values (solid data points) are compared for Rhodamine 6G in ethanol. The pump wavelength is 5106 Å , the lasing wavelength is 5720 Å , and the average oscillator input power at 6.0 kHz is given with each curve.

Amplifier power gains are analyzed using rate equations similar to those used by Teschke *et al.*,³³ for a dye-oscillator analysis. In his treatment, a steady-state solution is assumed. This assumption is valid for these experiments because the dye spontaneous lifetime is much shorter than the output pulsewidth. The relevant rate equations with reference to the energy-level diagram (Fig. 8-47) for the dye medium, follow:

$$\begin{aligned} \frac{dn_1}{dt} &= \sigma_{01}(\lambda_p)n_0I_p \\ &+ \sigma_{01}(\lambda_r)n_0I_r - \frac{n_1}{\tau_s} - \sigma_e(\lambda_r)n_1I_r. \end{aligned} \quad (10)$$

$$\begin{aligned} \frac{1}{c} \frac{\partial I_r(\lambda_r)}{\partial t} + \frac{dI_r(\lambda_r)}{dx} \\ = [\sigma_e(\lambda_r)n_1 - \sigma_{01}(\lambda_r)n_0] I_r(\lambda_r). \end{aligned} \quad (11)$$

$$\begin{aligned} \frac{1}{c} \frac{\partial I_p(\lambda_p)}{\partial t} + \frac{dI_p(\lambda_p)}{dx} \\ = - [\sigma_{01}(\lambda_p)n_0 + \sigma_{12}(\lambda_p)n_1] I_p(\lambda_p). \end{aligned} \quad (12)$$

In the above equations, n_0 and n_1 are the dye population densities; σ_{01} , σ_{12} , and σ_e are the relevant optical cross sections; τ_s and τ_{21} are the spontaneous and radiationless decay lifetimes; and I_p and I_r are the pump and laser optical intensities expressed in photons/cm². Triplet-absorption effects have been omitted because, for the case of a copper-vapor pump, the 30-ns pumping pulse duration is considerably faster than the singlet-to-triplet inter-system crossing rate, k_{st} . In addition, the population n_2 was taken to be zero because the radiationless decay time, ($\tau_{12}/\tau_s \approx 10^{-3}$ is much smaller than $\tau_s \approx 10^{-3}$). The steady state solution to Eqs. (10) and (11) can be expressed in the usual form for a homogeneous laser transition,

$$\frac{1}{I_r} \frac{dI_r}{dx} = \frac{g_0}{1 + (I_r/I_s)}. \quad (13)$$

For the small signal gain, g_0 , and the saturation flux, I_s , we obtain

$$g_0 = \frac{N\sigma_e \left(\sigma_{01}(\lambda_p)\tau_s I_p - \frac{\sigma_{01}(\lambda_r)}{\sigma_e} \right)}{1 + \sigma_{01}(\lambda_p)\tau_s I_p}, \quad (14)$$

$$I_s = \frac{\sigma_e \tau_s (1 + \sigma_{01}(\lambda_p)\tau_s I_p)}{\left(1 + \frac{\sigma_{01}(\lambda_r)}{\sigma_e} \right)}. \quad (15)$$

Similar considerations result in a corresponding relation that characterizes the pump absorption. The integration of Eq. (13) for a transversely pumped, dye-amplifier geometry (Fig. 8-44) yields a solution for the amplifier power gain. This solution, used in conjunction with the appropriate experimental cross sections and lifetimes for Rhodamine 6G, yields amplifier power gains in excellent agreement with experimentally measured values over a wide dynamic range of pump power and input signal power. A comparison of the experimental data and the results of the analysis outlined here are shown in Fig. 8-46 for Rhodamine 6G in ethanol. Extension of the analysis to higher pump powers than those available experimentally indicate that conversion efficiencies approaching the limit $\sim (\lambda_p/\lambda_r) (1-T)$, where T is the pump transmission through the dye cell, are possible.

Fig. 8-47. Energy level diagram for dye medium.

Fig. 8-48. Ring amplifier cell. A top view depicting internal beam paths is shown in an insert.

A highly efficient, resonant regenerative amplifier was also investigated as a candidate system. The design of this device is shown in Fig. 8-48. A flow of Rhodamine 6G in ethanol at 3.785 litre/min (1 gal, min) was maintained within the 1-mm gap between two quartz prisms. A smaller truncated 90° prism was used as an FTIR (frustrated total internal reflection) output coupler in a configuration similar to that used by Marowsky.³⁴ Narrow 0.5-mm strips of aluminum, 550 nm thick, were coated on the edges of the hypotenuse face of the small prism. A differential micrometer bearing on the truncated surface provided the force to change the spacing and hence the reflectivity of the FTIR unit.

The laser amplifier was also pumped with a discharge-heated, copper-vapor laser³⁵ and injected locked with a narrow-band dye oscillator of the type described by Hänsch.³⁰ The experimental arrangement is pictured in Fig. 8-49.

The unidirectional amplified signal in the ring was locked to the axial mode of the ring nearest the center frequency of the injected signal. The optical path length for the ring was approximately 6 cm; hence, modes were spaced by about 5 GHz. The mode width, averaged over a single pulse, varied from 200 to 400 MHz. Interpulse time-resolved spectral measurements made with a 4-GHz FSR air-spaced Fabry-Perot revealed that the "instantaneous" mode width was approximately 70 MHz

and that the mode center shifted in frequency during a pulse. We believe that this frequency "chirp" results from an intrapulse, thermally induced, refractive-index variation. If we assume that the temperature rise is linear during the pulse, the total shift is then given by

$$\Delta f_c = N_{RT} \frac{x}{\lambda} \left(\frac{dn}{dT} \right)_{\text{eff}} \frac{\Delta T}{\Delta t} \quad (16)$$

where N_{RT} is the number of round trips in the cavity during a pulse, ΔT is the total temperature change during the pulse, and Δt is the pulse width. The effective index change with temperature is given by³⁶

$$\left(\frac{dn}{dT} \right)_{\text{eff}} = \left(\frac{\partial n}{\partial \rho} \right)_T \frac{\partial \rho}{\partial T} + \left(\frac{\partial n}{\partial T} \right)_\rho \quad (17)$$

We have found good agreement between this model and the extent of the observed chirp.

The output amplitude from the ring varied in a somewhat random manner by a factor of approximately 3. These amplitude fluctuations were strongly correlated with an acoustic vibration that existed in the mechanical structure of this device. We believe that with an improved mechanical design, the acoustic vibration can be eliminated and the amplitude fluctuations removed. The observed

Fig. 8-49. Ring amplifier and copper-vapor laser facility. One copper laser (right background) is used to pump the input oscillator for the ring amplifier. The other copper vapor laser is used to pump the injection-locked ring amplifier (left center). The beam is diagnosed with a fixed Fabry-Perot interferometer and a streak/framing camera (right foreground).

average-energy-conversion efficiency, with the amplitude fluctuations present, was greater than 40%. The peak-energy-conversion efficiency on a per-pulse basis was then approximately 60%. For a 1.2-W pump at 6-kHz PRF, average powers of 0.5 W were observed.

We have also performed extensive computer modeling³⁷ with a rate-equation approach. This computer model has been used to predict optimum output reflectivities, dye concentrations, injected signal intensities, and optical path lengths.

References

30. T. W. Hansch, *Appl. Optics* **11**, 895 (1972).
31. B. B. McFarland, *Appl. Phys. Lett.* **10**, 208 (1967).
32. The electric discharge tubes were built to our specifications by the General Electric Company Space Sciences Laboratory, Valley Forge, Pennsylvania.

33. O. Teschke, A. Dienes, J. R. Whinnery, *IEEE J. Quantum Electronics* **E-12**, 383 (1976).
34. G. Marowsky, *Z. Naturforsch* **29a**, 536 (1974).
35. R. S. Anderson, L. Springer, B. G. Bricks, and T. W. Karras, *IEEE J. Quantum Electronics* **QE-11**, 172 (1975).
36. United Technology Research Center, East Hartford, Connecticut, unpublished Rept. P-N278 (1974).
37. A. A. Pease, O. G. Peterson, M. L. Spaeth, and W. M. Pearson, *An Injection Locked Ring Amplifier*, Lawrence Livermore Laboratory, to be published (1977).

Authors

R. S. Hargrove
T. Kan
A. A. Pease

Major Contributors

G. S. Dzakowic
D. G. Ball
P. O. Kippenhan
M. Pearson
C. Riley
T. Kuklo

LASER ISOTOPE SEPARATION PROGRAM

Jim Davis - Program Leader
Bobbi Bell - Secretary
Dennis Koci - Program Manager
Jerry Dow - Program Manager
Gay Witt - Secretary
Jim Rigg - Mechanical Coordinator
Bob Boben - Electronics Coordinator
Ann Setchell - Assistant Coordinator

System Studies Group

Rich Davis - Group Leader
Audrey Heine - Secretary
Stu Winter - Electronics Engineer - Application studies
Mike Schwab - Physicist - Systems analysis
Dena Duncan - Programmer

Experimental Research Group

Jim Dubrin - Group Leader
Beverly Pierce - Secretary
Ray Bedford - Chemist - Thermochemistry
Tony Bernhardt - Physicist - Spectroscopy; atomic physics
Lee Carlson - Chemist - Actinide spectroscopy
Hao-Lin Chen - Physicist - Source methods; kinetics; photochemistry
Hal Johansen - Mechanical experimental support/coordination
Steve Johnson - Electronics support
Neil Lang - Chemist - Molecular beam collision physics
Jeff Paisner - Physicist - Spectroscopy and atomic physics
Dick Solarz - Physicist - Spectroscopy and photochemistry
Dick Stern - Chemist - Molecular beam collision physics
Chuck Stevens - Chemist - Molecular spectroscopy
Earl Worden - Chemist - Actinide spectroscopy
Dick Foley - Mechanical experimental support/coordination
Bernie Roth - Mechanical engineering
Aubrey Miller - Mechanical engineering
Jim Sexton - Mechanical design
Stan Bishop - Electronics engineering
Dick Mattoon - Electronics coordination

Technicians:

Chuck Borzilleri
Bill Brunner
Lynn James
Mario Marcon
Charles May
Ed Schmitt
Gil Vayer
Chuck Fetterman

George Mattson
Ed Richards
Lee Spencer
Fred Wickman

Advanced Lasers Supporting Isotope Separation

Victor George - Group Leader
Patricia Anderson - Secretary
Don Ball - Electronics Engineer - Copper Vapor
Julius Goldhar - Physicist - Rare gas halides
Roger Haas - Physicist - Modeling/theory
Steve Hargrove - Physicist - Dye lasers
Tehmau Kan - Physicist - Copper vapor/dye lasers
John Miller - Physicist - Copper vapor
John Murray - Physicist - Raman compressors
Lyn Pleasance - Physicist - Rare gas halides
R. C. Barnes - Electronics Designer
Bill Smiley - Mechanical Coordinator
Woody Souza - Electronics Coordinator
Jim Dickie - Mechanical Technician
Jim Hill - Electronics Technician
Craig Riley - Mechanical Technician
Ed Schmitt - Mechanical Technician
Ray Weber - Mechanical Technician

System Development Group

James Holtz - Group Leader - Laser systems
Mary Spaeth - Alternate Group Leader - Dye lasers
Fran Harms - Secretary
Mike Lutz - Physicist - Plasma physics
Lloyd Hackel - Physicist - Spectroscopy
Kurt Kennedy - Metallurgist
Bob Vetterlein - Mechanical system engineering
Dick Gretler - Mechanical Designer
Bob Wong - Mechanical modeling/heat transfer
Al Pease - Laser systems
Mike Johnson - Physicist - Quantum physics
Jerry Coutts - Electronics Engineer - Electrooptics
Jim Early - Physicist - System analysis
Dick O'Neil - Physicist - Laser development
Nick Patlovich - Mechanical Designer
Tom Shepp - Physicist - Plasma diagnostics
Dean Kippenhan - Electronics Engineer
Peter Hammond - Chemist - Dyes
Bill Brunner - High vacuum systems
Steve Lowder - Physicist - Plasma physics
Bob Grove - Physicist - Laser development
Alan Throop - Electronics Engineer - Plasma physics

Rick Glaser - Computer Scientist - Codes
Chuck Fetterman - Electronics Technician Coordinator
Hal Johansen - Mechanical Technician Coordinator

Technicians:

Larry Booth
Tom Kuklo
Mark Vigars
Mike Rushford
Mike Pearson
Ernie Dragon
Dave Milani
Fred Wickman
Mike Brooks
R. Mattoon
Lee Spencer