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LASER PROGRAM ANNUAL REPORT – 1975

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LASER PROGRAM ANNUAL REPORT — 1975

Simultaneous beams

Right-hand beam delayed 42 ps

Effect of simultaneity of arrival of laser beams on plasma symmetry.

Into spatial filter

Exit from spatial filter

Effect of a spatial filter in the Cyclops chain. Note reduction in beam perturbation after filtering.

LAWRENCE LIVERMORE LABORATORY
University of California Livermore, California 94550

UCRL-50021-75

LASER PROGRAM ANNUAL REPORT — 1975

Scientific Editor: Alexander J. Glass

General Editor: Kent L. Cummings

MS. date: March 1976

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FOREWORD

This report is one of a continuing series documenting the progress of the laser program at the Lawrence Livermore Laboratory. These reports have been issued since 1971, under the publication numbers UCRL-50021-71 through UCRL 50021-75. The laser report was published semiannually from 1971 to 1973 and annually since then. Copies of the documents can be obtained from the National Technical Information Center in Springfield, Virginia, as set forth on the inside front cover of this volume.

To generate a report of this size is an undertaking which is demanding but eminently worthwhile. In a program as large as the laser fusion program, scientific discovery and technical innovation proceed at a rapid rate. Each year a great deal of new information is obtained, new problems are analyzed, and innovative approaches to these problems are devised. Some of these analyses, observations, and inventions find their way into the conventional literature of the field, but many do not. The annual reports provide a continuing and detailed record of the achievements of the program, both scientific and technological. Much of this material will not appear elsewhere, at least not in as much detail. These reports serve to disseminate the information obtained in the laser fusion program as rapidly and completely as possible, to the widest possible audience.

As in previous years, the report is organized programmatically. The first section contains a program summary and overview. Section 2 is concerned with systems studies for both laser fusion and laser isotope separation. Sections 3 and 4 deal with solid state laser systems and materials. Sections 5 through 7 are concerned with target design and fabrication and with the coupling of laser light to the plasma. Section 8 deals with target interaction experiments and diagnostics. Section 9 is devoted to research in advanced quantum electronics, or "new" lasers. The laser isotope separation program is the subject of a separate companion report.

The research reported in this volume was carried out during 1975. Obviously, some of the results reported

here have already been supplanted by newer data. The pace of the laser fusion program is swift, and the best thinking of a year ago may no longer represent the forefront of informed opinion today. We have tried to keep the amount of conjecture in the report to a minimum, concentrating instead on substantive achievement and cautious projections. The careful reader may find discrepancies among the different sections of the report. These represent honest differences of opinion among the various individuals who contributed to the document. At the end of each article the authors' names are listed; responsibility for the accuracy of the contents of each article ultimately rests with these authors. Inquiries concerning the contents of this report should be addressed to the individual authors.

This report represents the efforts of many people. Each major element of the report was the responsibility of a section editor, who worked closely with the appropriate associate program leader or group leader. The names of the section editors and their deputies are given in the individual sections of the report. The TID technical editing staff, consisting of Kent Cummings, Jane Staehle, Wallace Clements, and Bob Berlo, put in many hours of hard work to bring the report to completion, as did Paul Tanasovich in arranging for the editing, composition, and printing of the report. Special recognition is due Alex Glass, scientific editor of this year's report, who did a fine job of organizing and directing the entire effort.

Finally, thanks are due to all the participants in the laser program who contributed to the report, both by carrying out the research described herein and by cheerfully accepting the added burden of writing up last year's activities while this year's work continued. On behalf of the laser program, I'd like to express my thanks to all these people for their cooperation and assistance in bringing this report to completion.

J. L. Emmett

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1. LASER PROGRAM OVERVIEW

Section Editor: A. J. Glass

1. LASER PROGRAM OVERVIEW

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8.3 Diagnostics Hardware Development

The demands of laser fusion experiments to be able to make quantitative high-resolution measurements over a wide range of physical observables have strengthened our commitment to the applications of the highest possible quality diagnostics capability to our experimental program. These development and application efforts are pursued both "on-line" and "off-line" for maximum effectiveness and flexibility. In addition to the requirement to obtain complete data on each shot our efforts are aimed toward the goals of utilization of diagnostics with spatial and temporal resolution capabilities of $1\text{ }\mu\text{m}$ and 1 ps , respectively. Measurement techniques must be developed and applied to study a density range of 10^{16} to 10^{26} cm^{-3} and a temperature range from 50 eV to 500 keV . In addition to measurements of electromagnetic radiation from the x-ray through ir regions of the spectrum, diagnostics of the charged and neutral particle emissions from laser heated targets are essential to obtain a physical understanding of the interaction processes.

The extension of our ultrafast streak camera technique to the x-ray regime has been refined by new understanding of system performance capability, by time-resolved spectral and x-ray imaging applications to laser-target experiments, and by the engineering design of an improved x-ray streak camera system. Continued applications of x-ray imaging via grazing incidence microscopes and pinhole cameras and the use of new x-ray diagnostics systems including a low

energy x-ray spectrometer with real time hard copy spectrum presentation have contributed to target diagnostics capabilities. New techniques and applications for time-resolved x-ray diagnostics via fast scintillators as well as x-ray applications of "optical" techniques are being addressed.

New applications of calorimetry and photodiode arrays to studies of the energy balance in laser target experiments were employed this year. In addition to our neutron yield diagnostics a new time of flight system for neutron energy spectrum measurements has been designed and is being constructed for use at the Argus facility. Time of flight α particle spectrometers have been implemented and are yielding important ion temperature data on current fusion experiments.

The "Monopole" laboratory continues to be used as a reliable, valuable off-line diagnostics development facility. Some of the new x-ray diagnostics development is being done using radiation from laser irradiated targets at that facility. Our development of optical probing diagnostics for laser produced plasmas has been pursued at the Monopole laboratory. Details of accomplishments in each of these diagnostics development areas are presented in the following sections.

L. W. Coleman

8.3.1 SILICON PHOTODIODES FOR SPATIALLY RESOLVED SCATTERED LIGHT MEASUREMENTS

The scattered light distribution from a laser-irradiated target is important for determining the amount of energy absorbed in the plasma and the processes by which it is absorbed. A system to measure the time-integrated angular dependence of the $1.064\text{-}\mu\text{m}$ light scattered from targets irradiated by pulsed Nd lasers has been built and tested. It consists of an array of the small detector packages shown in Fig. 8-38. Each contains a light-sensitive silicon photodiode; a $1.064\text{-}\mu\text{m}$, $100\text{-}\text{\AA}$ bandpass filter; and an ND filter. Light incident on each photodiode forms a number of electron-hole pairs which is proportional to the total light energy absorbed in the diode. The charge is separated by an electric field applied across the detector and then electronically integrated.

Each detector package is calibrated as a unit under

conditions that approximate the experimental mode of operation. A 12-mm-diam, 150-ps, Nd:YAG laser pulse is expanded, recollimated, and apertured to produce a 1.0-cm-diam beam with a uniform energy density. It is split into two parts by a pellicle. The reflected beam, which is totally collected within the 1-cm^2 active area of a silicon photodiode, is used to monitor the relative beam energy from shot to shot. The transmitted beam overfills the 0.11-cm^2 active area of the diode package under calibration. Beam uniformity and diameter measurements are made with a Reticon linear diode array mounted in place of the detector package. Absolute energy calibration of the transmitted beam is done by replacing the diode package with a calorimeter that collects the entire beam.

Because the photon energy of $1.06\text{-}\mu\text{m}$ light is less

Fig. 8-30. Substrate stability for HP-20 Be 2-in. disks.

designed to provide stability with adjustment to properly illuminate the envisioned target sizes in their range of positional errors. The corrector lens mounts into a precision-lapped clamp ring which can be quickly and accurately inserted into an indexed mount outside the chamber window. The chamber window generously overlaps the chamber and has a unique clamped edge design which lowers the vacuum deflection by a factor of 5 over ordinary edge clamping. The lens and mirror positioners are described in Sec. 8.2.9.

The flat mirror mount is specially designed to offer the same adjustments available with the ellipsoidal mirrors and also provide an indexed mount for accurate insertion of the clamping fixture retaining the mirror.

The 10-mm-thick, 360-mm-diam mirror presents problems in fabrication which may be resolved by

resorting to a precision-lapped clamp ring which offers 5 times lower deflection over a freely mounted configuration. The clamp ring may also be used to freely mount the mirror again as a subassembly.

The Argus illumination system presented an excellent solution to the problem of focusing power on targets with a minimum of glass to prevent loss of focusable power up to a maximum of 6 TW. Above this power, it becomes more economical to add more beams, and additional beams require some alternate type of illumination such as in LLL's Shiva laser system which has 20 beams and can only accommodate a refractive illumination system.

S. S. Glaros
A. J. Glass

thermonuclear-burn physics, laser/plasma coupling, and fluid dynamics of high-density, high-temperature plasmas. Sophisticated techniques have been devised for making targets for our present experiments. Finally, we have achieved unmatched developments in high-peak-power, high-brightness, solid-state laser technology and fully integrated laser test facilities. The future of laser fusion requires predictive capabilities such as the above, as well as developments in experimental hardware.

We are working toward five milestones for achieving laser-induced fusion:

- Reaching an adequate understanding of the physics of the interaction between laser light and plasma.
- Demonstrating a high-density laser-induced implosion (defined as occurring when compressions of 100 to 1000 times liquid density are attained).
- Achieving significant thermonuclear burn (defined as occurring when a fusion energy output greater than 1% of the laser light energy is attained).
- Achieving light energy breakeven by raising the pellet burn efficiency until the fusion energy produced is of the same magnitude as the light energy in the laser pulse.
- Achieving net energy gain by raising system efficiency until the fusion-energy output substantially exceeds the energy input to the whole laser system.

These are *scientific* milestones as compared with *applications* milestones (e.g., prototype reactors) described later. To achieve these milestones, a series of glass laser systems has been designed and constructed with increasing power output, yielding correspondingly increasing pellet gain (see Sec. 3.1).

In achieving the first and second milestones, we had to determine the kind of laser output pulse—in terms of energy, duration and shape, wavelength, coherence properties, and symmetry—that is required to compress a DT pellet to burn conditions. Then we had to design and build a laser to produce this output pulse. In May of 1975, with a target of the exploding-pusher type first developed at Livermore in 1970, we achieved a 10^7 -neutron yield from laser-fusion implosion.¹ In this and other experiments, the target yield has been well predicted by our implosion codes, suggesting that the observed neutrons are from DT compression and genuine thermonuclear burn rather than from reactions of accelerated, non-Maxwellian fuel ions. Alpha-particle measurements have confirmed the thermonuclear nature of these neutrons.

We are continuing our basic laser/matter experiments with well-characterized Nd:glass lasers of moderate size. Pulse energies will range from tens of joules to about 1 kJ, and pulse lengths will range from the

low-nanosecond region to tens of picoseconds. The main purpose of these experiments is to provide a data base for comparison with theoretical calculations.

Our target date for the third milestone—significant thermonuclear burn—is FY 1978-79 and depends on success with the Nd:glass Shiva laser system scheduled for completion in late 1977. We believe that Nd:glass lasers offer the most reliable means for reaching the first four milestones and probably even the fifth on a single-pulse basis. However, the high energy and high average power eventually required for controlled thermonuclear power generation will preclude solid-state lasers as now conceived. We are investigating several alternatives, including gas lasers.

Glass Laser System Development

Nd:glass lasers are presently the best understood high-energy, short-pulse lasers and thus are well suited to laser fusion development. They are capable of delivering tremendous amounts of energy in short bursts to tiny targets. Our solid-state development program calls for a series of scaled-up Nd:glass laser systems as driving sources for target experiments.

Three of the systems are now operational: Janus (0.4 TW), Cyclops (1 TW), and Argus (2 TW). Shiva, at 25 TW, is scheduled for July 1977. Break-throughs with solid-state materials and laser components now permit the construction of laser systems that can operate at unprecedented, higher power levels. Based on these technological advances, we envision the possibly of an upgraded Shiva system with target irradiations up to 200 TW.

Laser fusion target irradiation puts unusual requirements on the laser system. For this application, peak power performance is more important than total energy extraction. This emphasis leads to severe nonlinear optical constraints on beam propagation and laser design. Considerable effort has gone into understanding these problems; the payoff has been a sixfold increase in the maximum power capability of a single laser chain. Detailed optimization studies have indicated the best approaches to laser system staging, and engineering studies have resulted in reliable, cost-effective components.

Near-Term Systems. With the Janus system we first attained 10^7 -neutron fusion yield and verified the thermonuclear nature of the neutrons. With the Argus system (described in Sec. 3), which is nearing completion, the fusion-energy yield from the targets will be adequate to measure the neutron spectrum and conclusively prove the thermonuclear origin of the neutrons from these fusion reactions. Argus will remain operational to supplement Shiva and ensure efficient use of

this costlier and more complex system. An upgraded version of Argus is being considered but is not yet funded.

Shiva System. This system will produce more than 20 TW from 20 simultaneously fired laser chains. The number of chains and their convergence geometry have been chosen to enhance the uniformity of spherical target illumination. With this combination of very high power and uniform illumination, isentropic spherical compression of DT targets to many thousand times the liquid density of DT should be possible. We should be able to demonstrate significant thermonuclear burn yielding a few percent of light energy breakeven at this level.

Figure 1-1 shows the Shiva system and the building in which it will be housed. This building is nearly completed. The technological developments for Shiva in high-laser-power optics and propagation, system control, laser diagnostics, optical stabilization and alignment, large-system maintenance, reliability engineering, and target-chamber design will be directly applicable to future laser fusion systems using advanced laser media.

Options for the upgraded Shiva are given in Table 1-1. The alternative configurations and choices represent many advances in materials, propagation physics, and construction techniques. If funds become available, this system—delivering 100 to 300 TW of on-target power—could be operational early in the next decade.

Fusion Targets

The thermonuclear energy generated by a laser-driven implosion can be significantly affected by the laser energy, peak power, temporal pulse shape, low-level prepulse energy, wavelength, angle of light incidence on the target surface, and temporal and spatial symmetry of target irradiation. The various target designs have somewhat different sensitivities to these laser parameters, the sensitivity decreasing as laser energy increases. We are continuing to explore this extremely complex multidimensional parameter space with a sophisticated computer program, LASNEX, that simulates laser-driven implosions.

Thermonuclear-energy generation can also be significantly affected by the tolerances to which the target is fabricated. Important parameters include the surface finish, uniformity of shell thicknesses and densities, concentricity and sphericity, and presence of impurities. LASNEX once again is the workhorse code. Because of fluid instabilities, surface finish is the most severe constraint. For targets capable of reaching light energy breakeven when imploded by a 10-kJ laser pulse, the surface finish of the ablator and pusher shells must be accurate to within ± 100 nm for spatial wavelengths varying from one-tenth the shell thickness up to the shell thickness. For 1% breakeven pellets, the surface finish need be accurate only to about ± 1000 nm.

Within these confines, the task of our fusion targets program is to design and fabricate the tiny targets for our fusion experiments. Target-design calculations

Fig. 1-1. High energy laser facility showing Shiva laser.

The experimental setup is shown in Fig. 8-48. Note that the detector is far (276.75 cm) from the source of α particles, thus effecting a large energy dispersion. The energy resolution of the system is:

$$\Delta E = 2E \frac{\Delta t}{t},$$

where t is the α particle flight time, E is the α particle energy, and Δt is the detector time resolution (FWHM). Thus, for example, for a 3.3-MeV α particle with $\Delta t = 4$ ns, and $t = 207$ s,

$$\Delta E = 130 \text{ keV.}$$

The electromagnet is set at 0.56 T and is used to separate the α particles from the more intense light, x-rays, and electron beams. The energy range of the instrument is 2.6 to 3.9 MeV for α particles. The experiment was designed so that α particles in this range that pass through the entrance aperture of the magnet are deflected by the magnetic field onto the scintillator. Thus, the geometry for determining absolutely the total number of α particles emitted from the source is well known. The drift tube has baffles to minimize the background signal from light and x rays. The entire pipe is pumped to 10^{-5} Torr. The scintillator is 10-mm-thick, bare NE 111 fluor coupled to an Amperex 2106 photomultiplier tube. The calibration of the pulse arrival time and the measurement of the time width of the photomultiplier were made with the detector in its shot configuration and with the same Tektronix 7904 oscilloscope and cables used to take the data. These timing calibrations were done with light from the laser operated at low power. The light was frequency doubled and reflected from the center of the chamber to the detector. With these calibrations, the arrival time of the α particles can be determined to ± 1 ns.

The scintillator photomultiplier was calibrated absolutely with 5.8-MeV α particles from a ^{241}Cm source. To apply these calibrations at lower energies, a semiempirical relation by Birks³⁸ that relates the light emitted from the scintillator to the range of the α

Fig. 8-48. Experimental setup for alpha-particle detection.

particle in the scintillator material was used. The ranges used were from Nuclear Data Tables.³⁹ (Recently this semiempirical relation was confirmed by experiment by reducing the energy of the 5.8-MeV α particles with a known air path. The calibrations were done in the region of 1.9 to 5.8 MeV.) The time response of the detector for counting individual α particles was measured to be 4 ns FWHM. This was used to correct for instrument response in determining the time-of-flight spreading of the α particles from the plasma.

V. W. Slivinsky
K. G. Tirsell
S. S. Glaros
D. E. Campbell
H. Catron

8.3.6 MULTICHANNEL X-RAY MICROSCOPY OF LASER FUSION TARGETS

The x-ray emission from laser fusion targets provides data from which may be inferred implosion symmetry, energy absorption, volume compression, and various other plasma parameter distributions associated with the implosion event. Our diagnostic capability to spatially, temporally, and spectrally resolve this emission was significantly improved during

the past year. The following section describes our efforts to further refine our x-ray imaging techniques.

During 1975, several multichannel grazing incidence x-ray microscope systems were absolutely calibrated and routinely operated on the Janus and Cyclops laser-target irradiation facilities. These instruments exploit the total reflection properties of x rays at grazing

Fig. 8-38. Si photodiode detector package. The parts of the package from left to right are the housing, photodiode, spacer, bandpass filter, spacer, ND filter, spacer, and cap.

than 0.1 eV greater than the bandgap of Si, the photodiode response to this radiation has been carefully examined. The absorption coefficient is 0.1 cm^{-1} and rapidly varying with wavelength. In our detectors, which are $300 \text{ }\mu\text{m}$ thick, the energy is deposited quite uniformly throughout the active volume, whereas visible light is deposited within the first $10 \text{ }\mu\text{m}$ of the front surface. A measurement has been made to show that the detectors are operated with sufficient reverse bias voltage to insure complete charge collection. Calibration stability over a 6-month-use period was found to be excellent. However, calculations indicate that the calibration is strongly temperature dependent ($\sim 0.5\%/^{\circ}\text{C}$ at 300°C for $1.06\text{-}\mu\text{m}$ light). Measurements show that the diodes are linear to power densities over 10^9 W/cm^2 for 150-ps pulses. The detector package with an appropriate ND filter may be used to measure pulsed power densities in the range between 1 and 10^9 W/cm^2 .

Arrays containing 20 to 40 detector packages are used to map the angular distribution of the $1.06\text{-}\mu\text{m}$

light scattered from targets at our irradiation facilities. Inside the plasma chamber, the diodes are mounted on sets of semicircular rings which contain diode mounting holes spaced every $7\frac{1}{2}^{\circ}$. No diodes can be placed in the cone subtended by the focusing lens system because they would block the incident laser energy. The scattered energy in this cone is measured with diodes placed outside the target chamber. Energy scattered back through the lens is collimated and directed towards the diodes by a set of beam splitters. Two computer codes have been written for use with the diode arrays. One handles the preshot preparation, and the other does the data analysis which includes generation of the energy distribution curve and an estimate of the total scattered energy for each target shot. Data taken with diode arrays at our target irradiation facilities are illustrated and discussed in Sec. 8.5.7.

R. A. Lerche
D. W. Phillion

plane information has been essential for analyzing the experiments.

This year, we will use 4π illumination systems on Janus and Argus for both low- and high-density implosions. Argus will be used also with $f/1$ and $f/2.5$ lens focusing.

In diagnostics development, we are continuing to adapt and improve our streak cameras, particle and x-ray diagnostics, and microscope imaging systems. We have started developing ultrafast framing cameras and a computer program for data acquisition and analysis.

Our x-ray streak camera has been used for experiments on Janus with six K-edge channels of data. The data show a temporal peak emission at the time of implosion, which agrees with LASNEX calculations. This camera has also been coupled to a pinhole camera to make the first time-resolved x-ray pictures of imploding laser targets. New high-resolution x-ray microscopes have been designed and built by means of single-point diamond machining. We have also developed a capability for optical probing with the fourth harmonic of the Nd:glass laser frequency. Thus, in 1976, we will be able to make measurements in the plasma corona up to densities of 10^{21} cm^{-3} .

Minicomputers are used for data acquisition and analysis. On Janus and Cyclops, one-dimensional data are gathered and scaled by PDP-11/10 computers. The system for Argus will use a PDP-11/40 and will gather and reduce both one- and two-dimensional data.

Advanced Quantum Electronics

In laser fusion, our advanced quantum electronics program is already looking past the scientific milestones to the applications milestones—hybrid and pure-fusion prototype reactors and eventually a pilot reactor—whose time schedules stretch into the 1990's. Although the scientific milestones may be achieved on a single-pulse basis using facilities being constructed (Shiva) or planned (Shiva upgrade), laser fusion reactors will require new, more efficient lasers capable of delivering high average power in the form of a continuous series of short pulses ($>100 \text{ kJ}$; $\geq 1 \text{ ns}$). During the past year, we have theoretically predicted and experimentally demonstrated several promising new laser media and measured their characteristics. The development of such media on a time scale that will maintain laser fusion as a viable option in the national energy program is a priority matter.

For laser isotope separation we need reliable, high-repetition-rate, high-peak-power laser systems that function at the proper wavelengths for economical operation of enrichment plants. For both programs, our research in advanced quantum electronics seeks not only to develop advanced lasers but also to establish

sound theoretical bases for understanding atomic and molecular reactions for future applications.

Performance requirements for advanced lasers for fusion applications vary radically with respect to various target designs. During the past two years, we have emphasized low-yield targets that demand the most rigorous performance of laser sources (10% efficiency and short wavelengths). In response, the advanced quantum electronics program has been directed toward identifying laser media and pump technologies to satisfy these requirements. Several interesting candidate media have been identified: photolytically pumped atomic iodine, oxygen, and sulfur, and *in situ* electron-beam-pumped, rare-gas group VI excimers such as KrO , XeO , and ArO . Experiments have been performed to establish the operating-parameter regimes (mixtures, pressure, voltage, current density, geometry, etc.) of these media. Progress in these experimental and theoretical studies has led to a gain-saturated krypton oxide laser and an atomic iodine laser photolytically pumped by an electron-beam-driven ultraviolet fluorescer, the XeBr^* excimer.³ A new generic class of fusion lasers based on trivalent rare-earth molecular vapors has been identified on theoretical, analytical, and limited experimental grounds. This class is currently being assessed at a low level of effort.

Our criteria for candidate media appear to be well satisfied by the group VI elements—oxygen, sulfur, selenium, and tellurium—and by the electronic analogs carbon, silicon, germanium, and tin.

For high-performance targets, lasers of lower efficiency ($\geq 0.1\%$) and longer wavelength ($\leq 3 \mu\text{m}$) are of interest. Relaxation of efficiency and wavelength requirements opens new vistas for both laser media and pumping techniques. For this work, we have developed a critical capability in electrical-discharge physics and we have designed and built an experimental facility (Fig. 1-4) for rapid assessment of spectroscopic and kinetic parameters of many new potential laser media.

To support the multistep photoionization laser isotope separation of atomic uranium vapor, we have quantitatively assessed the current copper-vapor laser technology. Performance data for both metallic copper and copper-halide laser devices have been assembled. Basic kinetic and laser-staging models have been defined, inadequacies and scaling laws isolated, and limiting device technologies determined. Several dye oscillator designs consistent with transient pumping by copper laser pulses have been identified.

To optimize use of the experimental facilities completed in FY 1976, we have created a small theoretical atomic and molecular physics effort to help interpret experimental spectroscopic and kinetic data and direct the experimental effort in the most productive directions.

Fig. 1-4. Electron-beam-pumped krypton oxide visible laser using the MEG II facility at LLL. The multipass 50-cm-long cell provides optical gain at 557.7 nm for a saturating pulse from a pulsed dye laser.

During FY 1977, we expect to identify and evaluate several new laser media and pumping techniques and also to consolidate our knowledge about laser media already identified: rare-gas excimers, rare-gas-group

VI excimers, rare-gas halogen photolytic sources, and rare-earth molecular vapors. Based on this information, we will be making recommendations about future experiments and device development.

1.2 Laser Isotope Separation Program

The conceptual basis of our laser isotope separation process is the ability of a laser to excite the atoms of one isotope selectively without affecting atoms of other isotopes that are present. This is possible because the various isotopes respond to different frequencies (wavelengths) of light. The difference—the so-called isotope shift—is slight, barely a thousandth of a percent, but lasers can be fine-tuned within this range. Once the atoms have been excited, they can be separated by various techniques.

The driving incentive behind laser isotope separation is largely economic. The demand for separated uranium isotopes will soon outstrip U.S. production capacity by the existing gaseous diffusion plants, forcing the construction of new plants whose cost may total

some \$40 billion by the year 2000. Laser isotope separation plants show promise of being less expensive to build and operate.

The potential advantages of laser isotope separation over gaseous diffusion are many. Even allowing for laser inefficiencies, LIS may require much less energy. It may also be simpler, performing in one stage the equivalent of many stages of gaseous diffusion separation. Indications are that laser separation may be capable of extracting a much higher percentage of ^{235}U from a mixture with ^{238}U than gaseous diffusion. Each of these advantages translates into lower costs. The laser isotope separation program is discussed in a companion report.⁴

1.3 Program Resources

The Lawrence Livermore Laboratory program for laser development dates back to the early 1960's, soon after the invention of the laser. The ability of lasers to

produce a concentration of energy in space and time comparable to that achieved at the heart of a nuclear explosion was of paramount interest. From the start,

lasers have been regarded as an interesting and potentially valuable tool for studying inertial confinement fusion, which might someday compete with, and supplement, other approaches such as nuclear fission and magnetic-confinement fusion.

Early studies, carried out at LLL under sponsorship of the U.S. Atomic Energy Commission, were aimed at understanding fundamental laser science and technology. These relatively modest efforts were a part of the LLL nuclear explosives and military applications programs, but they suggested nonmilitary uses, such as laser fusion and laser isotope separation. As the technology advanced, these applications began to receive more serious attention. The early work carved out at LLL contributed heavily to the AEC decision, arrived at in the early 1970's, to expand the laser program and increase its emphasis on nonmilitary applications.

Manpower

The LLL laser program in its present form began in 1972, with perhaps 20 scientists drawn from several divisions of the laboratory. As part of a diverse and expanding national program, the volume of laser work at LLL has grown from a \$1 million project to its present size. Currently, the laser program comprises an organization of some 350 scientists, engineers, and administrative and support personnel, who are responsible for a \$30 million program in laser technology development. The program is strongly oriented toward applying laser technology to important national problems. Over 62% of the scientific staff currently employed in the laser program came to LLL with significant laser experience. The staff represents a combined total of more than 400 man-years of laser-related research and development. Forty-five percent of the cur-

rent staff are scientists, with the remainder engineers, designers, and administrative and support personnel. The organization of the laser program is shown in Fig. 1-5.

The level of effort in the laser fusion program was held essentially constant from 1974 to 1975. This leveling-out of manpower for the laser fusion program reflects a commitment by LLL to increasingly involve industry in the program as laser fusion advances from basic research to advanced development. The same management philosophy will be applied to the LIS program, but funding limits the current and projected manpower levels.

Funding

Operating costs for 1975 total nearly \$27 million, \$21 million for laser fusion and \$6 million for laser isotope separation. The Livermore laser fusion program represents about 40% of the total ERDA laser fusion budget, while the laser isotope separation program at Livermore is about 12% of the total ERDA laser isotope separation program.

Currently more than 40% of the total LLL laser program budget is spent outside the laboratory. Of this, about 10% goes to other government agencies with the remaining 30% being spent outside ERDA. Part of the monies spent outside LLL go for research and development in areas where specific expertise or a unique capability exists. Table 1-2 shows the history and a projection of outside R&D contract funding for the total program.

In 1975, the LLL laser program obligated \$3.1 million in capital equipment. Approximately 30% of all equipment purchases were for operational hardware

Fig. 1-5. Laser program organization chart.

Table 1-2. Laser program outside R&D contracts

	1973	1974	1975	1976 ^a
Other government laboratories	0	38	358	268
Universities	118	201	308	300
Nonprofit	0	149	66	121
Industry	13	153	705	1542
Totals	131	541	1437	2231

^aEstimated cost in FY 1976.

associated with the Cyclops, Janus, and Argus laser systems. Items in this category include power supplies, vacuum pumps, oscilloscopes, small computers, and interface equipment. Another 30% of the budget was spent on basic research equipment to support all elements of the program; this category includes diagnostics equipment such as spectrum analyzers, special purpose oscilloscopes, and recording and display systems. Since the nature and problems of laser target fabrication require a significant expenditure of equipment monies for both target manufacture and quality control, more than 10% of the equipment budget was spent for this purpose in 1975. An even greater amount will be required in future years.

Facilities

General Plant Projects. In July 1975, 1130 ft² of laboratory space was added to Building 177 by upgrading an existing room. The laboratory will house experiments in laser photochemical research as part of the LLL laser isotope separation program.

During September 1975 construction began on the addition of a clean room plus remodeling and upgrading of 2000 ft² of laboratory space in Building 174, which houses the Janus and Cyclops glass laser experiments. The clean room will be operated at class 100 level, using horizontal, laminar air-flow. Its primary use will be to assemble laser heads and other optical components in order to reduce costly damage to laser optics operated at high energy density. Half of the 1600-ft² area in the clean room will serve as the component cleaning area; the other half will be used for component preassembly. Operation of this facility is scheduled to start in April 1976.

Preliminary design of Building 161, the Laser Isotope Separation Development Laboratory, was completed in late 1975. This building will contain five laser laboratories totaling 4500 ft² of net floor area. When completed in the fall of 1976, the laboratories

will be used for research in uranium molecular spectroscopy, metal-vapor atomic spectroscopy, excited-state atomic and molecular collision processes, and electron-beam source diagnostics.

Laser Fusion Laboratory, Building 381. The LLL Laser Fusion Laboratory, which was completed in November 1974, became operational in 1975. The laboratory wing contains 38,000 ft² of laboratory space including a 10,000-ft² basement for capacitor banks, associated laser equipment, and a machine shop. Laboratory space consists of a high bay and smaller laser laboratories, control and diagnostics rooms, and target fabrication laboratories. The high bay is 60 ft wide, 240 ft long, and 28 ft high with a 25-ton bridge crane running the length of the bay.

One unique feature of the "laser qualified" laboratory space is its controlled environment. The design incorporates special controls on factors such as vibration, noise, temperature, air flow, humidity, and dust that can adversely affect laser operation. The laboratory will accommodate a variety of basic research activities and prototype laser systems for investigating laser fusion concepts. The controlled environment and the convenient space for capacitor energy storage will allow the development of high-energy glass lasers for the 10-kJ laser system. The laboratory will also be suitable for laser/plasma interaction experiments and for the construction of multibeam laser systems for plasma studies. The operation of any particular laser system within this facility will not be permanent, and the building has been made as flexible as possible to provide for any foreseeable laser system development or laser/plasma experiments.

High-Energy Laser Facility, Building 391. The LLL High-Energy Laser Facility (HELFF) is a \$25 million project funded by ERDA and administered by its local San Francisco Operations Office. Of the total funding, \$8.8 million is allocated for construction of the building and \$16.2 million for the laser and target system.

The goal of the HELFF is to demonstrate significant laser-driven compression and thermonuclear burn of a fusion pellet. To do this, a high-energy laser system will be constructed. It will consist of three major components: a high-powered and well-controlled pulsed laser, a target-handling and irradiation chamber, and a diagnostics array. These components are integrated to explore the basic physical processes fundamental to laser fusion. The laser is being designed to deliver a total of 10 kJ on target in a configuration that will permit spherically symmetrical irradiation of the target with twenty 500-J beams. Experiments designed to prove the concepts of laser fusion will be conducted with this system.

The building to house the laser system (Fig. 1-6) will consist of five major elements: a main laser bay, a target room, an energy-storage area, a single-story laboratory element, and substantial mechanical equipment areas. The laser bay, target room, and a clean laboratory require stringent temperature and dust control for advanced laser research. The gross area of the building is approximately 66,000 ft², and the enclosed volume is approximately 1,660,000 ft³. The facility is being constructed due north of the Laser Fusion Laboratory, which houses the principal laser research groups at LLL. It will accommodate about 50 technical personnel.

The main bay and the target room, which are 8800 ft² and 3600 ft² in area respectively, are vertical, laminar-flow clean rooms, class 1000 with an allowable 1°F variation in room temperature. The assembly room for laser components is a class 100 clean room with an area of 3000 ft². The total volume of air handled in the building is approximately 1,000,000 ft³ per minute.

To expedite this project and maintain an accelerated schedule, we have used phased construction techniques (fast track) coupled with a construction-management concept. The Norman Engineering Company of Los Angeles is the architect engineer and the construction

manager. Excavation and foundation work (Phase 1) began in August 1974, before the design of the remainder of the building was finally completed. The second phase of construction commenced in March 1975, and the current construction schedule projects completion in July 1976.

Laser Isotope Separation Laboratory, Building 481. LLL proposes to construct a laboratory and office building approximately 100,000 ft² in area to house 200 scientists, engineers, and other support personnel. This project is conceived as a critical step in meeting national goals in energy development, primarily through substantial reduction in the cost of uranium enrichment. The estimated cost of the project is \$16,300,000, assuming funding in FY 1978.

The conceptual design of this project was completed in 1975 by the architectural engineering firm of Daniel, Mann, Johnson and Mendenhall of Los Angeles, California. This design provides a laboratory wing that includes 15 laboratories from 750 ft² to 5000 ft² in area, support shops, a control room, a 6000-ft² basement, a radioactive materials vault, and related personnel safety facilities. The office wing is a two-story structure with many features similar to those used in the successful design of the offices in the Laser Fusion Laboratory Building.

Fig. 1-6. High energy laser facility, June 1976.

References

1. *Energy and Technology Review*, Lawrence Livermore Laboratory, Rept. UCRL-52000-76-2 (Feb. 1976).
2. *Energy and Technology Review*, Lawrence Livermore Laboratory, Rept. UCRL-52000-75-4 (April 1975).
3. *Energy and Technology Review*, Lawrence Livermore Laboratory, Rept. UCRL-52000-75-11 (Nov. 1975).
4. *Laser Isotope Separation Annual Report-1975*, Lawrence Livermore Laboratory, Rept. UCRL-50040-75 (1975).

2. SYSTEMS STUDIES

Section Editor: J. Maniscalco

2. SYSTEMS STUDIES

Laser Fusion Systems Studies

- These studies have emphasized applications in electrical power and fissile fuel production. They have focused on deriving and analyzing conceptual designs for laser fusion power plants and on developing concepts for fusion-fission hybrid reactors that can play a logical role in the development of a fusion power economy.
- We have identified and analyzed major technological considerations, such as first-wall problems.
- We have identified the laser and pellet performance required for commercial production of power and of fissile fuel.

Laser Isotope Separation: Systems Studies

Our system studies in laser isotope enrichment support the near-term goal of uranium enrichment by:

- Developing systems models of LIS processes.
- Analytically evaluating LIS schemes in preparation for feasibility demonstration and scaled system designs.
- Developing preliminary LIS plant concepts.
- Evaluating the economic viability of candidate LIS processes.
- Monitoring, guiding, and providing technical liaison for modeling support efforts by outside agencies.
- To support the longer term goal of cost-effective LIS schemes for other important elements, we have initiated studies to identify alternative LIS applications by assessing potential markets for less costly LIS enrichment. Of particular interest are those applications where order-of-magnitude reductions of impurities are required. Such reductions may be achieved at relatively low cost with LIS. Potentially large scale LIS applications exist in all phases of nuclear fuel cycles, not only in providing enrichment fuel, but also in reducing handling costs, in providing improved cladding materials, in reclaiming valuable materials, and in improving waste containment.

2. SYSTEMS STUDIES

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2. SYSTEMS STUDIES

2.1 Overview

Systems studies in laser fusion and laser isotope separation (LIS) are being done to determine what lines of research will yield the maximum benefit in the shortest possible time. These studies, ranging from detailed engineering designs to cost-benefit analyses, are providing insight into the eventual value of the work being performed and the relative merits of particular lines of research. Several different but interdependent types of systems studies are being conducted. They include:

1. In-depth design studies which attempt to integrate all elements of the system into a self-consistent design, thereby defining the engineering limitations on the important subsystems.
2. Parametric systems analyses to determine the sensitivity of systems performance and cost to the functional requirements and technological limitations which constrain the design, thereby defining the optimum system.
3. Exploratory investigations to identify new systems concepts and new applications.
4. Cost-benefit studies to investigate both the performance required for entrance into the economy and the impact of the new technology on the economy.

All four of these different types of analysis have been applied to systems studies for LIS, whereas only the first three have been applied to laser fusion. Cost-benefit and economic analyses will be applied to laser fusion when more definitive and fundamentally sound approaches have evolved.

Before becoming a commercial reality, any new technology must pass through three successive stages of feasibility: scientific feasibility, engineering feasibility, and commercial feasibility. The scientific feasibility stage encompasses analytic development of the concept and experimental verification. For laser fusion and LIS, this involves providing the scientific data base required to (1) understand the underlying physics of the interaction between laser light and the medium of interest, and (2) develop and evaluate new lasers for these applications. The engineering feasibility stage includes component and subsystem development along with demonstration runs to investigate the integrated performance of the whole system. Commercial demonstrations are required in the commercial feasibility stage to compare the concepts with competitive alternatives.

Laser fusion and laser isotope separation are both in the scientific feasibility stage of development; how-

ever, LIS is rapidly advancing into the engineering feasibility stage. Our systems studies for both these promising new technologies deal primarily with conceptual designs appropriate to the engineering and commercial feasibility phases of development. This type of long range analysis can support the ongoing primary research by indicating the more promising directions and drawing attention to sensitive areas which will require special attention.

Laser Fusion Systems Studies

Laser fusion systems studies are being carried out at LLL, at other national laboratories, in private industry, and at several universities to identify suitable military and commercial applications of this new technology. Identification of major commercial applications is based on technological feasibility and economic comparability with existing alternatives. Some of the more attractive commercial applications identified to date include electrical power production, fissile fuel production, hydrogen production, propulsion, burnup of radioactive fission waste, and production of high-temperature process heat for industrial use.

In our systems studies for laser fusion, we have emphasized the electrical-power and fissile-fuel production applications. We have focused on deriving and analyzing reference designs for laser fusion power plants and on developing concepts for fusion-fission hybrid reactors that can play a logical role in the evolution of a fusion power economy. Specifically, our studies have attempted to identify the laser/target-pellet performance required to commercially produce electricity and fissile fuel with laser fusion. Our progress in this area is presented in Secs. 2.2.1 and 2.2.2.

When we analyze different power-plant concepts, the design of the first wall stands out as a unique and major problem facing laser fusion. This wall has the difficult task of separating the blanket portion of the reactor from the hostile environment created by the thermonuclear microexplosion. The importance of this function to the overall design of a laser fusion power plant is demonstrated by the fact that all of the conceptual designs put forth to date differ from one another primarily in the way the hot blast debris interacts with the first wall. With this in mind, we have initiated studies to identify and analyze the major problems associated with the design of a first wall. The results of our first-wall studies are presented in Sec. 2.2.3.

LIS Systems Studies

The near-term objective of the LLL laser isotope separation program is to develop economic processes to enrich uranium; the long-term goal is to develop cost-effective LIS schemes for other important elements whose isotopes are costly or extremely difficult to produce by conventional methods. To date, our main effort has been directed almost entirely toward uranium enrichment. Our systems studies support the near-term goal by developing plant concepts and systems models of LIS processes for uranium. In supporting the longer term goal, we have initiated studies to identify alternative LIS applications by assessing potential markets for less costly isotope enrichment.

Three different types of modeling are required to analyze the engineering and commercial feasibility of large-scale LIS enrichment of uranium. First, component modeling (done by LIS program personnel) is required to design the individual portions of a separation experiment. Then, system or process modeling is used to evaluate the performance of the separation system on the basis of component interaction. Finally, economic modeling is used to evaluate commercial feasibility by drawing upon results from system modeling and plant-related factors. The systems studies group does both the process and economic modeling.

The most significant conclusions from the results of our modeling studies are:

- Laser enrichment of uranium can have a significant capital-outlay advantage over conventional enrichment processes (gaseous diffusion, centrifuge.).
- LIS enrichment costs can be a factor of two smaller than for conventional approaches.
- LIS enrichment requires only 10% of the electrical power consumption of gaseous diffusion.

• LIS should be economic in much smaller plant sizes than conventional approaches.

• The economic tails assay for LIS will probably be less than 0.2% ^{235}U .

• The technology developed for LIS enrichment of uranium will create new applications in "quantum engineering."

The successful demonstration of laser enrichment of uranium at LLL and favorable cost projections for production-size LIS facilities have led us to look for alternative applications for this new technology. Our systems studies in this area are being conducted in two phases. The first phase, still in progress, is mainly concerned with identifying isotopes whose enrichment or separation might be done at lower cost by the laser process. The second phase will be concerned with determining the volume of separation required as a function of cost, as well as associated benefits.

By far the largest potential market for isotope separation is connected with the generation of nuclear power. In addition to the need for enriched fuel, markets may exist for isotope separation in providing advanced fuel for breeder reactors (^{15}N), in fuel cladding (^{50}Ti), and in the processing of spent fuel (^{232}U , ^{235}U , ^{238}U , ^{236}Pu , ^{238}Pu , platinum metals, etc.). Medical applications of radioactive and stable isotopes are growing rapidly; while the quantities needed for such use are not of the same magnitude as reactor requirements, their value is considerable. Various applications for improved isotope separation capabilities exist in the field of weapons development. Our progress in uranium enrichment and alternative isotope applications is reported in Secs. 2.3.1 and 2.3.2.

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2.2 Laser Fusion Systems Studies

2.2.1 THE COMMERCIAL ASPECTS OF LASER FUSION

To be a viable source of energy for the future, laser fusion must be scientifically feasible, technically sound, and economically competitive with existing energy producers. For the most part our studies have sought to evaluate the potential of laser fusion as an energy option by developing, analyzing, and comparing several conceptual power plants.

In analyzing these conceptual designs, we have found it useful to view a laser fusion power plant through a basic power flow scheme¹ with the equation

$$\frac{P_{in}}{P_g} = \frac{1}{\eta_L Q \eta_T (0.8M + 0.2)} \quad (1)$$

The simple expression gives the plant fractional recirculating power (P_{in}/P_g) as a function of laser efficiency (η_L), pellet gain (Q), thermal efficiency (η_T), and blanket energy multiplication (M). Recirculating power is, of course, a basic figure-of-merit for any power plant. (For reference purposes, fossil-fueled power

plants operate with recirculating powers less than 5% while the majority of present nuclear plants operate at or slightly above this figure.) The laser system efficiency is a lumped parameter which includes power conditioning, lasing, and optical transport efficiencies; blanket energy multiplication (M) is defined as the ratio of blanket thermal energy to fusion neutron energy.

From Eq. (1), it logically follows that the product of laser efficiency (η_L) and pellet gain (Q) should provide an excellent figure-of-merit for gauging the prospects of generating electrical power with laser fusion. This product, which we shall label fusion energy gain, represents the ratio of thermonuclear energy to laser input energy. Fusion energy gain is an extremely revealing performance parameter because economical power production with laser fusion will fundamentally lie with the pellet energy gains achieved and the overall efficiencies at which large pulsed laser systems can operate. In Fig. 2-1 the recirculating power fraction is plotted as a function of fusion energy gain for power plants with a blanket energy multiplication of 1 and several thermal efficiencies. Reference designs for laser fusion power plants at LLL¹ and LASL^{2,3} have used recirculating power fractions in the neighborhood of 25%. However, it may be difficult to compete economically at these high values because, in general, plant capital costs scale with the gross electrical power while revenues scale with the net electrical power.

The target and laser subsystems required for a laser fusion power plant form the basis of nearly all other

component designs. Target production, irradiation requirements, and debris spectra dictate the majority of the design constraints for a laser fusion reactor, while the combined target performance and laser system efficiency specifies economical plant operating conditions. Since the target performance and laser system requirements are so closely interrelated, they are discussed together in this section.

Targets for Laser Fusion

The dynamics of target compression and the difficulties associated with producing the conditions required for high-performance large thermonuclear gains have been described in detail elsewhere.⁴ Here we describe the main features of the target designs and give the gain predictions used in our studies.

Two types of targets, with variations, have been extensively investigated at LLL: solid and hollow microspheres containing stoichiometric mixtures of deuterium and tritium. Figure 2-2 shows a sample calculation made for a solid DT (about 1 mg) target. A low energy prepulse (about 20 J) explodes a thin outer shell creating an atmosphere around the target. This atmosphere is heated by another prepulse to ensure rapid electron thermal conduction. The implosion is started by the 2- μ m light and continues until the unablated target surface is roughly half the critical density for 1- μ m light. A frequency doubled pulse is then used for further compression and again doubled twice to maintain symmetry and assure good coupling with the plasma. The target's thermonuclear energy release is 40 MJ with a 0.9-MJ input, for a gain of 44. Solid targets are attractive for laser fusion power plant applications because of their ease of fabrication and potentially low cost. Unfortunately, the peak intensity during the final phase of the implosion exceeds that where backscattering due to Brillouin instabilities can occur. At these high intensities, as much as 50% of the incident laser energy might be reflected, thereby reducing the estimated gain given above.

Because of the backscatter problem at high laser intensities, hollow targets containing less mass were investigated. Although these targets might require roughly an order of magnitude less laser power and do not induce significant plasma instabilities, they are limited in performance by fluid instabilities. To date no known mechanism exists to stabilize these fluid instabilities for high gain targets.

The present consensus is that for laser pulse energies between 100 kJ and 1 MJ the best of these targets might achieve gains in the neighborhood of 100. Such performance must be evaluated in context with the fusion energy gain figure-of-merit, $\eta_L Q$, for the application of interest (see Fig. 2-1).

Fig. 2-1. Plant recirculating power requirements as a function of fusion energy gain.

Fig. 2-2. Example calculation for a solid target.

Lasers for Laser Fusion

The standard procedure for determining laser requirements for laser fusion systems has always emphasized target performance as a baseline, from which the laser is configured. For example, from the fusion energy gain product, low (less than 25%) recirculating power reactors will require lasers with efficiencies between 10 and 15%. Returning to Fig. 2-2, we see that the laser system must be able to irradiate the target in a particular way to achieve high gains. Two prepulses are required (20 J and 1.5 kJ); then in a precisely timed and controlled fashion, the laser intensity and wavelength vary over 5 and 1 orders of magnitude respectively. Twelve or more beams are required to maintain symmetry during the implosion, and a very high brightness laser is needed to focus on the small targets.

Lasers presently being pursued for laser fusion are listed in Table 2-1. Nd:glass systems have been developed to produce powerful beams of light with very good focusability for target irradiation experiments.⁵ (The term focusability is being used here to give some indication of the ability to focus the output power of the laser on a spot approximately 50 μm in diameter.) Single pulse CO_2 systems have also been used for target experiments. High average power experiments for developing gas flow equipment, power conditioning and optical subsystems have not been conducted to date. Examination of Table 2-1 shows that the currently operating gas lasers fall far short in efficiency and other characteristics of matching the requirements illustrated

graphically in Fig. 2-2. Extrapolations of the characteristics of these lasers and an oxygen system⁶ are summarized in Table 2-2 for comparison, along with an estimate of the ideal laser properties required to yield fusion energy gains that are greater than 10. Still, using the targets described previously, fusion energy gains are insufficient for commercial power plant operation. This approach to laser fusion systems design requires the discovery of an "ideal" laser, a task that is slow in yielding to R&D efforts.

A New Approach

Technical problems associated with developing highly efficient, highly controlled laser/optical systems that run at high average power appear overwhelming at this time. While target design is in its infancy, the question should be asked whether or not targets can be designed to produce useful applications with the laser systems that will certainly be available in the 1980's and 1990's, i.e., whether targets can be designed to match the lasers instead of vice versa. Then we should ask what systems applications make sense in this time frame. In time, higher-efficiency lasers will expand these applications.

Atomic iodine can be taken as an example of a near-term laser medium. Iodine is chosen instead of CO_2 , which has a considerable development base, because of the much shorter wavelength produced. Previous theoretical analyses have shown considerable

difficulties in producing gain at 10.6- μm wavelengths due to unfavorable electron spectra created during the photon absorption process.^{5,7} Such problems are less severe at 1.32 μm , and efficient frequency doubling is possible at the shorter wavelength. Although iodine presently has a low efficiency, various photolytic pumping schemes under evaluation promise significant increases in efficiency, such that final system efficiency (η_f) could be as high as 1%. Improvements beyond this might be possible using different pump/laser media in essentially the same system configuration. Iodine is scalable in pulse energy and peak power, and it can be extended to high average power. Scaling in energy/power is easier than achieving higher efficiency such that 100 kJ-1 MJ, 10 Hz systems can be envisioned with form factors comparable to CO₂.

In this example, target design would be oriented toward maximizing pellet gain, while utilizing the near-term iodine characteristics shown in Table 2-2, as well as reducing optical system requirements (e.g., number of beams). The trend has been toward inexpensive targets that keep fuel costs in line with electrical power generated from other means. If we ignore this constraint for the moment, more expensive complex targets might be possible that achieve higher gains. A summary of laser system and associated target characteristics is given in Table 2-3. If advanced, high-risk target designs for use with the low-risk laser systems can be developed, various laser fusion applications are possible that make sense as part of the laser fusion program. Table 2-4 provides an estimate of the fusion energy gain requirements and target design goals for

Table 2-1. Current status of lasers

Laser	Wavelength (μm)	Max power single beam (TW)	Efficiency (%)	Pulse energy (J)	Focusability	Wavelength convertibility (μm)
Nd: Glass	1.06	1 ^a	~0.1	100 (0.1 ns)	Very good	0.53 ~ 50% efficiency
		0.2-0.3 ^b		60 total	Nominal	0.35 ~ 30%
		1.5 ^c		150 (0.1 ns)	Unknown	0.27 ~ 20%
CO ₂	10.6	0.15 ^d	1-2	250 (1.6 ns)	Good	Not demonstrated at high power
Iodine	1.32	0.3 ^e	0.1	300 (1 ns)	Poor	Similar to Nd: glass
HF	2.7	0.15 ^f	~3	4000 (26 ns)	Very poor	Not evaluated

^aLawrence Livermore Laboratory.

^bKMS-F (uses pulse stack).

^cUniversity of Rochester.

^dLos Alamos Scientific Laboratory.

^eInstitute für Plasmaphysik, Garching.

^fSandia Albuquerque.

Table 2-2. Potential lasers for laser fusion

Laser system	CO ₂	HF	I	O	Ideal
Properties					
Wavelength (μm)	10.6	2.7	1.3	0.56	0.3
Energy (J)	10 ⁵	10 ⁵	10 ⁵	10 ⁵	10 ⁵ -10 ⁶
Pulse width (ns)	1.0	1.0	0.1-1.0	0.1-10	0.1-1.0
PRF (s ⁻¹)	>10	>10	>10	>10	>10
Efficiency (%)	5-8	5-13	≤1	4	10-15
Fusion energy gain (estimate)	0.1	~1	<1	>1.5	>10

Table 2-3. Laser/target system options

	Option A	Option B
	Matching laser to near-term target technology	Matching target to near-term laser technology
Target characteristics	Potentially inexpensive and easy to fabricate Gain appears limited by Rayleigh-Taylor instabilities and high induced reflectivity Highly uniform, near-normal irradiation required	Potentially expensive and difficult to fabricate Higher gain, improved coupling Nonnormal illumination
Laser system characteristics	High efficiency Numerous beams Low f-number optics Multiple frequency Pulse shaping High brightness	Low efficiency Longer pulse High f-number optics Reduced number of beams

Table 2-4. Estimated target gain and laser energy requirements for laser fusion systems

System	Thermonuclear		E_o (kJ)	Target gain	
	power (MW)	$\eta_L Q$		Present $\eta_L > 10\%$	Advanced $\eta_L < 5\%$
Engineering research facility (LFTF)	10	0.1	100	a	a
Experimental reactors (ELFR's, ELFFR's)	100	0.1-0.5	<300	a	a
Prototype reactors (PLFR's, PLFFR's)	100-500	0.5-1.0	<300	a	a
Demonstration hybrid power and fuel producers (LFFPR's)	100-1000	1-5	100-1000	10-50	20-100
Demonstration laser fusion power producers (LFPR's)	500-2000	>10	300-1000	>100	>200

^aTarget gains are not as critical as for power/fuel producing systems where economic questions dominate. Gains between 1 and 10 will probably be sufficient.

major facilities needed to evaluate and develop commercial laser fusion power. It is this approach that should be explored.

In Figure 2-3, a development scenario for laser fusion is superimposed over curves which give the fusion energy gain as a function of blanket energy multiplication for power plants with various percentages of recirculating power. The curves were generated from the previously given expression for recirculating power, and they emphasize the substantial decreases that take place in required fusion energy gain as blankets with higher energy multiplication are used.

The colored portions of Fig. 2-3 represent regions of potential commercial utilization for pure laser fusion and several hybrid concepts. Pure laser fusion and non-fissioning hybrid concepts can have blanket energy multiplications that are slightly larger than unity by using materials which exhibit neutron multiplication and exothermic capture reactions. Beryllium, with a large $(n,2n)$ and a small capture cross section is an example of a non-fissioning neutron-multiplying material, while ^6Li and sodium are examples of materials which exhibit exothermic neutron capture. $M < 2$ is a practical upper limit to the energy multiplication ob-

tainable from the non-fissioning process of coupling neutron multiplication with exothermic capture.

Thorium and depleted uranium (i.e., enrichment plant tailings) are attractive fuels for fissile-fuel producing hybrid blankets. Relatively abundant thorium is attractive because it breeds ^{233}U which is an excellent fissile fuel for thermal fission reactors. Depleted uranium is an attractive hybrid fuel because the U.S.

has a large and continuously increasing stockpile of this material. In comparing these fertile blanket materials, our results have shown that depleted uranium hybrids provide more energy multiplication and fissile fuel per unit of fusion energy produced whereas thorium-fueled concepts exhibit better performance on the basis of fissile production per unit of thermal energy produced.

Blankets other than thorium and depleted uranium

Fig. 2-3. A development scenario for laser fusion.

become attractive when higher-energy multiplying hybrid concepts which primarily produce power are considered. These include thermal fission blankets and plutonium-enriched fast fission blankets which could best be characterized as source-driven fast breeder reactors. The higher energy multiplication from these blankets is gained at the expense of fissile enrichment and reduced fissile production in more complicated blankets. With higher operating cost and lower fissile production, high-M blankets have to operate in a regime where a large portion of their revenue comes from power production. This is emphasized in Fig. 2-3 by requiring hybrid power producers to operate with less than 25% recirculating power.

The most desirable development scenario for laser fusion is one which will allow this new technology to contribute to our energy needs in the shortest possible time. The evolutionary path emphasized in Fig. 2-3

was chosen with this principle in mind. As such, the major route shows fissioning fissile fuel producers on the way to pure laser fusion. Depleted-uranium fueled hybrids have the potential to operate with fusion energy gains that are an order of magnitude lower than those required for pure laser fusion. When higher-fusion energy gains are achieved, thorium-fueled concepts could come into play. Likewise, power-producing hybrids could be an attractive alternative once the reliability of laser fusion has been established in fissile-fuel production. The scenario described here is based on our belief that fusion energy gains in the neighborhood of 1 will be achievable in the next decade whereas gains of 10 or more lie somewhere in the unpredictable future.

J. Maniscaco
R. Buntzen

2.2.2 FUSION-FISSION HYBRIDS

Fusion-fission hybrid reactors can be viewed as fissile fuel- and/or power-producers driven and controlled by an internal source of high energy neutrons, the fusion reactor. Such hybrids combine naturally the power-richness of fission systems with the fast-neutron-richness of fusion power sources. The term "fast-neutron-rich" should be emphasized because it is the 14.1-MeV neutrons from DT fusion that provide hybrid systems with the ability to generate substantial amounts of energy and fissile material from the abundant fertile materials, ^{232}Th and ^{238}U , thereby operating with low fissile-material inventories in a subcritical fashion that provides an absolute guarantee against a nuclear excursion.

Our approach has been to look at fusion-fission hybrids that make sense as part of the evolution of a laser-fusion economy. Specifically we have tried to couple near-term laser-fusion technology with well-established fission reactor technology. In keeping with these principles, our systems studies have been directed toward hybrid concepts which use energy-multiplying and fissile-breeding blankets based on different fission reactor technologies (liquid-metal and gas-cooled fast breeder reactors, high temperature gas-cooled reactors, liquid-metal-cooled thermal reactors, etc.).

The hybrid concepts analyzed in our systems studies could best be categorized as fast- or thermal-fission systems which fulfill one of the following roles:

- 1) An electrical consuming facility which produces fissile fuel.
- 2) An electrical breakeven facility which produces fissile fuel.
- 3) A producer of fissile fuel and electricity.

Here, fast-fission systems are defined as blankets in which the majority of fusion energy amplification is derived from fast fissions ($E > 1 \text{ MeV}$) in fertile materials, while thermal-fission systems are defined as blankets in which the majority of energy amplification results from thermal fissions in fissile materials.

Hybrid facilities which fulfill one of the first two roles are classified as fissile-fuel producers, whereas facilities which satisfy the third role are classified as either fissile-fuel or electrical-power producers. The distinction depends on whether fissile fuel or electricity accounts for the majority of the facility's revenues.

At present, it is unclear which of these roles will have the larger commercial impact; however, hybrid facilities which fulfill one of the first two roles may have the potential for earlier commercial application because thermodynamic efficiency, reliability, and duty-cycle requirements are not as stringent for fissile-fuel producers which are effectively decoupled from an electrical power grid.

Fusion-fission hybrids can be designed to maximize fissile production or fusion-neutron energy multiplication. In general, fissile production (per unit of fusion energy) is maximized in fast fission blankets containing fertile materials, while energy multiplication is maximized in thermal fission blankets containing heterogeneous lattices of fissionable material and moderator. Figures 2-4 and 2-5 show the configurations and material choices for hybrid blankets which fall into one of these two categories. The conceptual designs and material choices as presented encompass so many different fission reactor technologies (HTGR, LMFBR, GCFBR, etc.) that it will be fitting to give the reasons

Fuels

- 1) Type: metals, oxides, or carbides
- 2) Fertile isotopes: ^{232}Th or ^{238}U
- 3) Fissile isotopes: ^{233}U , ^{235}U , or ^{239}Pu
- 4) Cladding: stainless steel or refractory metals

Coolants: gas or liquid metal

Structure: stainless steel or refractory metals

Fig. 2-4. Fast fission blankets: configurations and material choices.

Same material choices
as given for fast fission
blankets

Fuels

- 1) Type: oxides or carbides
- 2) Fertile isotopes: ^{233}Th or ^{238}U
- 3) Fissile isotopes: ^{233}U , ^{235}U , ^{239}Pu
- 4) Cladding: graphite, zirconium, or stainless steel

Moderators: graphite or hydrides

Coolants: gas or liquid metal

Structure: materials with low thermal
neutron absorption

Fig. 2-5. Thermal fission blankets: configurations and material choices.

for not considering light water reactors (LWR's), since they represent the most widely used and established fission technology. Blankets for DT-burning fusion devices must breed tritium and will therefore contain substantial quantities of lithium. Water has not been listed as a possible coolant because of the possibility of tritium contamination and the hazards which result from its generally high chemical reactivity with liquid metals, particularly lithium.

Refractory metals such as niobium, and molybdenum have been chosen as structural materials in several fusion reactor conceptual designs because of their physical and chemical properties at high temperatures. These metals have also been considered as potential structural materials for hybrid blankets; however, it is anticipated that stainless steel will be the structural material of choice for first-generation hybrid reactors. The selection of stainless steel limits the high temperature operation of a hybrid blanket to values that are currently achieved in fission reactors. Nevertheless, it is consistent with our desire to consider hybrid concepts which could be built in the near future with minimal extensions of the state-of-the-art technology developed in the fission power economies.

Fissile Fuel Production with Laser Fusion

Thorium and depleted uranium (i.e., diffusion plant tailings) are two of the most attractive fuels for fissile-fuel-producing blankets. Fissioning induced by the fusion neutrons in these fertile materials enhances both the energy-multiplying and fissile-fuel-producing capabilities of fast-fission blankets. A thorium-fueled non-fissioning blanket is another type of fissile fuel producer. Strictly speaking, this concept is not a fusion-fission hybrid, and it is usually referred to as a "symbiotic" system, the term being used to indicate

that fuel is produced for consumption in physically separate fission reactors. Fissioning is suppressed in this type of fusion blanket by moderating the fusion neutrons to energies below the fission threshold in thorium and by continuously removing the bred ^{233}U . In comparison to hybrids, symbiotic devices provide very little, if any, energy multiplication and produce less fissile fuel per unit of fusion energy. However, proponents of symbiotic systems claim that the lower production capability may be offset by lower blanket and fuel reprocessing costs resulting from the absence of fission products.

A comparative summary of the operational characteristics of the three fissile fuel producers described above is shown in Table 2-5. The fissile fuel producers shown in this table can be considered to be neutronically optimized in that they have resulted from more than 100 separate transport calculations which are described in Ref. 8. The neutronics calculations were performed with the TART Monte Carlo Code⁹ and cross sections from the Evaluated Nuclear Data Library at Lawrence Livermore Laboratory.¹⁰ The comparative summary shows that depleted uranium hybrids maximize energy multiplication and fissile production per unit of fusion energy whereas thorium fast-fission concepts exhibit the best performance on the basis of fissile production per unit of thermal energy. Therefore, uranium-fueled fissile producers would appear to be more attractive if the laser- and fusion-associated costs dominate whereas thorium-fueled fast-fission hybrids would be more attractive if the blanket and heat-removal costs dominate.

Figure 2-6 gives the production capabilities of laser-driven fissile-fuel producers and fission breeder reactors along with the consumption requirements of thermal burner and convertor reactors. (Reactors are considered "burners" for values of $C < 0.8$, conver-

Table 2-5. Comparative summary of fissile-fuel-producing blankets

Operational characteristics	Thorium, non-fission	Thorium, fast fission	Depleted uranium, fast fission
Blanket energy multiplication	1.3	2.3	10.0
Tritium breeding ratio	>1.0	>1.0	> 1.0
Fissile production in kg per MW-yr of fusion energy	1.3	3.5	9.0
Fissile production in kg per MW-yr of blanket thermal energy	1.1	1.7	1.1
Maximum power density in fuel ^a (W/cm ²)	12.7	25.3	135.0
Maximum fuel burnup ^a (atom %/yr)	≈0.0	0.07	0.30
Fusion energy gain ($Q\eta_L$) for electrical breakeven	2.30	1.40	0.35

^aNormalized to a first-wall fusion neutron flux of 1 MW/m².

Fig. 2-6. The production and consumption of fissile fuel.

tors for $0.8 < C < 1.0$, and breeders for $C \geq 1.0$ where C , the conversion ratio, is defined as the ratio of fissile atoms produced to fissile atoms destroyed.) The left portion of Fig. 2-6 displays the net fissile production capabilities of both fusion and fission breeders normalized to a unit of thermal energy. On this basis, thorium fast-fission hybrids outperform uranium-fueled concepts. The most attractive feature of fusion breeders relative to fission breeders is that fusion breeders produce approximately 10 times more fissile material per unit production of thermal energy.

The fissile consumption requirements of present burner and advanced convertor reactors are presented in the right side of this figure. It is interesting to match the consumption requirements of the fissile users to the production capabilities of the breeders. Here we see that a thorium fast-fission hybrid provides enough fissile material to fuel 23 HTGR's of equivalent thermal power while a depleted uranium-fueled hybrid produces enough fissile material to fuel 8 LWR's of equivalent thermal power. Conversely, fast breeder reactors do not produce enough excess fissile material to fuel even one LWR of equivalent thermal power. (It is well known that the excess fissile material produced in a FBR is best used to fuel another FBR.)

A scenario with laser-fusion driven hybrids providing fissile fuel for thermal fission reactors appears to be a viable alternative to the present nuclear power R&D strategy which is based on fission breeders providing adequate quantities of fissile fuel. This hybrid alternative would become increasingly attractive if fission breeders cost much more than fissile burners.

Hybrids That Produce Electrical Power and Fissile Fuel

The energy multiplication characteristics of all the hybrid blankets that have been neutronically analyzed are summarized in Fig. 2-7¹¹ which gives the fusion energy gain requirements for laser fusion power plants with various percentages of recirculating power as a function of blanket energy multiplication. The curves in Fig. 2-7 were generated from the expression for plant recirculating power with thermal efficiency set to 35%. Figure 2-7 dramatically points out the order-of-magnitude decreases that take place in required fusion energy gain as fission blankets with higher energy multiplication are employed. In Fig. 2-6 we saw that thorium-fueled hybrids outperformed uranium-fueled hybrids on the basis of fissile fuel produced per unit of thermal energy. Figure 2-7 shows that uranium-fueled hybrids can produce fissile fuel in an energy breakeven mode with fusion energy gains that are 2 to 6 times lower than those required for thorium blankets.

Power-producing hybrids are defined as facilities which operate with recirculating power less than 25%. Blanket designs other than thorium and depleted-uranium fueled concepts become attractive when we consider hybrid facilities that produce electrical power as well as fissile fuel. These include plutonium-enriched fast-fission blankets and thermal-fission blankets. In Table 2-6, neutronically optimized versions of these two power-producing hybrids are compared to the previously shown depleted-uranium fast-fission blanket which is now being operated at a high enough fusion

Fig. 2-7. Laser fusion core gain requirements for hybrid fusion-fission systems.

Table 2-6. Comparative summary of power-producing fusion-fission hybrids

Operational characteristics	Depleted uranium, fast fission	Natural uranium, thermal fission	Plutonium-enriched, fast fission
Blanket energy multiplication	10.0	25.0	80.0
Tritium breeding ratio	>1.0	>1.0	>1.0
Net fissile production in kg per MW-yr of fusion energy	9.0	4.6	20.1
Net fissile production in kg per MW-yr of blanket thermal energy	1.1	0.22	0.31
Maximum power density in fuel ^a (W/cm ³)	150.0	230.0	810.0
Maximum fuel burnup ^a (atom%/yr)	0.30	0.77	2.55
Fusion energy gain ($\eta_L Q$) for 25% recirculating power	1.39	0.56	0.18
Fusion energy gain ($\eta_L Q$) for 10% recirculating power	3.5	1.4	0.44

^aNormalized to a first-wall fusion neutron flux of 1 MW/m².

energy gain to be a power producer. Plutonium-enriched fast-fission blankets could best be characterized as source-driven fast breeder reactors (LMFBR or GCFBR). They exhibit the largest energy multiplication and fissile production per unit of fusion energy. The curves in Fig. 2-7 indicate that plutonium-enriched hybrids have the potential to produce electrical power with the lowest fusion energy gains. At first glance these neutronic characteristics make a plutonium-enriched blanket concept look very attractive. However, the large inventories of fissile material resulting from plutonium enrichments in the neighborhood of 10% make it necessary to operate this blanket at much higher power densities with effective neutron multiplication factors (k_{eff}) very close to unity, thereby negating some of the inherent safety features of hybrid systems.

Thermal-fissioning hybrid concepts exhibit the largest energy multiplications with the lowest fissile-

material inventories. In fact, the thermal fission blanket presented in Table 2-6 provides an energy multiplication factor of 25 when it is fueled only with natural uranium. In comparing thermal and depleted-uranium fast-fission hybrids as power producers, Fig. 2-7 shows that thermal fission blankets can efficiently produce power with fusion energy gains that are 2 to 4 times lower than those required for fast-fission blankets. However, the comparative summary (Table 2-6) indicates that the enhanced energy multiplication is gained at the expense of reduced fissile production and higher power density requirements in larger, more complex blankets. Consequently, a final ranking of these two hybrid concepts must await studies which treat the engineering and economic requirements, as well as the neutronic aspects.

J. Maniscalco

2.2.3 FIRST-WALL STUDIES

Introduction

The first wall of a laser fusion reactor separates the microexplosion cavity from the remainder of the reactor. This wall protects the reactor from the hostile microexplosion environment while allowing the pellet injector, laser beams and vacuum system access to the microexplosion cavity. Since about 20% of the microexplosion energy is deposited in a layer of the first wall less than 50- μ m thick within about 1 μ s, the first-wall surface is subjected to very high temperatures and stresses roughly proportional to the inverse of the first-wall radius squared. Also, the cost of the reactor and blanket varies as the first-wall radius squared, and the lifetime of the power supplies and laser optics varies as the inverse of the first-wall radius squared. Thus, the importance of the first-wall design to the design of an economically and technologically viable fusion reactor system cannot be over-emphasized. With this in mind, we have initiated a program to study the effects of the rapid deposition of the microexplosion debris energy in the first wall of a laser fusion reactor.

Surface conditions in a conceptual laser fusion reactor are dependent on the first-wall materials, the energy flux, and the partition of the energy from the various sources of pellet irradiation and burn as shown in Fig. 2-8. The materials are important in terms of energy attenuation coefficients, strength, fatigue lifetime, equation of state, and thermal properties. The partition of energy from pellet irradiation and burn is a function of the ratio of the thermonuclear power to laser output

energy Q , pellet mass, and the pR of the pellet compression.

The first-wall design in a laser fusion reactor will be determined from the allowable surface conditions at the first wall, which in turn are determined by the lifetime of the first-wall materials as well as the pumping power required to evacuate the microexplosion chamber to a pressure of 0.1 Torr prior to each explosion. In effect, the first-wall design will control the design of the entire reactor system.

Conceptual Laser Fusion Reactor Designs

Several conceptual designs have been proposed for pure laser fusion reactors to cope with the first-wall problems typical of inertially confined fusion reactors. The basic difference in the conceptual designs is in the design of the first wall. Three different approaches to the first-wall design have been proposed: dry wall, wet wall, and magnetically-shielded wall. These three approaches are distinguished by the way the first wall interfaces with the laser-pellet interaction/burn debris impinging on its surface.

The dry wall concept consists of using an unprotected wall between the blanket and microexplosion chamber. This wall may be fabricated from niobium, stainless steel, or other metal, or from a graphite or carbon curtain over a metal first wall.¹² The advantage of a metal first wall is that fabrication is relatively

Fig. 2-8. Effects of the laser and pellet characteristics on fusion reactor first-wall lifetime and vacuum pumping requirements.

simple and the vapor pressure is low so that the vacuum system power requirements are small. The disadvantage of the metal first wall is that the helium ash from the thermonuclear burn that is deposited in the first wall does not diffuse into the vacuum chamber but tends to concentrate until bubbles form, fracturing and spalling

the first-surface materials. The disadvantage of the graphite curtain over the first surface is that the hydrogen isotope debris reacts with the carbon, forming methane and acetylene¹³; these are more difficult to vacuum pump and recover tritium from than is inorganic pellet debris.

The wet wall concept features a thin liquid lithium layer over a niobium first wall.^{1,2} The lithium will protect the niobium from the soft x rays as well as the charged particle debris. A disadvantage of the wet wall concept is the large vacuum pumping power required due to the high vapor pressure of lithium. Another disadvantage is the complex first-wall design which must allow the coolant to migrate from the reservoir to cover the first-wall liners after each microexplosion.

The magnetically shielded wall concept uses a solenoid surrounding a lithium blanket to divert the pellet debris from a dry niobium first wall.³⁻¹⁴ The energy of the pellet debris is deposited in regions outside the microexplosion chamber. Note that in principle the energy of the pellet debris can be directly converted to electricity by exhausting the debris into an MHD duct. In general, the magnetically shielded first wall combined with direct conversion of the pellet debris is more of interest when the bulk of the energy from the laser/pellet interaction and thermonuclear burn is in the short-range charged particle debris (such as very low or very high gain DT reactions) or advanced fuel cycles such as D³He or p¹¹B. The magnetically shielded first-wall concept does not protect the first wall from the photon or soft x-ray flash during the microexplosion process. The disadvantage of a magnetically shielded first wall is that if a liquid metal is selected as a coolant, the pumping power required to move the liquid metal will increase if movement occurs across magnetic field lines. A second disadvantage of the magnetically shielded first wall is that the blanket modules and first wall are more inaccessible than in the dry-wall concept.

Energy Deposition in Laser Fusion Reactor First Wall

The temperature rise and stresses in the first wall are a function of the energy deposition of the various laser/pellet interaction and burn products in the first wall. The present models used to estimate the energy deposition in the first wall are described below.

The reflected laser light from the pellet is deposited in the first wall. The first wall will reflect a portion of the photon energy. Thus the photon energy will be deposited in a series of pulses, each with a diminished amplitude, which in effect reduces the temperature rise in the first wall due to the photons.

The first-pulse energy density of the photon deposition in the first wall is

$$q''(x) = 2 \left(\frac{r E_L}{\lambda R^2} \right) \exp(-\Sigma x),$$

where R is the first wall radius, λ is the wavelength of the laser light, E_L is the laser energy into the reactor

chamber, and r is the reflectivity of the pellet to the incident laser light. The photon energy attenuation coefficient Σ can be estimated using classical relationships for the propagation of electromagnetic radiation in homogeneous, isotropic conducting media at rest.¹⁵

The total x-ray energy from a typical reactor microexplosion is about 1% of the thermonuclear yield. From a typical x-ray spectrum, the energy deposition as a function of depth for several 0.7-mm-thick first-wall liner designs is shown in Fig. 2-9 for a 100-MJ-yield microexplosion with a first-wall radius of 1 m. The results scale to different microexplosion energy yields and first-wall radii by the ratio of the microexplosion energy fluence. The fraction of the incident x-ray energy flux that escapes through the liner is less than 10% for various liner material combinations, except for the solid graphite liner, which transmits about 60% of the incident x-ray energy flux. The bulk of the x rays

Fig. 2-9. Energy deposition as a function of depth for several first-wall liner designs.

are produced during the thermonuclear burn which is of a typical time duration of 10 ps.

The pellet-blast debris from a laser fusion reaction consists of tritons, alphas, and deuterons as well as residual products from the previous microexplosion, including some first-wall material. For a Maxwellian energy distribution of a given species of debris, assuming that these particles deposit their energy E uniformly over the range $P(E)$ in the first wall and that the range of a given species of debris is proportional to their energies such that $P_i(E_i) = \alpha_i E_i$, then the energy deposition at a depth x in the first wall is an integrated Maxwellian distribution as shown in Fig. 2-10. The total energy distribution in the first wall is given by summing the above distribution over all species. The pulse time over which 90% of the debris energy arrives is

$$\tau = 0.01R(M_i/\epsilon_T)^{1/2} \text{ s,}$$

where M_i is the mass of the pellet in grams, and ϵ_T is the energy into the mass in J. Note that the above expression for the pulse time neglects the lower 5% of the debris energy as well as 5% of the high energy tails.

The first wall neutron fluence per DT microexplosion is

$$\dot{n} = 2.8 \times 10^{13} \left(\frac{QE_L}{K^2} \right) \frac{n}{m^2} \text{ pulse,}$$

where E_L is the laser energy in kJ, Q is the pellet gain, and R is the first-wall radius in m. Since the neutrons from a laser fusion reactor arrive in a 10-ps pulse, the damage mechanisms for laser fusion reactors may be

Fig. 2-10. Charged particle energy in first wall. R =first wall radius; M_i =molecular weight of debris i ; m_i =mass of debris i ; M_T =mass of pellet; E_T =pellet energy; A_0 =Avogadro's number; α_i =range-energy constant for species i in first-wall material; $q_i'''(x)$ =energy deposition of species i at position x in first wall.

different from magnetically confined fusion reactors with the same time-averaged neutron flux.

Effects of Energy Deposition Time on Temperature and Stress

Assume over the pulse time τ that

$$q_i'''(x) = q_{i0}''' \exp[-\alpha x],$$

where q_{i0} is the energy deposition in the surface layer of the first wall and α is the energy attenuation coefficient through the first wall. Define the characteristic thermal time of the energy deposition in the first wall as

$$\tau_T = [\alpha^2 \alpha]^{-1},$$

where α is the thermal diffusivity of the first-wall material. Also define the characteristic mechanical time of the energy deposition in the first wall as

$$\tau_m = [\alpha c]^{-1},$$

where c is the wave velocity in the first-wall material. Typical energy attenuation coefficients, pulse times, and thermal and mechanical times are shown in Table 2-7 for fusion reaction products. The x-ray energy attenuation coefficient given is due primarily to the soft portion of the x-ray spectrum. For the purpose of this study, the alpha particles are assumed to be part of the charged particle debris. For low ρR pellet burns, the alpha particle energies will be deposited in the first wall over time comparable to the burn time of the pellet since the alpha energy will not be greatly attenuated by the pellet. For a pellet with a ρR of 1, only about 5 to 10% of the alpha particles have an energy significantly greater than the average pellet-debris energy. The neutron energy deposition in the first wall is small, but the data given in Table 2-7 is relevant to the interaction of the neutrons with the blanket material.

A quantitative comparison of the various times from Table 2-7 is shown in Table 2-8. Also shown in Table 2-8 is the relative surface-layer energy deposition, which is simply the surface flux times the energy attenuation coefficient.

The temperature rise and peak stress for the x rays and neutrons can be estimated using very simple models since the pulse time is short compared to the characteristic time. The simple model for the temperature rise is given by

$$\Delta T(x) = \frac{q_i'''(x)}{\rho C_v}$$

and for the peak pressure by

$$\Delta p(x) = \Gamma q'''(x),$$

where Γ is the Grüneisen constant, $q'''(x)$ is the energy deposition at position x in the first wall, and ρ and C_v are the density and specific heat of the first-wall material, respectively. The use of the simple models for the photon stress and temperature will result in overestimates of both the stress and temperature since there will be some stress relief and diffusion of heat during the photon pulse time. The stress due to the charged-particle energy deposition can be determined by quasi-static thermoelastic theory.¹⁶ The largest surface-layer energy deposition is from the charged particles. However, high first-wall surface-energy deposition may result from the laser photons reflected from the pellet.

Conclusion

The surface problems in an inertially confined fusion reactor are different from those in a magnetically confined fusion reactor with the same time-averaged first-wall neutron energy flux. These differences are

due to the arrival of the charged particles, x rays, and neutrons in extremely short-time pulses in the low duty cycle inertially confined laser fusion reactor as opposed to the long-time pulse in the high duty cycle typical of the magnetically confined fusion reactions.

Because of the complexity of the solution of the laser/pellet interaction and burn, as well as the interaction of photons, x rays, and burn debris with the first wall, the models presented here for the energy deposition in the first wall are only simple estimates. The response of the first wall to the short pulse times will require obtaining better equation-of-state data for some proposed first-wall materials, as well as the solutions to the mathematical behavior of continuous media under dynamic conditions. We propose to develop models which can couple the output spectra from pellet-burn codes such as LASNEX¹⁷ with coupled radiation-hydrodynamic codes such as CHART D¹⁸ to assist in evaluating the tradeoff between laser/pellet designs and first-wall designs for conceptual laser fusion reactor studies. Finally, the analysis and lifetime of the first wall will need to be verified under experimental conditions using a laser fusion research facility.^{19,20}

J. Hovingh

Table 2-7. Energy attenuation factors and the pulse time and mechanical and thermal characteristic times for laser fusion reaction products in typical first-wall materials

	Photons	X rays	Charged particles	Neutrons
σ, m^{-1}	10^8	10^5-10^6	10^5-10^6	1-10
τ, s	10^{-10}	10^{-11}	10^{-6}	10^{-11}
τ_m, s	10^{-11}	$10^{-9}-10^{-8}$	$10^{-9}-10^{-8}$	$10^{-4}-10^{-3}$
τ_T, s	10^{-11}	$10^{-7}-10^{-5}$	$10^{-7}-10^{-5}$	10^3-10^5

Table 2-8. Relative comparison of the surface layer energy deposition and qualitative comparisons of pulse, mechanical and thermal characteristic times of burn reaction products

	Surface energy deposition	Times
Photons	$3 \times 10^7 (r/Q)^a$	$\tau \approx \tau_T \approx \tau_m$
X rays	5×10^3	$\tau < \tau_m \ll \tau_T$
Charged particles	$5 \times 10^5 [0.2 + (1-r)/Q]$	$\tau_m \ll \tau_T \approx \tau$
Neutrons	1	$\tau \ll \tau_m \ll \tau_T$

^a r = pellet reflectivity to incident laser light. Q = thermonuclear gain of the pellet.

2.3 LIS Systems Studies

2.3.1 URANIUM LASER ISOTOPE SEPARATION

One of the primary objectives of our laser isotope separation (LIS) systems studies effort is to provide insight into the eventual value and relative merits of particular lines of research. To accomplish this end, an extensive modeling capability is continually being generated to evaluate general LIS processes from a component, system, plant, and economic viewpoint. This modeling capability, which has been applied predominantly to uranium atomic vapor processes since the publication of our last annual report, has resulted in the following preliminary conclusions.

- Laser enrichment of uranium can have a significant capital outlay advantage over conventional techniques. The estimated capital cost of a 9 million separative work unit (SWU) commercial plant is less than \$1 billion, representing a factor of 3 to 5 reduction in initial capital investment when compared to gas centrifuge and gaseous diffusion.

- Preliminary economic studies of uranium metal vapor LIS processes indicate that enrichment costs can be a factor of two smaller than for conventional approaches. Assuming seven new 9 million SWU/yr units between 1988 and 2000, LIS results in a separation work cost savings of over \$15 billion.

- LIS can be designed to require only 10% of the electric power needs of gaseous diffusion, which makes it consistent with national energy independence goals.

- LIS should be economic in much smaller plant sizes than conventional approaches. This results in siting flexibility, broad multiproject competition within private industries, and close matching between plant construction and demand.

- LIS lends itself to modular construction, which means the lead time for expansion of capacity is minimal, thus allowing a close matching between supply expansion and demand.

- Due to the projected lower unit cost of separative work, the economic "tails" assay for LIS will probably be less than 0.2% ^{235}U with the result that substantially less of the valuable ^{235}U will be rejected, thereby conserving our uranium resources.

- Reprocessed uranium typically has a high concentration of ^{236}U which is difficult to separate from ^{235}U by conventional techniques. LIS has the unique potential of removing the ^{235}U from ^{236}U as part of its normal operating procedure, thus resulting in little or no enrichment penalties for reprocessed fuel.

- The selectivity inherent in a LIS process combined with its modular construction presents the possi-

bility of separating ^{232}U from ^{233}U . This would strongly impact the thorium uranium fuel cycle discussed for high temperature gas (HTGR), light water breeder (LWBR), and Canadian deuterium reactor (CANDU).

- Unlike conventional mass separation techniques in existence since the 1940's, the technology developed for LIS of uranium will create new applications in "quantum engineering." Unique quantum characteristics could be utilized to selectively activate, identify, separate, and modify atoms and molecules in new laser-driven processes having application to waste cleanup, photosynthesis, catalysis, and biological modification.

Table 2-9 specifically summarizes the key points of comparison among gaseous diffusion, gas centrifuge, and LIS for large scale uranium enrichment plants required for supply of LWR grade material. We will discuss the atomic vapor LIS baseline designs and the economic analysis that resulted in these preliminary conclusions later in this section.

Although we envision a technically feasible process for which an analysis of process economics appears very attractive, within the broad category of LIS there are a large number of options, many of which could be more promising than the baseline atomic vapor approach discussed in our modeling. Also, within the subset of atomic vapor processes there are a great number of tradeoff options available for each system, causing us to believe that great advancements can be made over any baseline design on which preliminary comparisons are made. However, critical time constraints will never allow us to delay development of a process until the ideal set of conditions can be achieved. The background and motivation section of the detailed LIS discussion makes it obvious that there exists a significant present value to commercializing a uranium LIS process no later than the early 1990's.

Process Models

The modeling capability essential for evaluating alternative LIS processes and determining the economic feasibility of large scale plant operation starts with a system concept. From this concept each necessary component can be identified and characterized. Operating parameters can be traded off and geometries established. These geometries and optimized operating characteristics can then be used to formulate plant concepts amenable to economic modeling.

Table 2-9. Comparative summary of enrichment processes

	Gaseous diffusion	Gas centrifuge	Laser isotope separation
Status	Highly reliable	Commercial operation not demonstrated	Major R&D required including component scaleup
Technology base	Conventional speed rotating machinery and materials	High speed rotating machinery and materials	Laser/electrooptical and materials
Capital outlay	High (~ \$3.3 billion/plant at 9,000,000 SWU/yr)	High (~ \$3.3 billion/plant at 9,000,000 SWU/yr)	Low (less than \$1 billion plant at 9,000,000 SWU/yr)
Power consumption	High (~2,400 MWe/plant at 9,000,000 SWU/yr)	Low (~250 MWe/plant at 9,000,000 SWU/yr)	Low (~200-300 MWe/plant at 9,000,000 SWU/yr)
"Economies of scale"	Not economic on small scale -- 9,000,000 SWU/yr minimum plant size	Economic on smaller scale than gaseous diffusion	Economic on smaller scale than gaseous diffusion

For atomic vapor ionization processes some of the key process elements in a systems concept are:²¹

- Feed preparation
- Feed distribution
- Vapor source
- Reaction region
- Flow channel
- Ion extractor
- Collector
- Lasers
- Optics
- Controls

To properly evaluate the interaction of each of these elements, the characteristics identified in Table 2-10 must be well understood.

The primary goal of any system model is to determine the most desirable operating regime for a particular system concept. Note that it is the complete system concept that is optimized, not necessarily each individual component. To achieve this goal, tradeoffs must be made to determine the physically allowable operating regime of the required components as well as the economically allowable regime. Some of the component parameters that impact the economic evaluation of a process are component lifetime, efficiency, and costs (capital, replacement and repair). Some of the systems parameters that impact the economic evaluation are atom utilization, photon utilization, throughput, and assay (product and tails).

An example of the use of systems modeling to determine process sensitivity to various parameters in atomic vapor uranium processes is shown in Figs. 2-11

and 2-12 for the source and Fig. 2-13 for the lasers.

For processes utilizing thermal sources, the radiative energy loss from the high temperature oven will be a significant fraction of the total energy budget. Note in Fig. 2-11 that the fractional energy loss decreases with temperature since the atom generation rate rises faster than the radiative loss rate. However, as shown in Fig. 2-12, at high temperatures population of the low-lying uranium energy states becomes significant and ultimately will represent a reduction in atom utilization or loss of selectivity.²² Oven lifetime also becomes a limiting condition at temperatures beyond 3000 K. At temperatures between 2600 K and 2800 K, only about 50% of the uranium atoms are in the ground energy state (0 cm^{-1}) and about 27% of the atoms are in the 620 cm^{-1} energy states. Preliminary cost studies indicate that as a minimum both the 0 cm^{-1} and 620 cm^{-1} states must be made accessible for economic IIS operation. This results because the number of atoms in accessible states has a dramatic influence on the atom utilization, which in turn significantly affects the process tails assay and cost. Other factors impacting atom utilization, defined as the number of ^{235}U atoms ionized divided by the number of ^{235}U atoms exiting the oven, are laser saturation intensities and flow geometry. Note that the total oven energy loss per ^{235}U atom collected is the oven energy loss per ^{235}U atom exiting the oven divided by the atom utilization and the collector efficiency. When these losses are considered, it becomes clear that temperatures on the order of 2700 K are required to obtain an advantage over proposed gas centrifuge energy costs.

Table 2-10. Component characteristics required for systems modeling

General	Feed preparation and distribution	Vapor source	Reaction region/ flow channel	Ion extractor
Lifetime	Feed material	Flux (x,y,z,t)	Contaminants	Charge exchange
Efficiency	Form of feed	Velocity (x,y,z,SD)	Spectroscopy/ kinetics	Elastic scattering
(power consumption)	Feed rate	Thermal ions		Product assay
Costs	Detector requirements	Doppler effects	a) Laser lineshape (x,y,z,v)	a) Thermal ions (TI)
a) Capital		Thermal state population	b) Cross sections	b) TI suppression
a) Replacement		Thermal environment	c) Wavelengths	c) ^{238}U absorption
c) Labor		Spatial limitations	d) Lifetimes	d) Neutrals
		Design support	e) Branching ratios	Failure mechanisms
			f) Hyperfine structure	Extractor efficiency
			g) Isotope shifts	
			h) Coherence effects	
			i) Field effects	
			Geometry	
Collector	Lasers	Optics	Controls	
Sticking coefficient	Line shape	Enhancement	Feed rate	
Product form	a) Temporal	a) Gains	Laser pulse	
Tails form	b) Frequency	b) Losses	synchronization	
Beam blowup	c) Spatial	Line overlap	Laser line center	
Collection efficiency (collected/available)	Energy variation	Line shape	Alignment	
	Pulse duration	Beam quality	Diagnostics	
	Jitter	Alignment	Computer	
	Beam quality	Environmental control		
	Pulse rate	Photon efficiency		
	Line center variance			
	Environmental control			
	a) Spatial jitter			
	b) Temperature			
	c) Cleanliness			
	Power			

For lasers, the set of curves shown in Fig. 2-13 illustrates energy required to separate an atom versus energy necessary to generate a photon of arbitrary frequency. The tradeoff parameters of interest are the laser efficiency (photon energy out divided by electrical power out of the wall), photon utilization efficiency (^{235}U ions formed divided by the number of photons required), and atom collection efficiency (^{235}U atoms collected divided by ^{235}U ions formed). Note that for a three-step process utilizing visible photons, the energy loss per generated photon would be about 2 KeV per laser for 0.1% efficient lasers. Thus an energy per

separated atom on the order of 60 KeV is possible with reasonable photon utilization and atom collection efficiencies ($\eta_o, \eta_p \sim 10\%$). The laser energy consumption would approach that of a gas centrifuge plant only when the product of the laser efficiency, photon utilization efficiency and atom collection efficiency, becomes less than 2×10^{-5} . From these energy considerations as well as power supply capital cost issues, it soon becomes clear that uranium atomic vapor LIS processes require laser efficiencies not less than 0.1%, to be economically attractive.²³

The atomic vapor approach has gained particular

Fig. 2-11. Radiative energy loss from oven.

Fig. 2-12. Uranium level populations in high temperature lasers.

Fig. 2-13. Separation energy vs photon utilization.

interest for uranium enrichment partly because of the availability of states relatively uniformly distributed from ground to continuum.

Some of the possible atomic vapor schemes modeled over the past year are shown in Fig. 2-14. In all processes both the ground (0 cm^{-1}) and the thermally populated (620 cm^{-1}) states are used for the isotopically selective excitation step. Scheme I requires three excitation steps using orange-red lasers to bring the atom close to the continuum ($E \sim 6.2\text{ eV}$) where field ionization or ir-laser irradiation can then kick it into the continuum producing the desired ionization. Scheme II eliminates the "kicker" and uses the third step to go directly into the continuum. Scheme III is a two-step-plus-kicker concept that requires blue-ultraviolet lasers to approach the continuum. Again ir-laser irradiation, field ionization, or some other low energy transfer procedure can be used as the kicker to achieve ionization. Scheme IV is a two-step process using blue-uv lasers, with the last step going directly into an auto-ionization level. This was the process used in the Morehouse experiment to successfully enrich macroscopic quantities of uranium.²⁴

The first and one of the most critical steps in the evaluation of a particular process is an analysis of the reaction region. This requires a complete understanding of spectroscopy data such as cross sections, hyperfine structure, line widths, isotope shifts, lifetimes, and decay channel branching ratios.

Once the spectroscopy data for a process is determined a computer program, AVIS (Atomic Vapor Isotope Separation), solves the necessary rate equations to determine ion production rates from atomic vapor

LIS schemes. This program is based on a finite-difference technique that analyzes state populations in a differential volume element within the irradiation/separation zone. Typical input consists of the oven temperature, slit geometry, vapor density, vapor velocity, spectroscopy data, and various laser parameters. The model output consists of ^{235}U mass yields, utilization ratios, and required laser intensities along with other housekeeping data. The program has been used to successfully model experimental separation systems such as Morehouse. It has also been useful in evaluating the impact of various phenomena and physical parameters such as spectral line shape and bandwidth, laser extinction over the optical path, ^{238}U absorption, charge exchange, and amplified spontaneous emission.

We have developed a procedure for optimizing photon utilization which is a first-cut analysis technique useful in determining approximate laser operating regimes. However, when plant concepts are formulated and economic analysis is done, optimization tradeoffs too, lengthy to discuss in this report must be performed.^{25,26} Specifically, when particular geometries and operating conditions are established, the final laser intensity optimization requires several computer runs over a variety of laser intensities. Other factors must be included, such as power broadening effects, geometric constraints, optical component limitations, the cost of lasers as a function of power, etc.

The geometry of a stage used in a plant concept is determined by analyzing the parameter interactions that result in reaction zone spatial constraints. Those scaling limitations specific to processes using continuous wave lasers were discussed in detail in the last annual report. To summarize, the maximum height of the irradiation zone in the vapor dimension is constrained by decay rates from the desired excited atomic states to undesired metastable levels, and the minimum height is determined by the laser beam divergence; the maximum slit width is constrained by ion charge exchange, the minimum width is determined by source tolerances, throughput requirements and beam divergence; the maximum slit length is constrained by oven fabrication difficulties, laser alignment, beam divergence, intensity reduction, and amplified spontaneous emission, whereas the minimum length is determined by photon utilization and throughput requirements.

Some of the design determinants for pulsed laser processes are shown in Fig. 2-15.^{23,25} Beyond one slit width from an effusive source, there is an approximate $1/r$ drop in atomic number density due to vapor dispersion. The implications this has on required laser energy, atom utilization, photon utilization, and extractor geometries result in a maximum limit to the height of the irradiation zone in the vapor dimension. The minimum height is determined by throughput require-

Fig. 2-14. Schemes for uranium selection photoionization/field ionization.

Fig. 2-15. Interaction region design determinants.

ments and the maximum laser repetition rates economically achievable. The maximum slit width is constrained by charge and collisional exchange losses as well as optical window size limitations. The minimum slit width is determined by throughput, oven tolerances, laser pulse repetition rates, beam divergence, and laser beam overlap. The maximum source length is constrained by laser beam divergence, superfluorescence, oven tolerances, laser line overlap, and photon absorption, whereas the minimum length is determined by the economics of photon utilization and throughput requirements.

All of these tradeoffs went into the stage designs investigated in past studies.²³

LIS Plant

Plant Concept. The economics of a particular process can best be assessed in the framework of a plant concept. In a conventional cascade separation, elements are grouped in series and in parallel. The elements operating in parallel on material of the same

mole fraction form a "stage." In a continuous process, enriched and depleted fractions from different stages are combined and passed through further stages in series for enrichment or depletion. In LIS, a stage can be defined in the same way, but the grouping of stages will differ from conventional methods. Because the uranium can be enriched from natural (0.71%) to reactor grade (about 3%) in one stage, the enriched product need not be processed further except for a possible dilution step. The tails, however, may have to be processed through several stages in series where the number required is a function of the atom utilization (the number of ²³⁵U atoms collected divided by the number of ²³⁵U atoms leaving the source) and the desired tails assay. Such a collection of stages is called a "module."

The module is a grouping of stages which can be conceived of as a miniplant, because the feed, product, and tails assay for a module is the same as for a plant. The number of modules required for a complete plant is a function of the size of the plant and the operating stage characteristics.

Table 2-11. Baseline capital cost assumptions

	I Continuous operation, continuous wave mode	II Batch operation, continuous wave mode	III Continuous operation, pulsed mode	IV Batch operation, pulsed mode
Vacuum pumps	\$ 2,600/stage	\$2,600/stage	\$ 2,600/stage	\$2,600/stage
Visible laser	\$ 1,800/W	\$1,800/W	\$ 1,000/W	\$1,000/W
Visible laser, power supply	\$0.14/W electrical	\$0.14/W electrical	\$0.14/W electrical	\$0.14/W electrical
Visible laser modulator	0	0	\$0.30/W electrical	\$0.30/W electrical
CO ₂ laser and power supply	\$5/W	\$5/W	\$50/W	\$50/W
Interstage materials Handling	0	\$0.43/kg of tails	0	\$0.43/kg of tails
Blending facility	\$0.60/kg of product ^a	\$0.60/kg of product ^a	\$0.60/kg of product ^a	\$0.60/kg of product ^a

^aProduct is 3.2% enriched uranium.

Table 2-12. Baseline capital cost assumptions for component life, replacement time, and cost

	Lifetime (hr)	Replacement time (hr)	Cost (\$)
Items used in either pulse or cw operation			
Visible laser, pump cavity	4,000	2	300/W
CO ₂ laser, EB gun	4,000	4	1/W
Items used in pulse operation only			
Visible laser modulator	1,000	4	0.10/W of visible laser output

Based on conservative conceptual module characteristics, first-order cost assumptions were made to allow preliminary costing of LIS plants. Battelle Columbus, under contract to LLL, investigated these assumptions and worked with LLL to generate a realistic cost model.²⁷ Some baseline assumptions used in this model are given in Tables 2-11 through 2-13. In some cases current costs and performance of lasers were not used because it is reasonable to expect future developments to substantially improve their performance and lower their price. Also note that replacement costs and component lifetimes are necessary in determining module down time, maintenance manpower requirements, and equipment repair costs. These factors in

Table 2-13. Baseline cost assumptions

Interest rate	9%
Construction period	4.66 yr
Start-up period	4 mo
Cost of capital	12.2%
Visible laser efficiency	0.001
CO ₂ laser efficiency	0.1
Power cost	\$0.015/kWh
Labor cost	\$7 per man-hr
Number of operators per stage	2/3 for type 1 operation 1/2 for type 2 operation

turn have a significant impact on LIS plant yearly operating costs. Because much of the technology assumed in the cost analysis is in its infancy, we are constantly re-evaluating realistic values to use in our cost assumptions.

Table 2-14 shows a typical cost breakdown for a

pulsed laser plant. A complete breakdown of the critical capital cost components can be seen in the capital cost summary. Notice that the direct installed process equipment represents less than 40% of the total capital required.

In the capital cost summary, the project indirect

Table 2-14. LLL/Battelle cost model for pulsed laser base case

Case III: Continuous oper (type 2), pulsed wave mode – N photon process I, cw 120 modules, 3 stages per module, 9.00 million SWU plant.

Capital cost summary		
Item		Cost (\$1,000,000)
Land		0.3
Process building		16.2
Site preparation		1.3
Direct installed process equipment		347.4
Project indirects		104.2
Plant support facilities		90.4
Home office costs and fee		108.4
Total plant cost		668.2
Other capital requirements		
Environmental impact statement	6.0	
Interest during construction	140.1	
Start-up cost	58.7	
Working capital	9.1	
Total for others		213.9
Total capital required		882.1
Operating cost summary		
Item		Cost (\$1,000,000)
Utilities		38.0
Process labor		14.9
Repair and maintenance		92.2
Laboratory charge		3.0
Operating supplies		0.9
Administration and general plant overhead		10.3
Local taxes and insurance		16.7
Depreciation		65.7
Capital charges		107.6
Total operating cost		349.3
Cost per SWU =	\$38.8/SWU	
Operation summary		
Annual production of 3.2% enriched uranium		1916017.9 kg
Tails assay – 0.204% uranium		
Capacity factor – 89.6%		

category includes: sales and other taxes; freight, packing and insurance; labor burden and field supervision; temporary facilities; construction equipment, small tools, etc. The plant support facilities include such items as auxiliary buildings, water distribution, fire protection, raw material storage, electric main substation, fencing, electric distribution, etc. The home office costs include cost engineering, engineering, procurement, and other services. Also, the fee or profit is included.

Besides the operating cost summary given in Table 2-14, a more detailed component breakdown of capital costs, replacement costs, and power costs is given for cw processes in Fig. 2-16 and pulsed laser processes in Fig. 2-17. Information such as this is extremely useful in assessing the economic importance of a particular

component.

The dominant power consumption in an equilibrium atomic vapor LIS module comes from heating the oven and operating the lasers. For this analysis laser efficiencies of 0.1% for visible and 10% for CO₂ were assumed. The ratio of energy loss between the oven and laser is sensitive to the number of stages, oven temperature, laser efficiency, and photon utilization of the process. This particular set of module characteristics represents only one set of conditions.

Finally a comparison of LIS costs to costs of conventional processes is given in Fig. 2-18. Of course, there is considerable uncertainty in the projected costs for LIS. Gaseous diffusion costs are supported by over 30 years of design and operating experience, and centrifuge costs are based on 15 years of research and

Fig. 2-16. CW LIS cost breakdown: Battelle study.

Fig. 2-17. Pulsed LIS cost breakdown: Battelle study.

development experience. However, the LIS costs, though based only on scientific experiments and scoping studies, offer exciting potential for gain and justify an aggressive research and development program.

Again the LIS costs presented are based on low risk technology and conservative design assumptions. They were generated to test out the economic modeling

methodology. Other more attractive alternate plant concepts capable of substantial cost improvements are the subject of present engineering design and economic studies.

R. Davis

2.3.2 LIS ON OTHER ELEMENTS

Background

Isotopes of the same element exhibit a variety of distinguishing properties which can be beneficial or undesirable according to the application. Among these properties are neutron cross section, decay chain,

isotope half-life, electronic and molecular spectrum, mass, rate of chemical reaction, and phase transformation. It is in applications and processes where these properties make a difference that specific isotopes and, hence, isotope separation is required.

In recent years the use of isotopes has increased

Fig. 2-18. Separation work cost comparison: Battelle study—9 million SWU/yr. Costs are typically discussed in terms in \$/SWU. Separative work is a measure of the net increase in value when a given feed is separated into product and tails. Separative work is commonly measured in kg of uranium.

rapidly throughout the world both in the amount consumed and in the variety of applications that have been developed. There is every expectation for that trend to continue, especially as new technologies are developed which lower the cost of obtaining enriched isotopes. Recent experiments and cost projections indicate that laser isotope separation (LIS) may be such a technology. (See Sec. 2.3.1.) Because of this potential, a study was initiated to look at isotopes other than ^{235}U and ^{239}Pu to determine other applications in which LIS could be of significant value.

Nuclear Power Generation

By far the largest need and the largest market for isotope separation is connected with the generation of nuclear power, not only for producing fuel but also for producing moderating materials and fuel cladding, controlling radioactivity, limiting the activation of reactor components, and reprocessing fuel material. Other applications of isotopes may be of great value, but the primary market appears to lie in reactors.

Advanced Fuel for Breeder Reactors. In the past

two years there has been renewed interest in advanced fuels for LMFBRs. Designs using the present plutonium and uranium oxide fuels, (Pu, U)O₂, have fuel-doubling times of 25 to 30 years. By going to carbide or nitride fuels, it may be possible to achieve doubling times of less than 10 years. The economic benefit from now to the year 2020 of such a reduction is estimated to be \$15 billion.²⁸

Caspersson *et al.*²⁹ have compared the nuclear performance characteristics of heavy metal carbide and nitride fuels. They conclude that even though nitride fuels have a higher heavy metal density, a higher melting point, and only two-thirds the fission-induced swelling rate of the carbide fuels, nevertheless the carbide fuels are superior because of their substantially better neutron economy. The poorer neutron economy of nitrides is due almost entirely to the absorption cross section of ¹⁴N which comprises 99.635% of natural nitrogen. The other 0.365% is ¹⁵N which has an even lower neutron absorption cross section than carbon. By enriching ¹⁵N one could obtain a more optimum fuel. But for nitride fuels made of highly enriched ¹⁵N to be economically competitive, it would be necessary to decrease the cost of ¹⁵N by an order of magnitude or more from the present \$65 per gram.^{30,31}

Another reason for using highly enriched ¹⁵N instead of natural nitrogen for nitride fuels would be to reduce the amount of radioactive ¹⁴C that would otherwise be produced by an "n,p" reaction in ¹⁴N. By going to 98% enriched ¹⁵N, the ¹⁴C production from nitride fuels would be comparable to that from carbide fuels containing 1000 ppm nitrogen as an impurity.³¹

If highly enriched ¹⁵N nitrides fuels are used in LMFBRs, the demand for ¹⁵N would exceed 200 tons per year by the late 1990's. Since the potential demand for ¹⁵N is so great, further evaluation of this application is underway.

Cladding Material. Present light water reactors are limited in the efficiency with which they convert heat into electricity partly by the thermal properties of the Zircaloy cladding. It has been suggested by R.W.F. Gross that ⁵⁰Ti would make an improved cladding material.³² His major argument was that due to titanium's greater strength at elevated temperatures, less material would be required, enough that the ⁵⁰Ti cladding would be economically competitive even including separation costs. This may be overly optimistic in itself. However, the economic situation improves considerably with the possibility of operating reactors at higher temperatures due to titanium's higher strength and corrosion resistance at temperatures above 350° C.

Fabricated nuclear fuel costs are expected to reach 45¢ per million Btu (about 4.5 mills/kWh) within the next decade. At that cost, the fuel saved by operating

50° C higher in temperature is equivalent to a capital investment value of \$16 million per 1100 MWe reactor which can be applied to producing ⁵⁰Ti cladding (Fig. 2-19). If the ⁵⁰Ti cladding were as thick as the present Zircaloy cladding, each reactor would require 13 tonnes per full loading.

To support a nuclear reactor population of a thousand 1100-MWe plants at some time in the future, an in-core inventory of 13,000 tonnes would be needed. Building up to that level over 30 years would require an average production of over 800 tonnes per year, including initial cladding and one set of replacement cladding. Recycling would meet 90% of subsequent replacements. To realize a cost saving the separation costs would have to be less than \$1000/kg. This assumes that the cladding hulls would be recovered from the waste processing stream with a 90% recovery factor.

With only a 50° C rise reactors could still operate in a pressurized water regime. Higher temperatures could lead to higher efficiencies and higher cost savings but would put them in a superheated steam regime. While superheat operation may be possible in the future, present reactors are not designed to operate with appreciable amounts of superheated steam. The potential for superheat operation should not be overlooked nor should it be counted on; the nuclear industry has been pursuing nuclear-powered superheat concepts for over a decade with little success. Since ⁵⁰Ti comprises only 5.34% of natural titanium, 250 tons of titanium feed

Fig. 2-19. Added capital investment possible as a function of core steam temperature (0.8 duty factor and 0.15 capital recovery factor).

would be needed to provide the cladding for each 1100 MWe reactor, assuming total extraction of ^{50}Ti . The amount needed annually would be small in comparison to our present consumption of 450,000 tons per year and even less of the projected demand of 1 to 2 million tons annually by the year 2000. If metallic titanium is required for feed, a large percentage of the annual consumption (19,000 tons at present) would need to be processed to supply the ^{50}Ti demand. The tails would be resold to standard titanium metal users. For cladding made of ^{50}Ti to be comparable to Zircaloy 2 in its thermal neutron absorption, an enrichment of 95% or greater will be required.

While ^{50}Ti appears to offer a potential improvement for reactor core cladding, reactor manufacturers are not interested in pursuing a new core cladding evaluation program at this time. They are reasonably satisfied with Zircaloy and are concentrating their efforts on more urgent problems. Nevertheless, in view of the long-term, large-scale potential, evaluation of the production capability and costs of 95% enriched ^{50}Ti by LIS is being continued.

Removal of Uranium Isotopes. In the recycling of light water reactor fuel, some attention must be given to the removal of ^{236}U which is created during reactor operation. In the present gaseous diffusion separation, 60% of the ^{236}U would go into the product stream with the enriched ^{235}U . Repetitive processing would lead to increased buildup of the ^{236}U content. Since the neutron-capture cross section of ^{236}U is higher than that of ^{238}U , higher fissile enrichment of ^{235}U would be required to compensate for the greater absorption with ^{236}U present.

Moreover, if the high temperature gas cooled reactor (HTGR) becomes a reality, it would be desirable to recover the residual ^{235}U in the fuel rods which have a 30% ^{235}U content mixed with 50% ^{238}U . Here, where percentage difference in mass is so slight, LIS has an enormous advantage over other separation techniques.

Another separation of uranium isotope is important if the HTGR or other reactors operate on the thorium- ^{233}U cycle. In that cycle, in addition to ^{233}U , 400 to 1600 ppm of ^{232}U are also generated. At the end of the decay chain of ^{232}U , 2.6-MeV γ 's are emitted which require shielding during handling and rework. Such high concentrations of ^{232}U will be a problem for gaseous diffusion facilities which can only handle uranium with up to 10 ppm of ^{232}U during a thirty-day period after processing. If the ^{232}U is removed early in reprocessing, subsequent steps can be performed with ease. If separation is not made, all processing will have to be done remotely with heavy shielding, incurring the attendant high costs. Further definition of the costs of laser separation of ^{238}U and ^{232}U and the potential

benefits to be gained is being pursued.

Reactor Products

Four different groups of reactor products are of interest from an isotope separation point of view: recyclable fuels, radioisotopes which can be used as power sources, long-lived actinides which may be part of a disposal problem, and scarce and valuable elements.

Recycling of uranium has already been discussed. Radioisotope power sources are treated below in a section of their own. Although interest exists for isotope separation connected with actinide burning, not enough is known to report on at this time. Similarly, reactor products other than the platinum group metals discussed below have yet to be looked at.

Precious Metals. Annual production of platinum-group metals (palladium, rhodium, and ruthenium) in fission reactors has been estimated at between 850,000 and 1,300,000 troy oz by 1990.³³ The United States consumption of platinum-group metals in 1974 was 1.9 million troy oz, which was about one-third the total world's consumption.³⁴ These metals are essential due to their catalytic properties, electrical conductivity, and resistance to chemical corrosion, heat, and oxidation. The U.S. produces less than 2% of the platinum metals it uses, and its reserves are estimated to be only 3 million troy oz. At today's prices, (rhodium, \$225/troy oz; ruthenium, \$60/troy oz; and palladium, \$40/troy oz) there is clear incentive to recover these reactor products.³⁵

The major difficulty in utilizing these reactor-produced materials is that radioactive isotopes are present along with the stable isotopes of these elements. One way to decrease the radioactive content is to store the material and let the radioisotopes diminish through natural decay. With this approach, the material must be stored for several half-lives before being available for general use. Waiting until the radioactivity level is below 10 $\mu\text{Ci/g}$ of the element, which is the current requirement, has been judged economically unattractive in past market analyses.

An alternative to letting the radioactive isotopes decay is to separate them out. ^{103}Rh is stable and of the radioactive isotopes of rhodium produced in reactors, only ^{102}Rh and ^{102m}Rh have half-lives greater than 1 day. Half a year after removal from the reactor, the ^{102}Rh and ^{102m}Rh concentrations are 153 ppb and 255 ppb, respectively.³⁶ They would need to be reduced to 1 ppb and 5 ppb, respectively, for each to contribute only 5 $\mu\text{Ci/g}$ per gram of rhodium. Less separation might be acceptable for ^{102}Rh since its half-life is only 206 days.

For palladium the separation looks easier. Only ^{107}Pd is radioactive. Six months after removal from the

reactor, it comprises 18% of the total palladium and needs only to be reduced to less than 2.2% to produce less than 10 $\mu\text{Ci/g}$ of palladium.³⁶ If easily achieved, greater reduction may be desirable to further reduce its level of radioactivity. Little help comes from natural decay since the half-life of ^{107}Pd is 7 million years.

The stable isotopes of ruthenium (99, 100, 101, 102, and 104) comprise 95% of the total. ^{103}Ru and ^{106}Ru are 0.07% and 4.9%, respectively, of the total.³⁶ Reducing the radioactivity of ^{106}Ru to 5 $\mu\text{Ci/g}$ requires that its concentration be only 1.5 ppb. ^{103}Ru must be reduced to one-tenth that level. Alternatively, ^{103}Ru could be reduced to 1.5 ppb and allowed to decay another 4 months to reach 5 $\mu\text{Ci/g}$ of ruthenium since it has a half-life of 40 days. The economic advantage of precious metal recovery is highly uncertain at present since reductions in concentration by an order of magnitude or more have not been demonstrated at concentration levels of ppm or less.

Radioisotope Power Sources

Radioisotope power generators (RPG) are useful in applications where remote operation and long term reliability are prime considerations. They are essential for deep space probes and can be cost-competitive with solar arrays on low orbit missions where storage batteries are needed for supplemental power when in the earth's shadow. The need for hardening to prevent radiation damage also weighs in favor of RPG's on some space missions. Underwater, RPG's are the optimum choice of power for missions requiring watts to hundreds of watts for from one to ten years.^{37,38} Above water and in remote land locations they have performed well, but their economic competitiveness has not been clearly proven over other alternatives. Cardiac assist pacemakers, and in the future, totally implanted artificial hearts are a third major application of isotope power. A tabulation and comparison of radioisotopes suitable for power sources was recently compiled by J.C. Graf and O.E. Brown.³⁹

Space Power. The reference isotopic fuel for RPGs in space is $^{238}\text{PuO}_2$. ^{238}Pu has been selected primarily because of its long half-life and low-level radioactivity. ^{238}Pu is an α emitter, and ^{17}O and ^{18}O are removed to reduce their contribution to radiation from (α ,n) activity.

Speculative demand for ^{238}Pu for space RPGs ranges as high as 100 tonnes cumulative through the end of the century. This large quantity is based somewhat on ^{238}Pu being available at reduced costs. The present cost of ^{238}Pu is \$750/g for standard ^{238}Pu (80% ^{238}Pu , 1.2 ppm ^{236}Pu). This is expected to drop to \$200/g when \$30/g ^{237}Np becomes available from reactors. ^{237}Np is a precursor of ^{238}Pu as it is now made. An

even cheaper method of obtaining ^{238}Pu would be by direct separation from reactor-produced plutonium. About 1% of that plutonium is ^{238}Pu . An added benefit of separating ^{238}Pu from spent fuel plutonium would be the reduction of handling problems in subsequent plutonium fuel fabrication. ^{244}Cm may displace ^{238}Pu for space power applications at some time in the future on missions which are not sensitive to radiation. Its specific power of 2.65 W/g is 5 times that of ^{238}Pu which could lead to reduced weight and cost for a given amount of power. At the present, there is too much uncertainty regarding ^{244}Cm fuel properties and costs to know how suitable and competitive it can be.

Remote Terrestrial Power. Radioisotopes chosen for terrestrial power (including underwater) are ^{90}Sr and ^{238}Pu . Navy requirements were estimated in 1972 to grow to 1700 RPGs by 1990.⁴⁰ Assuming a nominal size of 100 W, the ^{238}Pu requirements for this purpose could be over 5 tons. It is expected that ^{90}Sr will be used for terrestrial power sources where cost is more important than size, weight, and the amount of shielding required.

Pacemakers and Artificial Hearts. During 1970, 50,000 cardiac pacemakers were implanted worldwide; 130,000 more were estimated to have been implanted in 1975,⁴¹ half of which were in the U.S. Chemical batteries power most of these units, but the long life and high reliability of nuclear power units make them attractive for the future. However, improvements in lithium batteries may lead to 10-yr-implanted lifetimes, thereby reducing that advantage of nuclear sources.

^{238}Pu and ^{147}Pm are the primary radioisotope choices for pacemaker application based on half-life, power density, cost, radiation properties, and availability. One hundred to 400 milligrams of ^{238}Pu and 150 milligrams of ^{147}Pm are used per pacemaker. Each has an accompanying problem isotope. For ^{238}Pu it is ^{236}Pu which emits a 2.6-MeV γ at the end of its decay chain. For ^{147}Pm the problem is ^{146}Pm which emits 0.7-MeV γ 's. The concentration of both of these problem isotopes needs to be reduced for medical applications.

While the nuclear-powered pacemaker market is small in terms of material needed (about 4 kg for 10,000 units/yr), the ready acceptance and rapid growth of pacemaker implantations indicate that artificial hearts might also be readily accepted if they become available. For them the material requirement would be substantial.

Work began on artificial hearts in 1967 under the sponsorship of the National Heart and Lung Institute and the AEC. The projected growth in artificial heart devices has been estimated at between 130,000 and 400,000 by the year 2010, beginning in 1985 and increasing rapidly after 1990.⁴²

The pumping power requirements for 3 W continuous and peaks to 10 W eliminate chemical batteries as possible power sources. Daily energy demand would be about 1/2 MJ. An evaluation of possible power sources selected $^{238}\text{Pu}^{16}\text{O}_2$ as the best available, based on specific power, lifetime, and radiation effects. ^{238}Pu is an α emitter and ^{17}O and ^{18}O are removed to reduce their contribution to neutron radiation from (α, n) activity. Each "heart" will require 50 g of medical-grade ^{238}Pu and 7 g of ^{18}O ; hence the cumulative demand to 2010 would be for 6.5 to 20 tonnes of ^{238}Pu and 1 to 3 tonnes of ^{18}O . Assuming technical success in the development of an artificial heart, there will still have to be a general public acceptance of this use of plutonium and a substantial reduction in the cost of medical-grade ^{238}Pu from its current price of \$1,250/g before the number of devices can grow to the anticipated demand.

The cost of medical-grade ^{238}Pu could depend significantly on the ability to separate ^{238}Pu . It is planned to make ^{238}Pu by neutron irradiation of ^{237}Np in commercial reactors. Since producing ^{238}Pu with low ^{236}Pu content requires considerably more processing time than producing the same amount of ^{238}Pu with a higher ^{236}Pu content, it will be more expensive. If ^{238}Pu could be removed easily, ^{238}Pu could be made quickly without having to pay the penalty of waiting more half-lives until the ^{238}Pu reached an acceptable level.

Biological

Isotopes are used primarily as tracers in biological applications. For the most part, radioisotopes have been used due to the sensitivity of radiation detection instrumentation. Minute quantities are required of certain isotopes or isotopically-tagged compounds which concentrate in specific organs providing site specificity. In most cases it is necessary to use isotopes of high purity to minimize the radiation damage. High purity can be achieved either by starting with high purity precursor isotopes, or when possible, by choosing a production technique that avoids the production of undesirable isotopes.

Recently the use of stable isotopes of carbon, nitrogen, and oxygen has become practical due to the development of sensitive nuclear magnetic resonance diagnostic equipment. When working with stable isotopes, what is detected is a difference in the ratio of the isotopes from the natural abundance ratio. Since carbon, nitrogen, and oxygen are basic to biological processes and since the stable isotopes present no radiation burden, their use is expected to grow considerably, especially if clinical mass scans can be developed.

Health Diagnostics. The report, *The Nuclear Industry*, states, "... one in every four patients admitted to hospitals is given a radioactive tracer as part of his medical diagnostic work-up."⁴³ Radiopharmaceutical sales totalled \$70 million in 1973 and are growing 25% per year. Growth is expected to continue at this rate for the near term. Stable isotopes of carbon, oxygen, and nitrogen have recently become available in kilogram quantities from the ICONS facility at Los Alamos. Fractional distillation of CO and NO is used to achieve the separation. Methods of clinical mass screening are being pursued. One such screening would use 16 ml (26 mg) of ^{18}O which would be inhaled. The exhaled breath would then be monitored over a period of minutes to determine certain metabolic functions. If one-fourth of the U.S. population were screened annually, the amount of ^{18}O required would be at least 1.3 tonnes, having a market value of \$390 million per year at the current prices. The cost to the patient being screened would be \$8 for material. A reduction in cost would facilitate such a large scale use.

Metabolic Studies. All of the stable isotopes of carbon, nitrogen, and oxygen are being used in the study of plant and animal metabolism. Since this is primarily a research endeavor, it does not appear that greater than kilogram quantities will be needed per year. Discovery of other mass screening applications for metabolic disorders could increase the demand substantially.

Agriculture. In addition to basic metabolism research, there is also an urgent need to understand the dynamics of using fertilizers under varying rainfall and irrigation conditions, with different soil conditions, and for different crops. ^{15}N and ^{14}N are used in kg and hundreds of kg quantities per year, respectively, on projects sponsored by the U.S. Dept. of Agriculture, the Tennessee Valley Authority, and the University of California at Davis. U.S. production capacity of ^{15}N at present is about 3 kg; another 3 kg capacity exists in western Europe and 2 kg more in East Germany. ^{14}N with $^{15}\text{N} < .01\%$ costs \$150/kg, and ^{15}N enriched to 95% or greater costs \$65/g. The long range market for labelled fertilizer is unknown; near term demand is estimated to be about double its present size.⁴⁴

Summary

Several isotopes where laser isotope separation could be of significant value have been identified, including some detail of the market factors for each: quantity, competitive price, degree of enrichment, etc.

Table 2-15. Isotope summary table

Application	Isotope	Desired property	Present cost (\$/g)	Target cost (\$/g)	Market volume (tonnes/yr except as noted)
Advanced breeder fuel	^{15}N 98%	Low neutron absorptions Low ^{14}C production	65	5	200
Core cladding material	^{50}Ti 95%	Low neutron absorption	>2500	1	800
Uranium cleanup	^{236}U ^{232}U <10 ppm	Low neutron absorption Low 2.6 MeV γ radiation	—		
Precious metal recovery	$^{102}, ^{102\text{m}}\text{Rh}$	Radioactivity reduced to less than 10 $\mu\text{Ci/g}$ (EPA standard)	—	7.0	8
	$^{103}, ^{106}\text{Ru}$			2.0	5
	^{107}Pd			1.3	8
Radioisotope power					
Space, terrestrial	^{238}Pu >80%				
	^{238}Pu >90%		750	200	100 ^a
Medical	^{236}Pu <0.3 ppm	Low 2.6 MeV γ radiation	1250	400	30 ^a
	^{145}Pm	Low 0.7 MeV γ radiation	—	200	
	$^{17}, ^{18}\text{O}$ ~ 100 ppm	Low neutron radiation	1.3		7 ^a
Biological					
Diagnostics	^{18}O	High $^{18}\text{O}/^{16}\text{O}$ ratio	300	30	1
Agriculture	^{15}N		65	5	
	^{14}N	High $^{14}\text{N}/^{15}\text{N}$ ratio	0.15	—	1

^aCumulative volume to the year 2000.

Table 2-15 summarizes much of this information. In the case of uranium cleanup, the target cost would be on the order of the cost of producing suitable uranium from other sources. Similarly, for the precious metals,

the target cost is the current market price of each metal.

S. Winter

References

1. J. Hovingh, J. A. Maniscalco, M. Peterson, and R. W. Werner, in *Proc. First Topical Meeting on the Technology of Controlled Fusion* (San Diego, 1974), vol. I, p. 96.
2. J. M. Williams, T. Merson, F. T. Finch, F. P. Schilling, and T. G. Frank, in *Proc. First Topical Meeting on the Technology of Controlled Nuclear Fusion* (San Diego, 1974), vol. I, p. 70.
3. T. Frank, D. Freiwald, T. Merson, J. Devaney, in *Proc. First Topical Meeting on the Technology of Controlled Nuclear Fusion* (San Diego, 1974), vol. I, p. 88.
4. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975).
5. J. A. Glaze, in *Proc. Nineteenth Annual Technical Symposium of the Society of Photo-Optical Instrumentation Engineers* (San Diego, 1975).
6. R. Buntzen and C. Rhodes, in *Proc. First Topical Meeting on the Technology of Controlled Fusion* (San Diego, 1974), vol. I.
7. A. R. Thiessen, *Utility of 10.6- μ m Laser Light for High Density Laser Induced Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-74923 (1973).
8. A. Cook and J. Maniscalco, " ^{239}U Breeding and Neutron Multiplying Blankets for Fusion Reactors," *Nuclear Technology* (in press).
9. E. F. Plechaty and J. R. Kimlinger, *TART Monte Carlo Neutron Transport Code*, Lawrence Livermore Laboratory, Rept. UCRL-522 (1971).
10. Lawrence Livermore Laboratory Evaluated Nuclear Data Library.
11. J. A. Maniscalco, *Nuclear Technology* (Jan. 1976).
12. J. M. Williams, F. T. Finch, T. G. Frank, and J. S. Gilbert, in *Proc. Fifth Sym. on Eng. Prob. of Fusion Research* (Princeton, 1973), p. 102.
13. M. Balooch and D. R. Olander, *Trans. A.N.S. 1975 Winter Meeting* (San Francisco, 1975), p. 164.
14. J. Nuckolls, J. L. Emmett, and L. Wood, *Physics Today* (August, 1973).
15. M. Born and E. Wolf, *Principles of Optics*, 5th ed. (Pergamon Press, Oxford, 1975), p. 614.
16. B. A. Boley and J. H. Weiner, *Theory of Thermal Stresses* (John Wiley, New York, 1960), p. 41.
17. G. B. Zimmerman, *A Numerical Simulation of the High-Density Approach to Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-74811 (1973).
18. S. L. Thompson and H. S. Lauson, U.S.A.E.C. Report SC-RR-71 0713 (1972).
19. J. Hovingh, in *Proc. Int. Conf. on Radiation Test Facilities for the CTR Surface and Materials Program* (Argonne National Laboratory, 1975), to be published.
20. D. A. Freiwald and J. J. Devaney, in *Proc. Int. Conf. on Radiation Test Facilities for the CTR Surface and Materials Program* (Argonne National Laboratory, 1975), to be published.
21. R. W. Davis, "LIS Component Requirements/Design Parameters," presentation to Lawrence Livermore Laboratory Scale-Up Design Team (October 1, 1975).
22. E. F. Worden, private communication (1974).
23. Lawrence Livermore Laboratory Laser Isotope Separation Program, briefing for industrial participants, Livermore, California (June 6, 1975).
24. S. A. Tuccio, et al., *Macroscopic Isotope Separation of Uranium by Selective Photoionization*, Lawrence Livermore Laboratory, Rept. UCRL-76829 (1975). Also IEEE/OSA Conference on Laser Engineering Applications (Washington, D.C., 1975).
25. R. W. Davis, "Economics of LIS," presentation to LLL Scale Up Design Team (October 8, 1975).
26. R. W. Davis and J. T. Early "LIS System Tradeoffs," presentation to SU review team, LLL (December 17, 1975).
27. M. S. Farkas and J. N. Broehl, *Cost Model for the Laser Isotope Separation of Uranium*, Battelle Columbus Laboratories.
28. *Environmental Statement for the LMFBF Program*, WASH-1535, Vol. IV, Sec. II, (December 1974), pp. 11.2-27.
29. S. A. Caspersson, R. C. Noyes, and J. A. Vitti, "Economic and Nuclear Performance Characteristics of 500-Mw(e) Oxide, Carbide, and Nitride LMFBFs," in *Advanced Reactors: Physics, Design and Economics*, Kalfelly and Karem, Eds., (Pergamon Press, New York, 1975), p. 125.
30. Y. I. Chang and W. P. Barthold, *Trans. Am. Nuc. Soc.* **21**, 407 (1975).

31. V. Tennerly, Hollifield National Laboratory, Oak Ridge, Tenn., private communication.
32. R. W. F. Gross, *Optical Engr.* **13**, 506 (1974).
33. L. L. Clark, et al., *A Market Analysis of the Fission Products Rh, Pd, Ru, and Tc*, BNWL-1690, UC-4 (1973), p. 11.
34. *Commodity Data Summaries 1975*, Dept. of Interior, Bureau of Mines, pp. 124-5.
35. *CRC Handbook of Chemistry and Physics*, 56th ed., (CRC Press, Cleveland, 1973), pp. B 26-31.
36. W. Sande, Battelle Pacific Northwest, Richland, Wash., private communication.
37. H. Victor, in *Proceedings of the Conference on Power from Radioisotopes* (Madrid, Spain, 1972), pp. 517-523.
38. J. F. McCartney and M. A. Cates, in *Proceedings of the Tenth Intersociety Energy Conversion Engineering Conference* (IEEE, New York, 1975), pp. 1318-1327.
39. J. C. Graf and P. E. Brown, in *Proceedings of the Sixth Intersociety Energy Conversion Engineering Conference* (IEEE, New York, 1971), pp. 918-932.
40. R. P. Cope and T. P. Fleming, *Isotopes and Radiation Technology*, **9**, 329 (1972).
41. K. A. Gasper and K. E. Fester, in *Proceedings of the Tenth Intersociety Energy Conversion Engineering Conference* (IEEE, New York, 1975), pp. 1205-1213.
42. W. E. Mott, et al., in *Proceedings of the Conference on Power from Radioisotopes* (Madrid, Spain, 1972), p. 724.
43. *The Nuclear Industry 1974*, AEC, WASH-1174-74.
44. V. Avona Mound Laboratory, private communication.

3. GLASS LASER SYSTEMS

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3. GLASS LASER SYSTEMS

Janus Laser System

- More than 300 successful target shots were made.
- Neutron yields of 12 million were achieved.
- Clamshell optics were designed, fabricated, and tested.

Cyclops Laser System

- Operated as the world's most powerful single-aperture laser (1-TW, 150-ps pulse).
- The first successful use of a pinhole vacuum spatial filter to strip nonlinearly induced breakup ripples from a high-intensity laser beam was demonstrated.
- More than 700 laser shots were fired.
- Extensive laser system operating data were acquired.
- Neutron yields of 15 million were achieved.

Argus Laser System

- The 2-TW, two-beam Argus laser system was conceived, designed, 90% fabricated, and 50% assembled in 1975. It is the first laser system to use multiple spatial filters to suppress small scale self-focusing.
- Argus will be the workhorse laser system of the LLL laser fusion program for the next two years.

Shiva Laser System

- The 20-TW, 20-beam Shiva laser system was conceived and the optical system was designed in 1975.
- Sixty percent of the hardware is in procurement.
- This congressionally funded High Energy Laser Facility (laser and building) is on schedule and current cost experience is within 5% of projections.
- Completion is scheduled for October 1977.

3. GLASS LASER SYSTEMS

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3. GLASS LASER SYSTEMS

3.1 Overview

The solid state laser program at LLL is responsible for designing and building Nd:glass lasers for laser fusion experiments. These lasers are designed to produce pulses having extremely high peak power (10^{12} – 10^{13} W), substantial energy content (greater than 100 J), and well-controlled temporal pulse evolution. Over the past three years the Nd:glass laser has been developed into a versatile, reliable irradiation source that has met the initial requirements of the laser-fusion experimental program.¹ The remaining engineering and physics problems associated with Nd:glass laser systems are now well recognized, and the glass laser program's present goals are to overcome these problems and complete the objectives shown in Table 3-1. To this end the program has been divided into three specific project areas:

- System design and assembly.
- Component design and engineering.
- Laser physics (propagation and materials).

The first of these areas will be discussed in this section, the other two in Sec. 4.

To accomplish its task the glass laser program now has 82 people assigned directly to it. Additional laboratory support is used as needed. The FY 1976 operating budget is \$7.2 million, and there is an additional line-item FY 1976 expenditure of \$9.6 million (out of the \$25-million total cost) for the High Energy Laser Facility (HELF), which comprises the 10-kJ

Shiva subnanosecond laser irradiation facility and the building that houses it.

Figure 3-1 shows the expected relationship between target yield and system development. Janus II at 0.4 TW and Cyclops at 1.0 TW are the laser systems that are currently operating. Table 3-1 shows the anticipated performance of future systems. The possibility of achieving fusion reactions that approach scientific breakeven with an irradiation power of 20 TW is the motivation behind the Shiva laser project.

Our experience in building Janus and Cyclops has given us confidence that systems such as Argus and Shiva are possible. The single-beam Cyclops chain has demonstrated performance at 1 TW—the level required by each of the two Argus and 20 Shiva laser chains. The 1-TW performance was made possible by the development of high-power spatial filtering and measurement techniques to measure beam breakup processes.

Upgrades to the present and planned laser systems are also noted in Table 3-1. They are possible because spatial filtering improves power capability of a single chain by a factor of 2 to 3 and because new laser host materials have been found that permit increased power loading by factors of 2 to 4. These results indicate that a laser like Janus could be upgraded to more than 1 TW, and a laser like Shiva to the 100-TW level, by using improved glasses and additional amplification.

J. F. Holzrichter

Table 3-1. Solid state laser program objectives

Argus laser:	2-3 TW (200 J in 100 ps), spring 1976	
Shiva laser:	>20 TW (10 kJ in 500 ps), late 1977	
Materials development:	2 × to 4 × increase in power capacity of system components	
Tailored laser performance:	Pulse shaping, frequency conversion, probe pulses, beam profiles	
Potential laser upgrade and modifications	Janus II → Janus II* (spatial filtering, (1976)	
	0.4 TW → 1.0 TW (new materials)	
	Argus II → Argus IV	(1976-77)
	2 TW → 4 TW	
	Argus IV → Argus IV* (new laser materials)	(1978-79)
	4 TW → 8 TW	
	Shiva → Super Shiva	(1980)
	20 TW → 200 TW (preliminary)

Fig. 3-1. Laser-fusion energy-yield projections.

3.2 Laser Systems and Environment

In the last few days of 1974 the Janus laser system had produced LLL's first laser-driven thermonuclear reactions; Cyclops was still in development, not yet operational; Argus was a vague concept; and the newly formed Shiva project team had evolved a preliminary system design. The year 1975 has been very active and productive for these four laser systems, as shown in Fig. 3-2, which illustrates these activities.

During 1975 Janus operated for 3 months with one beam and 6 months with two beams using f/1 lenses in the target chamber. Powers up to 0.25 TW per beam were achieved with a cumulative whole-beam phase retardation (ΣB) of about 4.5 rad. Conversion to clam-shell optics occurred in the last two months of the year, during which no target shots were fired. In all more than 300 target shots were made, some achieving up to 12 million neutrons. The first alpha-particle spectra measurements were made in the late spring and verified the thermonuclear nature of the laser-driven fusion reaction. A wide variety of targets—having different sizes, materials, configurations, and DT fuel pressures—were irradiated with this system and simulated with

the LASNEX computer code. This has resulted in an extensive data base and a high level of confidence in the code normalization and computer predictions.

In the first half of 1975 the Cyclops laser was operated as a single beam on-line component test bed and achieved 1 TW with a 150 ps pulse and a ΣB of about 10 rad. This exceeded the power obtained from any other laser in the world by more than a factor of 2. This performance was made possible by the first successful use of a pinhole vacuum spatial filter to strip nonlinearly induced breakup ripples from the high-intensity beam. In mid-1975, engineering was started to convert Cyclops into a two-beam irradiation facility. System problems, such as alignment stability, oscillator and electrical system reliability, aberrations, component damage, and restaging in a crowded laboratory, made the conversion process longer than anticipated. In spite of these difficulties, more than 700 laser shots were fired on this system, yielding considerable laser system operating data. By the year's end, target shots began to produce laser fusion data. At this writing up to 15 million neutrons have been achieved.

The Shiva laser is now in the detailed design and procurement phase. This activity was initiated in July 1975, following the optical design freeze that finalized the number of laser chains and their specific staging. The optical design freeze was the culmination of the extensive optimization studies described in the previous annual report. This 20-beam design will produce 1.35 TW per beam at $\Sigma B = 8.8$ rad and $\Delta B_{\max} = 2.4$ rad with 5 spatial filters from the oscillator to the target.

The progress that has been made on Janus, Cyclops, Argus, and Shiva during 1975 is described in detail in the following articles, concluding with a description of the developments that have occurred in component assembly techniques.

T. J. Gilmartin
R. O. Godwin

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*FY 1976 has five 3-month quarters, because LLL is changing the start of its fiscal year from July 1 to October 1 in 1976.

Fig. 3-3. High Energy Laser Facility (HEL F) schedule.

3.2.1 JANUS LASER SYSTEM

The Janus laser system was in operation throughout 1975 as a target irradiation facility. For the first three months of the year, the system was configured for one-sided irradiation of targets in the single-beamline configuration described in last year's annual report.² In April 1975 the system was upgraded to two-beam operation for two-sided irradiation of targets. Figure 3-4 shows a schematic drawing of the completed two-beam system. The individual components in the system are of the same design as those described in the last annual report; in addition, a beamsplitter, three B-disk amplifiers, and two Faraday rotators were added to complete the two-arm configuration. Figure 3-5 is a photograph of the system with the target chamber in the center foreground.

For some experiments system output has been as high as 600 GW. However, at this high power the

focusability of the beam is adversely affected by beam filamentation from nonlinear instabilities. Better coupling of the beam energy to the target and hence better target performance occurs when the laser is operated at lower power, at which beam breakup is not so severe (see Fig. 8-3). For this reason the laser operates at 400 to 450 GW for most experiments. Figure 3-6 shows an optical schematic of the laser chain with beam power and accumulated ΣB values for several locations in the laser train for typical system operation.

The experimental arrangement shown in Fig. 3-7 was used to measure and set the simultaneity of the two beams at the target. A mirror, whose front-surface position was referenced to the center of the target chamber with an alignment telescope, retroreflected half of one beam to a beamsplitter and to the slit of a streaking camera. Half of the other beam passed by the

Fig. 3-4. Janus layout. From April to December 1975 the Janus II laser was configured as shown with $f/1$ focusing lenses in the target chamber.

Fig. 3-5. Janus II laser system, showing the target chamber in the center foreground. This system has produced 300 target shots during 1975.

edge of the mirror to the same streak camera. The streak camera readout was done with a silicon diode array or with film. A known thickness of glass was placed in one of the beams to introduce a known delay, whence the path length of one of the two beams was adjusted until the measured delay was equal to the delay through the glass plate. Beam simultaneity at the target position within 5 ps is achieved using this technique.

During 1975 more than 300 target shots were performed with the Janus laser system. A large amount of target data as well as laser performance data was collected. In about 20% of the attempted target shots some sort of malfunction occurred in the mode-locked oscillator—most frequently either a failure of the oscillator to produce a train of single mode-locked pulses or

of the laser-triggered spark gap and optical gate to properly switchout one of the mode-locked pulses. To improve this situation the laser-triggered spark gap that supplied the voltage pulse for the Pockels cell was replaced by an electronic pulse generator. This system is described in Sec. 4.2.2 of this report.

The next most serious problem arose because the disk amplifier lifetime was limited by damage to the laser disks resulting from dirt particles being burned onto the surfaces by the intense flashlamp radiation. The problem in the A amplifiers was the more severe. The average disk lifetime of a B amplifier was more than 200 shots. However, because of the higher pump level in the A amplifiers, they have lasted on the average only about 30 to 50 shots before reconditioning was necessary. Plans are now well underway to replace

Fig. 3-6. Janus II staging (optical schematic), showing the beam diameters, propagation distances, beam power, and B values at several locations in the chain.

Fig. 3-7. Arrangement for measuring the beam simultaneity in the center of the Janus target chamber. A glass delay plate inserted in one beam delays its pulse with respect to that from the other beam. The photograph and scope trace show the streak camera readout on film with the glass delay plate out of the beam (a) and from a silicon diode array with the glass delay plate in the beam (b).

the A disk amplifiers with 4-cm-diam rod amplifiers to reduce system downtime for maintenance.

During target irradiation experiments a single dye cell² was located at the output of the 25-mm rod amplifiers. This was inadequate to prevent damage to targets from prepulses. Oscillator interpulse noise, which was switched out by the optical gate and preceded the main pulse through the amplifier train by a few nanoseconds, was frequently energetic enough to damage targets. To suppress these prepulses a second dye cell with a small-signal transmission of 0.01 was placed at the oscillator spatial filter output. The dye cell at the rod amplifier was still necessary to prevent target damage from amplified spontaneous emission. A combined small signal transmission of the two dye cells of less than 0.001 has been sufficient to reliably prevent target damage from oscillator prepulses.

On occasion, turning mirrors and polarizers have been replaced because of optical damage from beam

filamentation. At the power levels at which the laser is routinely run, this occurred rarely and did not provide an operating constraint.

The laser system has provided the program with an abundance of extremely well diagnosed laser target data (Sec. 8.2.2). The repeatability of these data has been excellent. In addition, examination of the problems encountered in using this system for target irradiation has established the direction of future laser physics study, laser component design, and system design. At this writing the *f*/1 focusing lenses have been replaced by clamshell optics in the target chamber, and the Janus system is continuing to produce high-quality data from a variety of laser fusion targets.

D. R. Speck
E. K. Storm
J. F. Swain

Fig. 3-8. Janus upgrade.

Janus Upgrades

As stated above, the present Janus system is capable of focusing 450 GW (225 GW per beam) onto laser fusion targets at ΣB about 4.5 rad. Attempts to increase the output power by driving the system harder result in severe beam breakup and catastrophic loss of focusable power. However, the system performance can be improved by double passing and by using thinner optics, lower- n_2 materials, vacuum spatial filters, and 4-cm rod amplifiers instead of the 3.5-cm disk amplifiers. Such an improved system is shown in Fig. 3-8 laid out within the same facility and with the same 8.5-cm output aperture. With SiO_2 passive optics, FR-5 rotators, and silicate laser glass this system will produce 1.2 TW using f/1 lenses with ΣB about 9 rad. This not only is an increase of about 30% in power/nepers of self-focusing gain over the present system, but the

system will also have a substantially cleaner output beam. The use of phosphate laser glass and CaF_2 focusing lenses can increase the output power by an additional 65% without increasing the ΣB .

Although it is possible—by using two spatial filters per chain—to achieve 0.7 TW per arm at ΣB about 9 rad from a Janus-sized system, this system will not fit within the present facility.

These options for upgrading Janus are being considered so that this system can continue to be used for detailed, special-purpose experiments that do not require the full capability of the larger Argus and Shiva systems. In addition, other laboratories may be interested in the fact that about 1 TW of power can be achieved from standard 8.5-cm LLL-designed components when up-to-date staging techniques are used.

E. K. Storm

3.2.2 CYCLOPS LASER SYSTEM

Cyclops was originally built as a single-arm Nd:glass laser prototype for larger multiple-arm systems. For approximately 1½ years it served as a test bed for laser components and provided basic information about the nonlinear propagation effects that occur in large high-power lasers. Since May 1975 it has been dedicated to target irradiation experiments on a variety of single- and double-beam targets at output powers up to 1 TW.

The configuration of Cyclops is shown schematically in Fig. 3-9 along with the energy and power values attained on a particular shot. After the first spatial filter the beam expands to the apodizing aperture, which transmits a 4.7-mrad beam with a quadratic or super-Gaussian radial intensity profile. This beam continues to diverge through the rod and A disk amplifiers before being expanded and collimated for passage through the B disk amplifiers. The limiting aperture for the various amplifiers is listed in the bottom line of the figure.

When the beam is focused through the pinhole in the vacuum spatial filter, the high-spatial-frequency noise that has accumulated because of small-scale self-focusing is removed. As a result of this filtering the pulse energy on a high-power shot is reduced by about

25% before the beam is expanded and recollimated to fill the 20-cm diameter of the C disk amplifiers. Diagnostics are located at the positions shown in Fig. 3-10.

Each of the energy and spatial profile stations in the chain has both an absorbing glass-disk calorimeter and a near-field camera. The calorimeter readings and the oscillator pulse duration are used as inputs to a small computer code that provides the shot summary data shown in Table 3-2. The near-field cameras produce the beam photographs shown in Fig. 3-11. These photos provide a shot-to-shot monitor of beam quality. They are helpful in identifying effects resulting from plasmoids,³ pinhole misalignment, double pulses, and varying amounts of self-focusing. Small-scale beam breakup is seen to increase up to the B-amplifier output. At this point, the spatial filter removes the high-spatial-frequency components before the beam propagates on through the C amplifiers. At the C output some fraction of the energy is again contained in transverse structure with dimensions small compared to the beam diameter. The focusing properties of this output will be described below.

Attaining high overall optical quality in a laser this large requires careful specification and element-by-element testing of the 84 components and 164 surfaces

Fig. 3-9. Cyclops laser staging (July 1975), with parameters for a typical shot.

with which the beam interacts. Even then, it is difficult to estimate how the large number of small wavefront distortions will add. To monitor the overall optical

quality of the system, the radial-shear Mach-Zehnder interferometer⁴ shown schematically in Fig. 3-12 is used. The center of the beam in one arm is expanded to

Table 3-2. Stage by stage gain, power, and intensity values for a typical pulse as generated from the oscillator pulse duration and interstage calorimeter readings

Input pulse duration = 98 ps: $B = \int_0^L \frac{2\pi\gamma l}{\lambda_{vac}} dz$, where $\gamma \equiv \frac{\Delta n}{1}$

Component	Gain (%/cm)	Gain mod	Gain stage	Energy (J)	Power (GW)	Intensity (GW/cm ²)	Com- ponents (B)	Stage (B)	Total (B)
Apodizer				0.000	0.00	0.01	0.00		0.000
Rod	6.3	5.00		0.002	0.02	0.02	0.01		0.007
Polarizer				0.002	0.02	0.02	0.00		0.007
Polarizer				0.002	0.02	0.02	0.00		0.008
Rotator				0.002	0.02	0.02	0.00		0.008
Rod	9.1	10.00		0.018	0.20	0.16	0.04		0.049
Polarizer				0.018	0.20	0.18	0.00		0.051
Polarizer				0.018	0.19	0.17	0.00		0.052
Rotator				0.018	0.19	0.16	0.01		0.058
Rod	9.1	10.00	500.00	0.176	1.91	1.20	0.30	0.36	0.359
Polarizer				0.174	1.89	1.28	0.01		0.370
Polarizer				0.172	1.87	1.24	0.01		0.381
Pockels cell				0.170	1.85	1.13	0.10		0.481
Rotator				0.150	1.63	0.87	0.03		0.514
A mod	9.6	2.79		0.418	4.54	2.08	0.17		0.688
Polarizer				0.414	4.50	1.62	0.02		0.711
Polarizer				0.410	4.45	1.50	0.02		0.731
A mod	9.6	2.79	7.77	1.142	12.41	3.79	0.33		1.061
Rotator				1.005	10.92	2.56	0.10		1.159
100 cm lens				1.000	10.87	2.45	0.05	0.85	1.209
200 cm lens				0.995	10.82	0.49	0.01		1.221
B mod	6.6	3.04		3.029	32.92	1.50	0.23		1.452
B mod	6.6	3.04		9.221	100.23	4.56	0.70		2.155
Polarizer				9.129	99.23	4.52	0.12		2.274
B mod	6.6	3.04	28.21	27.791	302.07	13.76	2.12		4.393
Rotator				28.900	259.78	11.88	1.18	4.31	5.520
Spatial-filter lens				28.780	258.48	11.77	0.18		5.651
Pinhole			0.735	17.480	190.00				
Spatial-filter lens				17.398	189.05	21.76	0.24	0.37	5.992
Polarizer				17.045	185.27	15.67	0.41		6.306
Splitter				16.363	177.86	5.98	0.36		6.668
Cyl lens				16.281	176.97	4.88	0.12		6.791
Cyl lens				16.200	176.09	3.95	0.10		6.892
C mod				25.912	281.65	4.13	0.30		7.194
Col. lens				25.393	276.02	2.41	0.18		7.374
polarizer				24.886	270.50	2.36	0.07		7.448
C mod	5.3	1.60		39.804	432.65	3.77	0.41		7.858
C mod	5.3	1.60		63.666	692.02	6.04	0.65		8.512
Rotator				62.898	678.18	5.92	0.62		9.135
Polarizer				61.145	664.62	5.80	0.18		9.317
C mod	5.3	1.60	6.55	97.800	1063.04	9.27	1.01	4.43	10.322

Fig. 3-10. Cyclops target irradiation facility (January 1976), showing the location of diagnostics employed for determining the performance of the laser.

provide a relatively high quality reference, and the reflectivity of the two splitters is chosen to obtain maximum fringe contrast. The clear aperture of this instrument is approximately 2.5 cm, so the system output is down-collimated by high-quality optics and directed into the interferometer as shown. The interferogram in Fig. 3-12 is representative of those obtained with the present components using a cw YAG laser propagating through the entire Cyclops chain. It shows the accumulated optical distortions to be on the order of 0.5 wave in the central 80% of the beam; part of this is known to be spherical aberration generated by the spherical lenses in the vacuum spatial filter. Recent pulsed interferograms show that this overall optical quality is preserved when the amplifiers are fired (see Sec. 4.3.5). The several waves of astigmatism that one would expect to see as a result of having propagated through a number of tilted disks with a diverging beam have been canceled by a pair of rotatable cylinder lenses located just after the vacuum spatial filter. These lenses can also be adjusted on a shot-by-shot basis to compensate for thermally induced astigmatism, which is sometimes significant.

Of course, the ultimate test of laser output quality is to measure how well it focuses on a target. Figure 3-13 shows time-integrated and time-resolved photographs of the focused beam in a plane equivalent to the one where targets are normally placed. The radial profile is seen to have the shape of a ring whose diameter changes as a function of intensity. Specifically, the diameter decreases as the intensity increases, because the laser itself becomes a weak nonlinearly induced lens at high intensity and draws the point of best focus closer to the target plane. The ring caused primarily by the spherical aberration in the spatial filter lenses has been thought to be beneficial for target illumination but could be eliminated by the use of aspheric lenses. The temporal profile of the pulse is also altered by nonlinear effects. Most of the beam breakup occurs at the peak of the input pulse, so most of the energy that is rejected by the spatial filter comes from the peak. If the system is operated at sufficiently high power, the temporal profile in the target plane will actually show an intensity minimum at the time corresponding to the peak of the oscillator pulse. This effect is seen in the streak photo of Fig. 3-13.

Fig. 3-11. Near-field beam photograph. Obtained at each of the laser diagnostic stations, such photographs illustrate the changes in beam quality that occur as a pulse propagates through the Cyclops chain.

Fig. 3-12. Radial-shear Mach-Zehnder interferometer used to observe the wavefront distortion at the output of the Cyclops chain. The interferogram was obtained using a cw YAG laser propagating through the unpumped amplifiers with the same profile and divergence characteristics as the pulsed beam.

Fig. 3-13. Cyclops beam profile in the target plane. These representative photos show (a) the time-integrated energy distribution and (b) the time-resolved intensity variation across the beam diameter.

Since some beam breakup occurs in the C amplifiers after the beam has been spatially filtered, not all of the system output energy is focusable on a fusion-size target. The target may be thought of as having the opposite effect of a conventional spatial filter; that is, it transmits that part of the beam energy contained in high-frequency noise and stops the more focusable energy contained in the overall beam profile. The fraction of the laser output that is intercepted by the target varies from 100% to approximately 70% depending on the extent of beam breakup in a particular shot. The focused-fraction monitor shown in Fig. 3-14 provides a way of directly measuring the fraction of output energy contained in two different angular apertures.

Two other laser output characteristics have a strong influence on target performance. They are amplified spontaneous emission (ASE) energy and oscillator prepulse energy. Initially the ASE from Cyclops was controlled by the use of saturable absorbers. Unfortunately, the "saturated" transmission of the dye layer required is often still as low as 70%, and the solvents

make a noticeable contribution to nonlinear beam distortion. Therefore, the dye cells were replaced by a 2.5-cm-diam Pockels cell at the output of the rod amplifiers. With the ASE contribution blocked from everything ahead of the Pockels cell until several nanoseconds before the main pulse, the ASE reaching the target is limited to tens of microjoules—not enough to damage the target. This number has been measured directly with high-sensitivity calorimeters.

Oscillator prepulse energy can come either from interspike noise in the mode-locked 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. The magnitude of the prepulse energy is monitored by the arrangement shown in Fig. 3-15. 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 contrast ratio of better than 10^6 that

Fig. 3-14. Focused-fraction monitor for measuring the fraction of total laser energy focused within selected angular apertures.

Fig. 3-15. Prepulse monitor for measuring the energy that arrives at the target in the 20 ns immediately preceding the main pulse. This energy is typically a few microjoules.

Fig. 3-16. Status panel with color-coded LED's provides an electronic checklist for up to 100 items. This has proved to be a convenient and reliable means for verifying that the system is ready to fire.

is required to prevent target damage is 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.

As a prototype laser, Cyclops has undergone numerous staging changes in 1975 to improve the system or accommodate experiments. These changes have occurred an average of once every 2 weeks. During the year all or a portion of the disk amplifier system has been fired 724 times, which includes shots for amplifier prefiring, calibration, propagation, and target experiments. Of these, 60% were full-system shots with oscillator and switchout reliability of 87%.

Before firing the system, an extensive check verifies that all of the diagnostics are ready to operate and that alignment aids have been removed from the beam path. The present checklist contains about 50 items. A single panel located in the control room displays the status of up to 100 items with color-coded LED's as shown in Fig. 3-16. This procedure facilitates preparation for a

shot and minimizes the possibility of oversight.

A marked improvement has been effected in flashlamp reliability over the year. With 210 lamps currently in the system, all of which are monitored for each shot, only 16 have had to be replaced. Most of these failures were discovered during prefiring and in no case did the failures result in catastrophic damage. A running log of unit reliability of on-line amplifiers indicates a failure rate of less than one per 10,000 flashlamp shots out of over 100,000 monitored to date. None have occurred in more than 6 months.

The Cyclops system will continue to operate in the one- and two-sided target irradiation modes until the Argus system is operational early in 1976.

E. S. Bliss
J. A. Glaze
K. R. Manes
J. E. Murray
F. Rainer

3.2.3 ARGUS LASER SYSTEM

The Argus laser is a two-arm, solid-state laser amplifier chain specifically intended for high-power target irradiation and for experimental investigations of laser-induced fusion reactions. Its salient physical characteristics are outlined in Table 3-3. At the close of 1975, operations were expected to commence in March 1976. A photograph of the laser system in its partial construction phase, showing its general layout in the high-bay area looking toward the target from the oscillator, is shown in Fig. 3-17.

In the following sections, the various functional aspects of the laser and its projected performance will be described. Finally, Argus has been designed and built with flexible provisions for performance upgrading. Several of these upgrading options will be discussed.

Projected Performance

A schematic of the beam as it traverses the various components of one of the two amplifier chains is shown in Fig. 3-18 along with performance data. Of special interest are the sequential vacuum spatial filters, shown as paired lenses, which serve to remove high-spatial-frequency noise from the beam. The origin and growth of this noise have been fully described previously,⁵ as has the design rationale for multiple spatial filters⁶. Argus will provide the first full-scale testing of this design concept. The use of several spatial filters also provides the convenience of beam-expansion telescopes, enabling collimated beam propagation with attendant alignment simplicity throughout the Argus chain.

Fig. 3-17. Argus laser in partial construction, looking toward the target room located beyond the wall. In the near foreground is the 25-mm-aperture rod amplifier chassis. Along the center table are oscillator No. 1, the switchout unit, and associated small optics. Along each arm are various disk amplifiers, spatial filters, and isolator units. The B rack in the center contains the oscillator control units, spatial-filter vacuum-pump power supplies, PILC display panels, and a variety of cable patch junctions. Along the far wall is the nitrogen-cooling-gas flow control.

Chain splits not shown in Fig. 3-18 occur immediately following the apodized aperture for 2-beam operation and immediately prior to the B-booster stage for the 4-beam upgrade scenario. The beam diameters shown at various points along the chain are chosen to fill the B and C amplifier stages; these amplifiers in turn are identical in clear aperture to proven amplifiers in use in the Cyclops and Janus laser systems discussed earlier in this section. The final spatial filter causes the beam to diverge; it arrives at the target-chamber focusing lenses with a 280-mm diameter. This larger beam diameter accommodates several upgrade possibilities and in addition reduces the inherent B-integral contribution of the target focusing lenses.

Design center-beam powers at various stages throughout the chain are shown in Fig. 3-18; these numbers correspond to a focusable power rating of 1.5 TW from each beam at the target itself for a maximum ΔB of 2.2 rad between spatial filters and a whole-beam B of 8.5 rad. The incremental beam breakup integral ΔB between successive spatial filter pinholes and the whole-beam nonlinear phase retardation B , which is responsible for focal "zoom," are both given in Fig. 3-18.⁷ (To convert B to a readily visualized concept, $2\pi = 6.28$ rad corresponds to one wave of nonlinear beam wave front aberration.) Argus has been designed to minimize this whole-beam effect by employing, insofar as possible, minimal thickness optical components in high flux portions of the laser chain.

The incremental beam breakup integral ΔB is important because it defines a severe flux limitation for any amplifier stage for ΔB values in the neighborhood of 3. It can be seen from the figure that a 1.5-TW power rating for the Argus laser chain is relatively conservative; even so, some peak intensity flattening of the pulse temporal profile will be noticeable at the output stages.⁷ For this reason the flux (and B-integral contribution) is highest in the final C-booster amplifier stage.

Optical Train

Oscillator and Pulse-Selection Sections. There are two easily interchangeable pulse-oscillator chassis in the Argus system. One of these is the conventional dye-mode-locked oscillator in use by both Cyclops and Janus; it is intended for use in the 50-300 ps temporal regime. The other will be primarily for delivering pulses of longer duration. In both cases an electrooptic switchout unit selects a pulse from the mode-locked pulse train for further amplification. A 32-ns optical delay is incorporated between oscillator and switchout to accommodate circuit switching delay times in the electronic pulse amplifier; in this manner the pulse that triggers the switchout electronics by exceeding a settable threshold power is in fact the selected pulse. This scheme gives discrimination and target protection against weak or double-pulse trains that are occasion-

Table 3-3. Argus physical parameters

No. of optical surfaces (each arm)	141
No. of amplifiers (each arm)	
Rods	7
"B" - disks	18
"C" - disks	12
Optical pathlength (each beam)	
In glass	~280 cm
Total	~60 m
Glass volume (amp, disks, total, 2 arms)	~37 × liters
Energy stored at 1.06 μ m	~25 kJ
Clear aperture of final C-amplifier	200 mm
Peak power per arm (at 100 ps)	1.0-1.5 TW
Total pulse energy into target chamber (at 100 ps, 2 beams)	200-300 J
Beam radiance (each arm)	5×10^{17} W/cm ² -sr
Bank energy storage	<div> <div> ~3.1 MJ </div> <div> at 20 kV </div> </div>
System repetition rate	~2 hr
Bank charging time	~2 min

Fig. 3-18. Argus staging. The overall performance is 1.50 TW/8.5 neper with a ΔB_{max} of 2.2 nepers.

ally generated by the oscillator. A schematic version of these elements is shown in Fig. 3-19a.

Also shown in Fig. 3-19a is the 5-m-focal-length mode-matching lens, which collimates the Gaussian beam at an e^{-2} intensity diameter of approximately 6 mm.

Beam Profiling and Splitting Sections. Following its emergence from the switchout, the optical pulse passes first through one YAG preamplifier and two glass preamplifiers, each of 12 mm diameter and 130 mm active length with a net gain of typically 30:50 $\times$; then through a 100-cm-focal-length lens-pinhole spatial filter; next through a 3-lens expansion-collimation telescope and film apodized aperture²⁸; then through multilayer thin-film polarizers, which function as beam splitters; and finally through 45°-45°-90° retro prisms and turning mirrors. The beam paths are shown in Fig. 3-19b.

Energy equalization of the split beams is accomplished by rotation of a half-wave plate about the propagation direction; this tuning sets the beam polarization vector at 45° with respect to the polarizing beam splitter mentioned above.

A saturating dye cell is located on kinematic mounts just behind the spatial filter during target shot; this device serves to suppress amplified spontaneous emission (ASE) emanating from the preamplifiers and to suppress prepulse noise from the oscillator itself.¹⁰

The retro prisms are mounted on translation platforms, thus enabling beam path equalization and pulse synchronization on the target.

Rod-Amplifier and B-Disk-Amplifier Sections.

Three 25 mm $\times$ 250 mm glass-rod amplifiers with associated 25-mm Faraday rotators and polarizer pairs and one 40 mm $\times$ 250 mm rod amplifier comprise the rod amplifier section of the Argus chain. A 25-mm-clear-aperture Pockels cell is positioned following the 25-mm rod amplifiers to further reduce ASE. The first of the f/10 vacuum spatial filters expands the beam from 40 to 85 mm diameter. The arrangement is shown schematically in Fig. 3-20a.

The B-amplifier section comprises the intermediate-flux section of the laser chain. This portion of the chain consists of two B-disk, 85-mm-clear-aperture B75N modules, an f/10 B-to-B spatial filter, a cylinder lens pair for compensation of beam astigmatism, and another B75N module, together with two Faraday rotators and associated polarizers. Center power at crucial points is shown in Fig. 3-18. A beam splitter following the B-to-B spatial filter couples approximately 10% of the beam power into beam diagnostics. This splitter would be replaced by a 50% splitter in the event of a 4-arm upgrade. The B75N amplifier heads are described in detail in Sec. 3.2.5.

C-Disk-Amplifier and Final-Spatial-Filter Sections.

The C amplifiers comprise the high-power stages of the laser system. The arrangement is shown in Fig. 3-20c. In sequence, each beam passes through three 3-disk, 200-mm-clear-aperture C75L modules in the driver section, an f/10 C-to-C spatial filter, one C75L module serving as the booster, and a final f/10 C-to-C

spatial filter. Fabrication and assembly details of the amplifier modules are described in Sec. 3.2.5. The head assemblies are compatible with both solid-edge-clad and liquid-edge-clad C disks. The final amplifier module stands alone, isolated between spatial filters, and driven to as high a flux as is practical by the

preceding stage. Performance of the entire laser chain depends critically upon this module, which must have maximum specific gain. A capsule description of this final amplifier staging methodology has been given previously.¹¹

The last spatial filter in the amplifier chain serves

(a) Oscillator and switchout sections

(b) Beam profiling and splitting and path equalization

Fig. 3-19. Argus optical schematic. The upper schematic (a) gives the oscillator and switchout sections, showing mirror A mounted on kinematic supports, thus allowing use of either oscillator. The delay path for the optical pulse train enroute to the Pockels cell switchout crystal approximately equals the electronic circuit delay in the pulse amplifiers. The lower schematic (b) shows the beam profiling, splitting, and path equalization of the selected pulse. The dye cell is mounted kinematically for target shots.

(a) A-amplifier section

(b) B-amplifier section

(c) C-amplifier section

Fig. 3-20. Argus optical schematic. (a) Each beam traverses 25-mm and 40-mm rod amplifiers; the beam diameters at the 10^{-4} intensity contour are shown where appropriate. (b) Next the beam traverses the B-disk amplifier section of Argus, which contains three amplifiers, one spatial filter, and the astigmatism corrector lenses. (c) The beam traverses four amplifiers, three spatial filters, and two isolators in the C-disk amplifier section of Argus.

several purposes simultaneously. First, it removes the small-scale beam intensity ripples; without this filter, B for the final amplifier and target lenses taken together would exceed 4 rad at the 1.5-TW power level. Experiments with Cyclops and Janus have indicated that this B level is intolerable because small-scale beam breakup causes most of the power to miss the target. Second, this spatial filter to some extent protects the final turning mirrors and target lenses from damage by small-scale intense filaments. Third, it is convenient to diverge the beam from the spatial filter to the focusing lens without introducing additional beam optics. Fourth, the focus of the final spatial filter offers a convenient point for mechanical shuttering of the beam to further protect targets from ASE. Synchronized shuttering on a 10- μ s time scale will be incorporated into this spatial filter.

Mechanical Subsystems and Facilities

Argus is located in the high bay of Building 381, where it enjoys the benefits of a temperature- and dust-controlled environment. The floor that supports the laser is a single concrete slab 3 ft thick, which is in turn supported separately from the remainder of the building by reinforced concrete pillars. This stable "optical platform" concept is extended to the laser

support tables, which are themselves concrete and are grouted to the floor. Magnetic slotted stainless steel table tops allow various laser components to be solidly mounted in place. An example, which also shows the C spatial filter prior to lens installation, is shown in Fig. 3-21.

All of the Argus rod amplifiers and preamplifiers are cooled with circulating water solutions. The disk amplifiers are cooled with a dual-manifold nitrogen gas flow, which serves to remove heat from the flashlamp cavity and separately from the sealed optical cavity of each module. In addition, each of the liquid-edge-clad C amplifiers requires a closed, temperature-controlled circulation system for the index-matched ZnI_2 water solution used here.¹² The liquid systems operate continuously. The nitrogen flow system is semiautomatic and can be controlled from the system operator's console. The nitrogen flow control units are visible in Fig. 3-17 along the north wall near the table split. It has become apparent that temperature control of both the gas and liquid cooling systems for the disk amplifiers is required.

Large-aperture laser systems are troubled severely by turbulent temperature variations in the atmosphere through which the beam passes. Consequently, Argus employs sealed-beam tubes between each chain component. Experiments with Cyclops have shown that

Fig. 3-21. C-C spatial filter. With the Argus high bay in background, this spatial filter stands in the C-disk amplifier section of Argus.

turbulence can be reduced dramatically by completely enclosing the beam path between the final amplifier and the target lenses with insulating beam tubes, and recent experiments¹³ have shown that thermally conductive metal tubes do still better. Argus will use metal beam tubes in these locations.

Electrical Subsystems

The Argus laser is energized by a 6.8-MJ capacitive energy storage system located below the laser bay in the basement of Building 381. In its present two-arm configuration, Argus will use approximately 3.5 MJ of this capacity. A functional block diagram of the bank circuits is shown in Fig. 3-22. Details of the charge and fire controls will be described in Sec. 4.2.7. Here we mention three of the important features wherein Argus differs from Cyclops and Janus.

Operationally Argus is a manually controlled system. Laser control is centralized in one control room (Fig. 3-23), which is physically separated from the fusion-experiment control and diagnostics area.

Trigger Delay Generation. The Argus fire control system will incorporate the feature of external synchronization; this is necessary to accommodate the mechanical ASE shutters that will eventually provide the event signal upon which chain firing commences. The circuitry has been designed and is in the fabrication stage. It employs CMOS elements for higher signal levels and consequently greater noise immunity.

Block Charging and Firing. For a system as large as Argus, it is cost effective to charge capacitors and fire flashlamp circuits in parallel blocks. Charging to 20 kV is accomplished with 100-kVA power supplies, distributed in circuit blocks as shown in Fig. 3-22. Size-D ignitrons fire lamp circuits in blocks of 16 circuits (32 lamps) each. All disk amplifier flashlamp circuits are handled in this way, as are the C-size Faraday-rotator magnets. All rod amplifiers and smaller rotators are energized with 5-kV circuits. Again, parallel firing of both arms is employed.

Pulsed Ionization-Lamp Check (PILC). To avoid catastrophic lamp failure, it is desirable to check the state of each flashlamp circuit before firing a laser shot. Argus incorporates a separate lamp checking system called PILC, which charges and fires auxiliary capacitors through each lamp circuit upon command and presents the ionization results in the form of a Go/No-Go signal derived from each current waveform. The schematic of the PILC circuitry is shown in Fig. 3-24.

W. W. Simmons

Argus Upgrade

Computer simulations indicate that laser fusion target performance is a very sharply increasing function of laser power in the 5- to 20-TW regime. The performance of the Argus laser system can be increased to this power regime by enlarging the laser and using improved laser optical materials. Although funding for such an upgrade is not now available, the promising performance of targets in recent simulations has prompted a reexamination of the Argus upgrade potential.

Many possible upgrades have been considered, increasing the chain count by adding two 20-cm C aperture chains, increasing the chain length by adding two 30-cm-aperture D amplifiers per chain, double passing, overfilling apertures, and using phosphate or fluorophosphate glass. The implementation sequences, costs, and performances of these options are illustrated in Fig. 3-25. The combination of increasing to four chains and resuiting with new glass will yield 8 to 12 TW, depending on the fill factor. Of the intermediate upgrades, this has the highest performance, highest performance-cost ratio, and lowest technical risk. The further upgrade by addition of D amplifiers is less performance-cost effective and begins to duplicate the Shiva system capability without certain operational advantages—for example, automatic alignment and computer control. The implementation of a D-amplifier upgrade would require some time and cost to fully develop the D amplifier before using it in irradiation systems.

More Chains or Longer Chains. The C-chain and D-chain stagings and performances are illustrated in Fig. 3-26. This C-chain differs from the Argus C-chain in that a beam split after the B-to-B spatial filter requires the previous stages to be driven slightly harder, with a resultant increase in ΔB in the earlier stages. When the whole chain is driven to obtain a maximum ΔB of 1.5 nepers, the resultant ΔB is 6.3 rad with an output power of 1.0 TW per chain or 4.0 TW for four chains. Under the same operating constraint the D-chain produces 1.3 TW per chain or 5.2 TW from two chains with $\Delta B = 5.9$ rad. The incremental costs are \$3.4 million for additional C-chains and \$2.7 million for D amplifiers. By adding another spatial filter (right in all) between the D amplifiers, the D-chain option could yield about 3.4 TW but with ΔB about 1.3 rad. The C-chain option has a higher performance and higher performance-cost ratio. The relative merits of the C- and D-chain options are summarized in Table 3-4.

Fill Factor. The powers quoted above result from the use of a parabolic beam profile, which yields high illumination uniformity on spherical targets and causes little beam distortion at peak power. However, the

Fig. 3-22. Functional schematic of the Argus power conditioning and distribution networks illustrating the block-charging and block-firing scheme in present use.

Fig. 3-23. Argus control room. The racks in the background show the television area monitor displays and voltage control modules. The operator's console in the foreground contains the radio intercom, TV controls, master charge and fire panel, rate generator, and fault detector panels. The IIP 9830 unit on the right analyzes and presents calorimetric and photodiode information.

Fig. 3-24. Schematic diagram of the pulsed ionization lamp check (PILC) fault detection circuitry, which tests the integrity of the flashlamps before each shot by means of a low-energy ionization pulse.

Assumptions:

Condition	Improvement
Double C chains	X2
Add D amplifiers	X1.3
Fluorophosphate glass	X2
$\Sigma B = 6$ neper in all cases

Fig. 3-25. Argus upgrade options. Argus can achieve increased power (1) by adding two more C chains, (2) by adding two D amplifiers per chain, and (3) by using phosphate and/or fluorophosphate laser glass. The costs per modification are shown. The power variation resulting from the change in fill factor is illustrated by the length of the box in the figure; 1.5x is shown, but 1.7x may be achievable. If a whole-chain ΣB greater than 10 neper is usable, the improvement factor for the two-D option can be increased to about 1.6x; $\Sigma B = 13$ neper. However, the addition of two C chains to Argus appears the most reasonable route to the 10-TW regime.

power obtained with this profile (fill factor = 2.4) from any aperture is about 43% of that which would be obtained from a uniformly illuminated aperture (fill factor = 1.0). While some apodization is necessary to prevent Fresnel rings from occurring, aperture filling of up to 75% (fill factor = 1.3) in the final stages can be accomplished by special apodization. Targets that require less illumination uniformity and can tolerate moderate beam distortion at high power can be irradiated with more power from the same laser. This will increase the output power of the four-C-chain system, for instance, from 4.0 TW to about 6.8 TW

while operating at the same $\Delta B_{\max}$ of 1.5 rad and $\Sigma B = 6.3$ rad.

Double Pass. Double-pass options are discussed in the last annual report. In general these options will save about 20% of the incremental cost for the four-C-chain option at little performance penalty for 100-ps pulses but with about a 30% decrease in energy output for 1000-ps pulses because of saturation. For longer-pulse experiments, this decrease in output energy is undesirable. However, the performance and cost tradeoffs are close enough that this option is receiving further study within the context of the four-C-chain system.

New Glass. The implications of new laser materials are discussed more thoroughly below in Sec. 4.3.1. Simply stated, the performance of any Argus system can be improved by about $2\times$ by using phosphate and fluorophosphate laser glass, FR-5 rotators, and possibly CaF_2 lenses. The performance-cost ratio for this improvement to the four-C-chain system is about twice that of the initial upgrade of two additional C chains with silicate and borosilicate optics.

Summary. The initial upgrade concept of adding two more C laser chains to the existing two Argus chains still appears to be the highest performance and

performance/cost option. The further improvement available with new laser materials is very cost- and performance-effective. A reasonable schedule for this scenario would call for the fabrication of two chains and the procurement of new glass for installation after about a year of laser fusion experiments on the two-chain Argus system. This would increase the Argus power rating from the present 2-3 TW to 8-12 TW and access the 10-TW power regime sooner than is possible with any other laser system.

T. J. Gilmartin
W. W. Simmons

C chain with silicate glass

D chain with silicate glass

Symbols:

- spatial filter
- polarizer
- amplifier
- rotator
- lens

Fig. 3-26. Argus staging options. The differences in staging between the C chain and D chain upgrades are a beamsplit in the C chain and in the D chain the addition of one C polarizer, one D polarizer, two D amplifiers, and one D spatial filter with the C rotator moved forward one group. Both chains are driven to a maximum $\Delta B = 1.5$ rad and a whole chain ΣB of about 10 rad.

Table 3-4. Comparison of Argus upgrade options

System parameters	4 C chain	2 D chains
Total apertures	1260 cm ² in 4 apertures	1410 cm ² in 2 apertures
Performance	8 TW at $\Sigma B = 6$ rad	5 TW at $\Sigma B = 6$ radian
$\Delta B_{\max}$	1.5 nep	1.5 nep
Estimated cost	\$6.6 M	\$5.7 M
Performance/cost	150 GW/nep SM	90 GW/nep SM
Energy (100 ps)	0.8 kJ	0.5 kJ
(1 ns)	4.4 kJ	2.9 kJ
Flux maximum	15 GW/cm ²	9 GW/cm ²
Fluence maximum		
(100 ps)	1.5 J/cm ²	0.9 J/cm ²
(1 ns)	8.4 J/cm ²	4.9 J/cm ²

3.2.4 SHIVA LASER SYSTEM

Project Overview

Neodymium:glass laser technology has proceeded at a rapid pace for the past several years. Cleopas has demonstrated that reliable laser chains can operate at the terawatt power level with subnanosecond pulses. Additionally, analytical models for these lasers have been developed that permit performance and cost optimization, which is of paramount concern when large numbers of chains are to be incorporated into a system such as Shiva. The Shiva system represents the ultimate application of the most recent advances in glass laser design as well as electrooptical and control system technologies.

During 1975, the Shiva laser system transitioned from the system design phase into the detail design and procurement phase. This occurred at the optical design freeze in July 1975, at which time the neodymium laser glass and the major optical components were specified. In the following pages, many of the technical facets of the Shiva system are discussed in detail.

The first part of this article (*Laser Chain Design and Alignment System*) deals with the laser subsystem. Included there is a review of the staging methodology that has been applied to the Shiva baseline design, the expected performance characteristics for this design, and the electrooptical systems used for beam alignment and focusing. Specific functions performed by the electrooptical system include pointing and centering of the master and cw alignment oscillators, pointing at the apodizing aperture, and final beam centering, pointing,

and focusing. Characteristic of these functions is the use of highly accurate servo-controlled angle gimbals and translation stages. The final 30-cm-diam turning mirror, for example, requires angular control to an accuracy of several microradians. Alignment system studies were completed by several outside contractors. Follow-on contracts were awarded to Aerojet to design and prototype the main alignment system and to Hughes to develop their mode-locked pulse homodyne systems for synchronizing the pulses fired along the 20 laser chains.

The second part of this article (*Target Chamber*) details the requirements and design status of the target chamber system and the final focusing lenses. Target positioning apparatus, laser and plasma diagnostic instrumentation, the final focus lens and its concomitant drive mechanism are integrated into a spherical vacuum vessel 1.6 m in diameter. The 20 laser ports are located in an icosahedral pattern about the sphere with target and diagnostic ports at interstitial positions. Lens motions along the x, y, and z axes will be computer controlled to accuracies of about 1 μ m. The lens system is an f/1.6 doublet with a focal length of 46.5 cm. The outer lens, which is aspherized, also serves as a vacuum barrier. The inner lens has spheric surfaces and can be readily refinished when it becomes contaminated from target debris. Both lenses have been carefully designed as a doublet to eliminate damage-causing internal caustic foci and to provide near-optimum beam profile transformation for uniform target illumination. These lenses are now being pro-

totyped. The target chamber sphere design is complete and is currently being fabricated. The x-y-z lens transport system design is 70% complete.

The laser and target chamber support structures are discussed under the title *Mechanical Support Structure*. These structures, which are constructed from steel tubing, have been thoroughly analyzed with respect to acoustic, thermal, and stress-induced perturbations. Computer graphics, for example, have been used as an aid in visualizing vibrational modes that could be excited by ground motion. Calculations show that translation and rotation motions of the structures are well within the limit imposed by optical alignment tolerances providing thermal stability of the laser and target bays is maintained. To this end, a vertical airflow control system is being installed in the laser and target bays. This system is designed to limit point-to-point thermal drift to a value of about $\pm 0.5^\circ\text{C}$ over a 15-min period. Floor-to-ceiling temperature variations are expected to be no larger than about $\pm 1^\circ$ over the same 15-min period. The space-frame design and analysis for both the laser bay and target chamber is complete and being fabricated. The cradle for supporting the components on the space frame was prototyped and tested and the design finalized.

A discussion of the Shiva power conditioning system is found under the title *Power Conditioning*. At the heart of this system are the power supplies, ignitron switches, and capacitors required to deliver some 20 MJ of electrical energy to the flashlamp and Faraday rotator circuits. All capacitor voltages with the exception of those used for the master oscillator will be nominally set at 20 kV. The system is designed for a 10^5 -cycle lifetime at this voltage. Staging of the power supplies and switches are such as to provide gain control of common amplifier sections and individual gain control of one of the final power amplifiers in each chain. Such staging permits the optical power output of each amplifier group to be optimized and the total output power of each chain to be equalized. The power conditioning system design was completed and the components were studied by Maxwell and Physics International to improve manufacturability and reliability. The flashlamps were specified, bid, and are currently being procured.

Control system architecture is discussed in the last part of this article. To handle the wide diversity of functions that must be controlled, the system has been divided into four functional groups. These groups include power conditioning, beam diagnostics, optical alignment and target position control, and target diagnostics. The control system philosophy has shifted significantly toward a greater use of special-purpose computers and digital data buses as compared with hardwired data and control lines. In early stages of

Shiva development, the four groups will be functionally independent. In later stages they will be integrated through a central computer control. This concept is in the system design phase.

J. A. Glaze
R. D. Godwin

Laser Chain Design

This section describes the design and expected performance characteristics of the Shiva amplifier chain. The approach used in this analysis is to select an output stage that essentially determines the output power of the chain. The driver stages can then be determined from optimization conditions discussed shortly. The resulting chain designs are then compared on the basis of focusable power per unit cost to determine the most cost-effective amplifier chain.

Design Constraints. The focusable power of Nd:glass lasers operating in the subnanosecond pulse regime is primarily limited by nonlinear effects causing small-scale beam breakup. To design amplifier chains that minimize these nonlinear effects in a cost-effective manner, a figure of merit $Z = X/C$ was introduced, which measures the performance X per unit cost C of a laser system.¹⁵ The Z parameter is proportional to the focusable power on target per unit cost and was used as the primary guideline for the design of the amplifier chains without spatial filters. The quantity X is an unequivocal measure of the performance of an amplifier chain in that it depends only on material properties, geometry, and performance characteristics of the individual components in the chain but is independent of the beam profile and the power of the laser beam.

Without spatial filters in the chain, the Z criterion is sufficient to determine the optimum amplifier chain. However, with spatial filters in the chain additional design guidelines are required, because in this case the power on target is primarily determined by the power capability X_0 of the output stage alone. Spatial filters have been successfully tested to provide an effective means of reducing small-scale beam breakup and hence increase the power capability of the overall laser system. On the assumption that the spatial filters remove all troublesome hot spots in the beam, the effects of small-scale self-focusing could be eliminated by adding more and more spatial filters to the chain. Ideally the number of spatial filters in the chain should increase until the transmission losses, cost, and beam-breakup contributions of the spatial filters themselves begin to offset any further increase in system performance. This approach would result in amplifier chain designs that are almost flux limited. This becomes apparent if we take the extreme and assume that the transmission

losses, cost, and beam-breakup contributions of the spatial filter are negligible. In this case the chain design considerations are the same as for amplifier chains without nonlinear limitations, which results in general in flux-limited designs. Even though such a system design would have the maximum Z value, it would result in an unrealistic number of spatial filters and a correspondingly high ΣB value.

Since the spatial filters do not remove intensity ripples of low spatial frequency, the growth of these larger hot spots as well as the effects of whole-beam distortions on illumination uniformity of the target must be considered. Both of these effects are proportional to the whole-chain ΣB value, which is the sum of the beam-breakup contributions of all components in the chain. In contrast, the small-scale beam breakup can periodically be reset to zero and hence is only accumulated over the individual groups of components between spatial filters. Consideration of the whole-beam distortions leads to a design approach that maximizes the power on target per unit cost and per unit whole-beam ΣB . This approach, which maximizes the quantity $Z_w/\Sigma B = X_w/C/\Sigma B$, results in B-limited designs similar to the designs without spatial filters. However, these designs are more costly than flux-limited designs with identical output stages and hence reduce the total affordable power on target. A compromise between these two extremes uses the nearly flux-limited design approach for the expensive output stages and the B-limited design for the relatively cheaper driver and preamplifier stages.

Design Methodology. To determine the performance characteristics of different design approaches, the cost and performance data as previously outlined were used.¹⁶ These data are normalized to allow comparison of different amplifiers as characterized by $Z_A = X_A/C_A$, where $C_A = C/\ln G$ and $X_A = X(1-1/G)$. C_A is the specific cost per neper of gain, G is the numerical net gain, and X_A is the normalized power capability of the optimized disk amplifiers. This normalization assumes that the normalized cost and performance characteristics for an optimally designed amplifier are independent of the length of the amplifier, which is true as long as we can ignore end effects. In other words, several identical amplifiers in series have the same cost effectiveness $Z_A = X_A/C_A$ as a single unit. Hence an optimized amplifier can be completely described by X_A and C_A alone, and G is a variable that is determined by the assembly of the amplifiers within the chain.

The cost effectiveness of disk amplifiers reaches a maximum for clear apertures in the range from 15 to 20 cm. For larger clear apertures the cost increases faster with diameter than does X because of parasitic limitations and the cost of large optics, whereas for smaller clear apertures the performance X decreases faster than

the cost because of per-unit cost contributions that are almost independent of the clear aperture and hence dominate small-aperture devices.

Because the output stage of a chain dominates the performance as well as the cost of the chain, one can infer from this that a chain with an output aperture equal to or somewhat larger than the optimum clear aperture of the disk amplifiers should provide the highest power on target per unit cost. The approach used in this analysis is to select an output stage of clear aperture D_0 and then determine the optimum driver and preamplifier stages. Amplifier chains with various output apertures are then compared to determine which chain provides the highest cost effectiveness.

To reduce the ideal continuum optimized chain to discrete components, one can choose unit-length amplifiers, which divide an idealized continuous chain into "quantized" stages. The selection of unit-length amplifiers is a cost-effective approach because it allows standardization of components like flashlamps, energy storage banks, and support structures. This procedure is possible only because the cost effectiveness of the various amplifiers is relatively insensitive to variations in disk dimensions, which allows final adjustment of disk thickness and diameter to achieve optimum X values.

Selecting a unit-length output stage with a clear aperture D_0 defines X_0 and G_0 . This is sufficient to completely determine the design of the chain for either the flux-limited or B-limited design approach. The power on target P_T for a chain with spatial filters and a beam of uniform radial profile is given by

$$P_T = P_0 f(B_0) = X_0 F B_0 f(B_0) = G_0 P_1 f(B_1) f(B_0) \\ = G_0 X_1 F B_1 f(B_1) f(B_0) ,$$

where P_0 , P_1 , X_0 , X_1 , and B_0 , B_1 are the output powers, X values, and beam-breakup values for the output and first driver stages, respectively. The function $f(B)$ is the power transmission function of the spatial filters and F is the fill factor, defined as the ratio of the spatial average to peak beam intensity. From this equation the required X value of the first driver stage can be determined by

$$X_1 = \frac{X_0}{G_0} \frac{B_0}{B_1 f(B_1)}$$

The question now is which B values are optimal to obtain maximum power on target per unit cost. For chain designs without spatial filters, the power on target is determined by

$$P_T = X F B f(B) ,$$

which leads to an optimum B value for which the function $Bf(B)$ reaches a maximum. However, this is true only if the cost of input power to the chain or stage is negligible. For chain designs with multiple spatial filters, input power from the driver stages is costly; and, for large chains with many spatial filters, this becomes the dominating cost. In this case the optimum B value is approximately the B value for which the function $Bf^2(B)$ reaches a maximum, since $P_T \approx B_1 f(B_1) f(B_0)$ and $B_0 \approx B_1$ from considerations of cost effectiveness. Figure 3-27 shows the functions $f(B)$, $Bf(B)$, and $Bf^2(B)$ for a parabolic beam profile;

$$f(B) \approx \exp [-(B/3.4)^8]$$

for the present state-of-the-art amplifiers. For amplifier chains without spatial filters the optimum B value is about 2.6, whereas for amplifier chains with several spatial filters the optimal B value is approximately 2.4.

This results in a X value for the first driver stage of

$$X_1 \approx 1.06 X_0/G_0$$

Fig. 3-27. Power-transmission function for parabolic beam profile. The function $f(B)$ has been deconvolved from the experimentally measured transmission of spatial filters. The maxima of the functions $Bf(B)$ and $Bf^2(B)$ reveal the values of B for which the performance of amplifier chains with and without spatial filters is maximized.

The desirable clear aperture of the first driver stage can be determined for the flux-limited design approach by

$$D_1 = D_0 G_0^{-1/2}$$

and for the B -limited design approach by

$$D_1 \approx D_0 \left(\frac{u}{v} G_0 \right)^{-\frac{1}{u+v}}$$

where $u = \partial C / \partial D$ and $v = \partial X / \partial D$ as outlined in the last annual report. Specifying X_1 and D_1 defines G_1 and hence completely defines the first driver stage. The same process is then consecutively repeated for each driver and preamplifier stage. Several iterations of this process may be required to obtain fully optimized chains and components, but in general the results converge very rapidly toward the optimum solution.

Since u and v are typically in the range of 1.5 to 2,

$$D_1 \approx D_0 G_0^{-1/3.5}$$

In other words, the clear aperture of the various driver stages decreases faster for the flux-limited design approach than for the B -limited design. Both designs provide the same output power, but the flux-limited design is less costly while the B -limited design has lower whole-beam distortions.

The ideal solution would be to define a ratio of effective power on target to the incident power on target as a function of the whole-chain B value in the form $P_{\text{eff}} = P_T g(\Sigma B)$. Such a relationship should be obtainable by considering illumination uniformity and normality on the target and would allow a tradeoff between whole-chain B and power on target by maximizing the quantity $Z_0 g(\Sigma B)$.

Shiva Amplifier Chain. For the Shiva laser system, a compromise between the flux- and B -limited design approaches was selected to provide best overall performance and cost effectiveness. In addition, the individual stages were somewhat modified to extend the dynamic range of the system by improving the system performance for longer (1 ns) pulses, for which saturation effects become appreciable.

The individual stages of an amplifier chain, which are separated from each other by spatial filters, can be considered as providing focusable power to the next larger stage. Because the focusable power of each stage is limited, it is important to match the individual stages quite carefully so that they can provide sufficient drive power to each other. In other words, each link of the chain should be equally strong. A weak stage will reduce the overall performance of the chain, while an excessively strong stage will not improve the perfor-

mance but will increase the cost and hence reduce the cost effectiveness of the system. For the Shiva amplifier-chain design the safety margin for the succeeding driver stages is increased beyond optimum to ensure full use of the output stage, which, of course, is the most costly stage. This graded-margin approach results in preamplifier stages that are somewhat over-designed; but the cost impact is low, and hence this approach is a cost-effective way of reducing risk.

The design specifications for the present Shiva amplifier chain resulting from all these considerations are summarized in Tables 3-5 and 3-6. For short-pulse operation of the system (<0.1 ns) the small-scale beam-breakup contributions of the driver stages are successively lower than for the output stage to allow for saturation and provide the safety margin. For short-pulse operation the output stage is the limiting stage of the system, whereas for 1-ns operation the six β -disk amplifier stage becomes the limiting stage.

A schematic layout of this laser system is shown in Fig. 3-28. This system is designed for full isolation against perpendicularly polarized light but only 30% isolation against parallel-polarized light. This means that opposing beams at the target chamber must be perpendicularly polarized with respect to each other. The use of reflecting polarizers was anticipated for the output stages of this system because of the negligible B contributions of these polarizers. However, difficulties of keeping the system aligned as well as considerations of the cost and versatility of the system may require the use of transmitting polarizers with an attendant loss in focusable power. The output beam of each chain is diverging so as to reduce the beam intensity on the turning mirrors and focusing lens. Expanding the beam from 20 to 30 cm also reduces the B contribution of the focusing lens and hence allows a higher output power.

Expected Performance Characteristics. The nominal focusable power from each Shiva amplifier chain is expected to be about 1.35 TW, which corresponds to 27 TW for the 20-arm Shiva system. The whole-chain ΣB value at this output level would be $\Sigma B \approx 8.6$, which corresponds to an approximately spherical phase retardation of 1.4 waves. This phase retardation is equivalent to a shift of the focal point during the pulse of about 30 μm for the $f/1.6$ focusing lens. However, the performance of this laser system depends critically on the performance of several spatial filters in series, which has yet to be verified experimentally.

The intensity distribution along the chain is shown in Fig. 3-29. The peak beam intensity as shown in this graph corresponds to a smooth filleted parabolic beam profile with a fill factor of 0.43 and does not include hot spots in the beam nor changes of the beam profile resulting from gain nonuniformities or transmission losses in the spatial filters. The beam intensity inside

the laser disks is actually reduced by the index of refraction because of beam expansion at Brewster's angle. The highest beam intensities, about 12 GW/cm², exist at the input lenses of the spatial filters following the β and γ amplifiers. The antireflection coatings of these lenses have to be of exceptionally high durability or uncoated lenses have to be installed to allow full utilization of the system for pulses of 0.3 ns or longer as shown in Fig. 3-30. The peak beam intensities at the Faraday rotators, polarizers, and focusing lenses are less than 7 GW/cm² and hence should not limit the performance of the system. The expected output power of the Shiva laser system as shown in Fig. 3-30 was evaluated for a constant whole-chain B value of 8.6. In this case the output power decreases with increasing pulse duration because of saturation from about 27 TW to 15 TW for 0.1- and 1-ns pulses, respectively. The two curves shown in Fig. 3-30 correspond to the nominal performance characteristics of the system with and without antireflection coatings on the input lenses of the spatial filters following the β and γ disk amplifiers. This laser system should be capable of producing up to 30 TW as long as significant variations of the temporal and spatial beam profile can be tolerated.

W. F. Hagen

Alignment System

The ability to accurately align Shiva from oscillator to target in a timely fashion will be essential to productive operation of the system. Because present manual techniques are too slow for efficient day-to-day use on even the current one- and two-beam systems, Shiva alignment must be automated to the maximum possible extent, and adjustments requiring physical access to components that may be four or five stories above the laser bay floor must be minimized. Figure 3-31 is a schematic of the components related to Shiva alignment.

Because high repetition rates are not possible with the pulsed oscillator and preamplifiers used on Shiva for target shots, 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 for use with a 1-kHz, 1.06- μm source. The same or a similar oscillator operating in a cw mode-locked mode will be used for path-length equalization.

Collinear Alignment of the Pulsed and cw Oscillators. The oscillator alignment system automatically points and centers both the cw and pulsed oscillators with respect to a pointing and centering (PC) sensor,

Table 3-5. Shiva amplifier chain

Element	Clear aperture (mm)	Nominal beam diam (mm)	Thickness or length (mm)	Angle of incidence of beam (deg)	T_p^a (%)	T_s^b (%)	Small-signal net gain or loss	Power capability (TW)	Nominal output power at 0.1 ns (TW)	Beam-breakup contribution
Target							(0.94)		1.35	2.43
Focusing lens f=0.48 m	310	290	68	0	96	96	0.96	5.4	1.44	0.61
2 turning mirrors	300	<270		<55	1	1	0.98	∞	1.50	0
2 reflecting polarizers	300	<260		56.4	95	1	0.98	∞	1.53	0
3 β disks	208	202	32	57.3	98	70	1.95	2.66	1.56	1.35
Faraday rotator	220	198	14	0	98	98	0.98	14	0.80	0.26
2 reflecting polarizers	220	195		56.4	95	1	0.98	∞	0.82	0
Spatial-filter lens f=2.20 m	220	193	17	0	98	98	0.98	9.5	0.83	0.21
Pinhole	0.5						(0.98)		0.85	2.07
Spatial-filter lens f=1.60 m	160	145	12	0	98	98	0.98	6.8	0.87	0.30
4 γ disks	150	145	30	57.3	98	70	2.64	1.23	0.88	1.65
Spatial-filter lens f=1.60 m	160	145	12	0	98	98	0.98	6.8	0.33	0.12
Pinhole	0.3						(0.98)		0.34	2.00
Spatial-filter lens f=1.00 m	100	91	8	0	98	98	0.98	4.25	0.35	0.20
6 β disks	94	91	24	57.3	98	70	3.80	0.468	0.36	1.75
Spatial-filter lens ³ f=1.00 m	100	91	8	0	98	98	0.98	4.25	0.094	0.05
Pinhole	0.3						(0.99)		0.096	1.17
Spatial-filter lens f=1.00 m	100	91	8	0	98	98	0.98	4.25	0.097	0.05
2 transmission polarizers	100	91	10	56.4	96	1	0.92	†	0.099	
Faraday rotator	100	91	8	0	98	98	0.98	0.65	0.107	0.38
2 transmission polarizers	100	91	10	56.4	96	1	0.92	†	0.109	
12 β disks	94	91	24	57.3	98	70	14.4	0.37	0.118	0.73
Spatial-filter lens f=1.00 m	100	91	8	0	98	98	0.98	4.25	0.0082	0.004
Pinhole	0.15						(0.99)		0.0083	0.92
Spatial-filter lens f=0.48 m	50	44	5	0	98	98	0.98	1.3	0.0084	0.92
2 transmission polarizers	50	44	5	56.4	98	1	0.96	†	0.0086	
Pockels cell	50	44	60	0	96	96	0.96	0.10	0.0089	0.20
2 transmission polarizers	50	44	5	56.4	98	1	0.96	†	0.0093	
Rod	50	44	400	0	88	88	11.5	0.043	0.0097	0.52
Collimating lens f=0.48 m	50	44	5	0	98	98	0.98	†	0.0008	0.00
Expansion lens f=0.23 m	30	21	5	0	98	98	0.98	†	0.0009	
2 transmission polarizers	30	21	5	56.4	98	1	0.96	†	0.0009	
Pockels cell	25	21	40	0	96	96	0.96	0.04	0.0009	0.05
2 transmission polarizers	30	21	5	56.4	98	1	0.96	†	0.0010	
Rod	25	21	400	0	88	88	100	0.018	0.0010	0.13
Apodized aperture	50	21	10	0	10	10	0.10	0.15	10^{-6} 10^{-5}	0.00 8.60

^a T_p = transmission for parallel polarization.^b T_s = transmission for perpendicular polarization.

Table 3-6. Shiva preamplifier section

Element	Clear aperture (mm)	Nominal beam diameter (mm)	Thickness or length (mm)	Angle of incidence of beam (deg)	T_p^a (%)	T_s^b (%)	Small-signal net gain or loss	Nominal output power at 0.1 ns (GW)
Apodized aperture	50	21	10	0	10	10	0.10	0.010
5 X beamsplitter	100	44	10	45	20	20	0.15	.100
Rod	50	44	400	0	88	88	11.5	.667
5 X beamsplitter	100	44	10	45	20	20	0.15	.058
Spatial-filter lens $f = 0.48$ m	50	44	5	0	98	98	0.98	.386
Pinhole	.03	—	—	—	—	—	(0.50)	.394
Spatial-filter lens $f = 0.48$ m	50	44	5	0	98	98	0.98	.789
Rod	50	44	400	0	88	88	11.5	.805
Collecting lens $f = 0.48$ m	50	44	5	0	98	98	0.98	.070
Expansion lens $f = 0.23$ m	25	21	3	0	98	98	0.98	.071
2 transmission polarizers	30	21	3	56.4	98	1	0.98	.073
Pockels cell	25	21	40	0	96	96	0.96	.074
2 transmission polarizers	30	21	3	56.4	98	98	0.98	.077
Rod	25	21	400	0	88	88	100	.079
Oscillator + pulse shaper								0.0008

^a T_p = transmission for parallel polarization.

^b T_s = transmission for perpendicular polarization.

Fig. 3-28. Schematic layout of the Shiva laser system resulting from the optimization conditions discussed in the text. The focusable output power from this 20-arm Shiva system is expected to be about 27 TW, with a corresponding whole-chain ΣB value of 8.6.

which is mounted on a preamplifier table rigidly attached to the laser space frame. The oscillators may be mounted on separate tables with the possibility of some relative motion. However, since realignment in this part of the system can be done very quickly, such motion is not expected to be a problem. Centering of pinholes in the two spatial filters mounted on the preamplifier table will be monitored by imaging the pinhole planes through a turning mirror onto a silicon vidicon. The relative (x,y) positions of the beam and the pinholes can be determined by alternately inserting and removing a negative lens ahead of each spatial filter to overfill the pinholes. Frequent pinhole adjustments should not be necessary and will be done manually when required. Centering of the preamplifiers on the beam does not have to be done with great precision and recentering will rarely be required.

Centering and pointing errors in the oscillator and preamplifier sections are expected to be caused by drift in table supports, mirror mounts, and lens holders. In addition, motions of flat transmitting components such as rods, Pockels cells, and polarizers may cause some small centering errors. To maintain centering on the apodizer to within ± 1 mm, the beams leaving the preamplifier table must be pointed with an accuracy of

$\pm 25 \mu\text{rad}$. However, a more stringent requirement is placed on the pointing of the two beams by specifying that no more than 10% of the allowed $4\text{-}\mu\text{rad}$ pointing error at the target chamber arise from lack of collinearity between the cw and pulsed oscillators. This leads to a required pointing accuracy at the end of the preamp table of $\pm 2 \mu\text{rad}$. With this pointing accuracy the beams may then be decentered at this point by ± 1 mm without causing any problem at the apodizer.

Pulsed signals from quadrant detectors in the PC sensor are sent to peak reading sample-and-hold circuits. This signal could then be processed by a closed-loop analog system; however, the low 0.5-Hz sampling rate of the pulsed oscillator would severely limit the speed of such a system. Consequently, a digitally controlled system is being designed that reads the errors and calculates and implements the full corrections required on each shot. With this approach only a few pulses will be required to reach final alignment.

Front-End Pointing and Centering. To remain centered in the spatial-filter pinholes of each chain to within one focal spot diameter or about one-seventh of the pinhole radius, the beam must be pointed with an accuracy of $100 \mu\text{rad}$ at the input of each amplifier chain. Between the preamplifiers' PC sensor and the

Fig. 3-29. Intensity distribution along the amplifier chain for a smooth parabolic beam profile with a fill factor of 0.43. The highest beam intensities exist at the input lenses of the spatial filters following the β and γ amplifiers. Uncoated lenses are probably required for full use of this system at long pulse durations.

Fig. 3-40. Performance characteristics of the 20-arm Shiva system for various pulse durations. The damage limitations of the antireflective coatings on the spatial-filter lenses may result in reduced output-power capabilities as indicated for the case of uncoated spatial filter lenses.

apodizer, most beams transit seven mirrors; if the drift of all these mirrors were to add directly, each mirror would have to be stable to within 7 μ rad. If the mirror drifts were to add in an rms fashion, the average stability requirement would be $\pm 20 \mu$ rad. To measure the angular error at the front of each chain and to correct for drift outside these tolerances, a pointing sensor located immediately after the apodizer in each chain will drive a servoed pointing gimbal located incidentally on the corresponding path-length adjustment mount for that chain.

Because the dependence of the apodized profile on the relative centering of the incoming beam and the apodizer is weak, decentering errors on the order of ± 2 mm can be tolerated and automatic centering onto the apodizer will not be required.

Pinhole Positioning in the Main Chain Spatial Filters. The relative transverse positions of the focal spots and the pinholes in the main-chain spatial filters will be determined in the same way as described above (under *Collinear Alignment of the Pulsed and cw Oscillators*)—namely, the pinhole planes will be imaged onto a Vidicon. In this case the Vidicon will be located in the pointing, focusing, and centering (PFC) sensor located directly across the target chamber from the beam in question. Remotely controlled stepping motors will give the operator the ability to adjust pinhole positions as needed.

Centering on the Focusing Lens. The PFC sensor located behind the final turning mirror in each chain has several modes of operation. In the centering mode, a plane 50 cm ahead of the focusing lens is imaged onto a

quadrant detector in the PFC package. A reflecting screen is positioned in this plane with its center approximately on a line passing through the nominal target position and the center of the focusing lens. When the alignment beam is on, it is reflected back into the PFC sensor and any difference between the position of the beam centroid and the center of the screen generates an error signal in the PFC monopulse detector.

Several schemes are under consideration for recentering the beam when an error is detected. In the one shown in Fig. 3-31 the error signals drive translation servos on the apodizer. A centering error of 9 mm on the screen can be corrected by an apodizer translation of less than 0.8 mm, because the beam displacement resulting from such a motion is increased in direct proportion to the beam size as the beam propagates through the chain. The position of the beam in the spatial-filter pinholes is unaffected by such an adjustment, but extra clear aperture must be allowed in all the other components of the chain.

Pointing at the Target. In the pointing mode the centering screen is removed, a surrogate spherical target is positioned in the target chamber, and the PFC sensor images the same plane 50 cm ahead of the focusing lens onto its detector. When the focused beam arrives at the target with its central ray normal to the surface, the beam reflected back through the lens is centered in the plane being imaged and generates no error signal. If the beam arrives at the target at any other angle, the back reflection is off center and the PFC sensor generates error signals that drive the servos on the final turning mirror. This pointing procedure is

Fig. 3-31. Schematic of the components related to Shiva alignment.

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 onto the PFC detector. The smallest diameter is obtained when the incoming beam is focused toward a point about halfway between the center and the front surface of the spherical target. Because the PFC sensor optics image a plane 50 cm in front of the focusing lens onto a Vidicon as well as onto the quadrant detector, the operator can visually determine when this focusing condition is achieved. On a given shot the experimenter specifies what offset from the front half-radius position he desires and the focusing lens is moved along the beam by that amount with the remotely actuated lens drive described earlier.

Path-Length Equalization. Several techniques are being considered, and a contract for production of a prototype is being negotiated.

Target Exchange and Positioning. The PFC sensor also has the capability of imaging a range of planes in the target volume onto the vidicon. Upon completion of the alignment steps described above, two orthogonally located PFC sensors are adjusted to view the surrogate target back-illuminated by incoherent light from the opposing PFC units. The surrogate's position is referenced on the monitors and the fusion target is then inserted in its place. In this mode, and when no target is in place, the Vidicon may be used to view an Areal image of the beam over a range of target planes.

Alignment Controls. Control system design to date has concentrated on determining the functional requirements of the systems described above, as well as on developing a detailed preliminary plan for tying all sections together into a single unified control scheme. As presently envisioned, local control panels in the laser bay and target room will provide manual control and monitoring of all sensors, gimbals, and drives on a one-chain-at-a-time basis, as well as manually enabled simultaneous closed-loop control of up to 20 chains for either front-end pointing, centering on the focusing lens, or pointing at the target.

Unified monitoring and control of all the alignment-related subsystems will be implemented in the main control room. An alignment-control processor will provide:

- Automatic sequencing.
- Continuous monitoring of performance with real-time identification of failures.
- Display of residual errors and gimbal positions in meaningful units.
- Computation support for manual alignment tasks.
- Recording and storage capability for residual

error and gimbal position data. Subsequent summaries will identify trends resulting from alignment drift or changes in alignment system performance.

- Software capability for implementing automatic focus control when focusing criteria are quantified.

- The flexibility needed for adding additional automatic alignment tasks such as front-end centering if they prove necessary.

Division of Work. The work associated with the alignment systems described above is presently divided among LLL, Aerojet Electrosystems Company, Hughes Aircraft Company, and an as yet undetermined vendor as follows:

- **LLL.** Oscillator alignment, manual front-end centering, pinhole positioning, processing of PFC sensor Vidicon, output for use in manual-remote focusing, centering screen and focus lens drive, and unified system control.

- **Aerojet.** Prototype front-end pointing system, prototype PFC sensor and associated apodizer translation stage and final turning-mirror gimbal, and prototype local controls for the above. The prototypes are for one chain only except for controls that are expandable to 20 chains.

- **Hughes.** Path-length equalization system.

- **To be determined.** Production front-end pointing system, PFC sensors, apodizer translation stages, final turning-mirror gimbals, and local controls for 20-beam system.

E. S. Bliss

M. A. Summers

R. Cody

F. W. Holloway

Target Chamber

Target Chamber Requirements. The laser-fusion experimental target chamber serves several purposes: target injection and positioning, laser beam focusing and positioning, diagnostics instruments support, and vacuum maintenance. Figure 3-32 shows the 20-beam Shiva target chamber.

The target-positioning system first positions the surrogate target, a 2-mm-diam spherical mirror, for laser alignment and then exchanges it with the fusion target to 1- μ m accuracy. For frozen DT targets, a vacuum lock and transfer mechanism introduces and transports the target to the firing point.

The focusing lenses are designed to project the laser beams in a precise illumination pattern on the target surface while adding the minimum of static and dynamic aberrations to the beams.

The diagnostics instruments mounted on the target chamber are used to characterize laser beam parameters

Fig. 3-32. The Shiva target chamber—a 1.6-m-diam vacuum vessel consisting of a 3-cm-thick 304L stainless steel sphere with 20 focusing lenses and drives and 12 large ports for target positioning, target diagnostics, and vacuum systems.

and target performance for each experiment. A tritium-gettering system absorbs the unreacted tritium from each experiment and stores it for later recovery.

The vacuum vessel and vacuum pumps provide a clean, low-pressure atmosphere (10^{-7} Torr) to prevent dielectric breakdown of the gas near focus, contamination or melting of the target, and absorption of x-ray and ion radiation used to diagnose target performance.

Target Positioning and Control. The design requirements of the target-positioning system are that the system must center the pellet to the firing point within $\pm 1 \mu\text{m}$ accuracy. It must also maintain a stability of less than $0.1 \mu\text{m}/\text{min}$ and a vibrational amplitude of less than $0.5 \mu\text{m}$. The fine-positioning range required is $\pm 1 \text{ cm}$. The target pylon must be rigid, yet it must fit in the narrow space between the cones of focused laser beams and not ablate from pellet fluence and reflected

laser light. A system of precision ball-screws, driven by remotely controlled electric motors, will be used to drive the target pylon in x, y, and z axes. Two orthogonal Vidicon tele-microscope viewing systems will be used to verify proper firing-point positioning and to view the pellet during steering to the firing point.

In addition to the micropositioning of glass and frozen DT targets, a longer-range consideration of ballistically injected frozen DT pellets is necessary. The Shiva target chamber will have space reserved for a local DT-target injection system.

For remotely fabricated frozen DT targets, the target chamber must have a vacuum lock through which the pellet can be moved to the firing point after laser alignment on the surrogate target. From the time the DT microshell has been fabricated until it is imploded, its temperature must be maintained at no more than

about 17 K. This will be accomplished by a liquid-helium cooling system plumbed to the mounting base of the target stalk. The system will be located inside the pylon and will move with it during pellet transporting and positioning.

Shiva Target-Chamber Vacuum Vessel Design.

The Shiva target chamber is spherical, 1.6 m in diameter, with a 3.5-cm-thick 304L stainless steel wall. Thirty-two 400-mm ports are evenly distributed around the sphere: 20 laser-beam ports, 9 diagnostic ports, 2 target ports, and 1 pumpout and tritium-gettering port. In addition, there are sixty 60-mm ports for other diagnostics and target alignment. The vacuum system evacuates the chamber to 10^{-7} Torr in 1 hr using a combination of sorption, cryopumping, and titanium-sublimation pumping. The pressure produced will limit the buildup of contaminating elements on the target surface and will prevent attenuation of the soft x rays, ions, and electrons used for diagnostics.

Diagnostics Instrumentation. The instruments that diagnose the laser beam and the laser-plasma interactions all have positioning, collimation, solid-angle of view, and vacuum environmental requirements. Some instruments—e.g., x-ray microscopes and pinhole cameras—require very precise alignment, whereas others with wide fields of view—e.g., PIN-diode x-ray spectrometers and 1- μ m radiometers—are not critically aligned. These and other considerations determine the overall arrangement and size of the target chamber.

Lens-Positioning System. The lens-positioning system is basically a focus ball-screw drive mounted on a single-stage x-y translation plate that moves on ball bearings. Table 3-7 lists the design parameters. Geared-down electric motors and ball screws provide motions and linear transducers measure position. The systems will be operated remote open-loop.

Final Focus Lens

The focus lens requirements are tight. The wave-front distortion must be no more than 0.1 wave at 1.06 μ m. The f-number must be minimized to produce a low

angle of incidence of the marginal rays on the target surface. To minimize nonlinear focusing effects on the beam, the thickness of glass must be minimized, and the same reasoning requires the lens to be a vacuum barrier to eliminate a vacuum window.

Design. The focus lens is designed to be aplanatic, meaning that the principal surface (apparent origin of focused rays) is spherical. This results in minimum coma and minimum correction for spherical aberration. Lens design and aspheric coefficients were determined with the ACCOS V optical design program on an LLL CDC 7600 computer.

The Shiva lenses are f/1.6 doublets 330 mm in diameter and 465 mm focal length, aspherically figured to 0.1 wave at 1.06 μ m including the effect of vacuum deflection. Previous laser-fusion focus lenses have required holes drilled on axis 5-10 mm in diameter to prevent the initiation of cracks from internally focused ghost images that propagate and destroy the lenses. The resulting shadow on the fusion target causes intensity gradients on the target surface that locally perturb the imploding pellet and degrade the target compression. The surface curvatures and antireflection coatings on the Shiva lenses are designed to minimize the intensity of internal ghost focal spots. The calculated intensity is far below the internal damage threshold, and holes are not required. Figure 3-33 shows the focus lens.

Illumination Mapping

Requirements. The illumination uniformity requirements for high final compression of the imploding pellet are such that, in the first 10% power deposition of the pulse, the variation of the intensity over the target surface must be less than $\pm 10\%$. During the rest of the pulse, intensity variations of less than $\pm 50\%$ will be smoothed out by electron conduction in the plasma. To achieve the illumination smoothness and the $\pm 4\text{-}\mu$ rad pointing and $\pm 7\text{-}\mu$ m focusing accuracies, the static quality of the optical chain must be less than 0.5 wave at 1.06 μ m. Figure 3-34 shows the 20 focused beams on target.

Table 3-7. Lens-positioning system design parameters

Parameter	Focus drive	X-Y drive
Step size	0.5 μ m	0.5 μ m
Focus error, 1 σ	1 μ m	1 μ m
Pointing error, 1 σ	1 μ m	1 μ m
Resolution	1.0 μ m	1.0 μ m
Range	± 7 mm	± 5 mm
Slew rate	680 μ m/s	500 μ m/s

Illumination Mapping Analysis. A beam-intensity profile is changed in shape when focused through a lens and wrapped partly around a target. Also, since the target plasma reflects a portion of the light depending on the angle of incidence, the intensity profile is further changed, because the angle of incidence is not constant for a beam focused at planes other than target center. Figure 3-35 shows a beam focused at a plane beyond the target such that the target wrap angle, θ , is 55° . When 20 beams are icosahedrally located and focused, the overlapped spots sum to a high illumination uniformity, according to the LLL LUXCON code, if the proper intensity profile ($R = 0.63$, $I = 0.405$) is provided.

Reflection of Laser Light by the Target Plasma.

The light rays should enter the plasma normal to the pellet surface for maximum absorption of light. As the angle of incidence increases, the fraction of light absorbed by inverse bremsstrahlung falls off according to¹⁷:

$$\bar{A} = 1 - e^{-2p \cos^5(\theta - \beta)},$$

p = optical thickness,

θ = target-coverage half-angle,

β = focal angle shown in Fig. 3-35.

Absorption Efficiency. The fraction of the beam energy absorbed in the target plasma is:

Fig. 3-34. Shiva D-T pellet with 20 overlapped focal spots in icosahedral positions.

Fig. 3-33. The Shiva f/1.6 focus lens, showing ghost image focal caustic points, forms a vacuum barrier on the target chamber. The first surface is aspherical to correct spherical aberrations of all the surfaces.

$$\epsilon_A = \frac{\int_0^r \int_0^\theta \int_0^A I(r) \bar{A} \sin \theta dr d\theta dA}{\int_0^r \int_0^A I(r) dr dA} = \frac{\text{absorbed power}}{\text{incident power}}.$$

The numerical integration of this from Table 3-8 gives an absorption of 53% of the beam. Since this fraction would be 63% if the illumination were perfectly normal, the illumination efficiency is $0.53/0.63 = 84\%$.

Lens-Target Intensity Mapping. If a set of equally spaced beam rays is focused beyond the target surface, the relative spacing and thus the annular area between the rays is changed on the target surface. Because power is conserved from beam (B) to target (T),

$$\frac{I_B/P_B}{I_T/P_T} = \frac{A_T}{A_B}$$

and

$$\frac{I_T}{I_B} = \frac{A_B}{A_T} \equiv L,$$

Fig. 3-35. Shiva lens/target geometry, with the target much enlarged compared with the lens. The curved dashed lines show the trajectories of the rays in the target plasma.

where L is the lens/target mapping function.

As shown on Fig. 3-35, the beam area is given by:

$$A_B = \frac{\pi(r_2^2 - r_1^2)}{\pi r_0^2} = r_2^2 - r_1^2, (r_0 = 1). \quad (1)$$

The target area is given by:

$$A_T = \int_{\theta_1}^{\theta_2} 2\pi r_t^2 \sin \theta d\theta = 2\pi r_t^2 (\cos \theta_2 - \cos \theta_1).$$

Setting $\theta_1 = \theta_0$ and $\theta_2 = 0^\circ$ gives the total area, $2\pi r_t^2 (1 - \cos \theta_0)$, and the normalized target area is:

$$\begin{aligned} A_T &= \frac{2\pi r_t^2 (\cos \theta_2 - \cos \theta_1)}{2\pi r_t^2 (1 - \cos \theta_0)} \\ &= \frac{\cos \theta_2 - \cos \theta_1}{1 - \cos \theta_0}. \end{aligned} \quad (2)$$

The mapping function is given by:

$$L = \frac{A_B}{A_T} = \frac{(r_2^2 - r_1^2)(1 - \cos \theta_0)}{(\cos \theta_2 - \cos \theta_1)}. \quad (3)$$

From Fig. 3-35 and the law of sines,

$$\beta = [\sin^{-1} \left(\frac{Q}{r_t} \sin \theta \right)] + \theta \quad (4)$$

Fig. 3-36. Intensity profiles obtained with the $f/1.6$ aplanatic focusing lens.

$$\frac{Q}{r_t} = \frac{\sin(\theta - \beta)}{\sin \theta}.$$

For an aplanatic lens,

$$r = f \sin \beta,$$

Table 3-8. Shiva target-lens-to-pellet illumination mapping numbers for 55° mapping

r/r_0	A_B (Rel. beam area)	β	$I(r)$ (0.8/0.2)	θ	$\theta - \beta$	A_T (Target area)	$\left(\frac{A_B}{A_T}\right)$	$I(\theta)$ [$I(r)M$]	$\left(\frac{B}{A}\right)$ $\left(1 - e^{-2P}\right)$	M (1 B)	P_0 Incident power [$I(r)A_T L$]	P_A Absorbed power ($P_0 A$)	$\frac{A}{1 - e^{-2P \cos^2 \theta}}$	A_{T10} (Rel absorbed power)	$\frac{\theta}{\theta_0}$
1.0		17.178		55	37.822										1
0.95	0.19	16.29	0.0125	51.91	35.62	0.196	0.94	0.0056	0.473	0.445	0.0023	0.00069	0.299	0.0011	0.94
.90		15.415		48.91	33.50										.89
.85	.17	14.54	.1125	45.96	31.42	.173	.954	.062	.576	.560	.0186	.0068	.364	.0107	.84
.80		13.665	.2	43.04	29.38										.78
.75	.15	12.8	.297	40.19	27.39	.150	.97	.193	.671	.651	.043	.0183	.424	.029	.73
.70		11.93		37.35	25.42										.68
.65	.13	11.07	.472	34.56	23.50	.131	.963	.343	.755	.727	.0595	.0284	.477	.045	.63
.60		10.206		31.72	21.59										.58
.55	.11	9.35	.622	29.06	19.71	.107	.997	.513	.827	.825	.0664	.0347	.523	.055	.53
.50		8.49		26.34	17.85										.48
.45	.09	7.637	.747	23.65	.02	.088	.992	.657	.886	.080	.0652	.0365	.560	.058	.43
.40		6.783		20.98	.20										.38
.35	.07	5.933	.847	18.33	12.39	.0682	0.996	.786	.932	.928	.0575	.0339	.589	.054	.33
.30		5.082		15.68	10.60										.29
.25	.05	4.234	.922	13.05	8.82	.0485	1	.890	.965	.965	.0447	.0273	.610	.043	.24
.20		3.386		10.43	7.04										.19
.15	.03	2.539	.972	7.82	5.278	.0291	1	.960	.988	.988	.0293	.0177	.624	.028	.14
.1		1.6924		5.208	3.516										.095
0.05	0.01	0.8461	0.997	2.603	1.757	0.0097	1	0.996	0.999	0.999	0.0097	0.0061	.631	0.0097	0.047
0	0	0	0	0	0	0	1	1	1	1			0.632		0
											Total 0.3962	Total 0.2104		Total 0.3328	

where

f = focal length.

Total Mapping Function. The lens/target/plasma mapping function is given by:

$M = LB$

$B = 1 - e^{-2P \cos^5(\theta - \beta)} / 1 - e^{-2P}$

(normalized bremsstrahlung).

$$M = \frac{(r_2^2 - r_1^2)(1 - \cos \theta_0)(1 - e^{-2P \cos^5(\theta - \beta)})}{(\cos \theta_2 - \cos \theta_1)(1 - e^{-2P})} \quad (5)$$

Equations (2) through (5) have been programmed individually and in combinations for the HP-65. Using these programs, with analytic and numerical integration, tables such as Table 3-8 can be generated to give mapping factors at various r/r_0 and θ/θ_0 . When a given point on an intensity profile is multiplied or divided by the calculated mapping factor, a new point is found and a new intensity profile is developed, as shown in Fig. 3-36. The new profile is then best-fitted to a power-filled quadratic by successive trials.

Focused-Beam Diffraction Ripples. The fitted-quadratic profile shown in Fig. 3-37 is very slightly diffracted in the intermediate focal plane at the target surface 300 μm in front of the focal point, as shown in Fig. 3-38. A slightly lower laser fill factor is necessary to avoid all ripples close to the focal point.

Conclusion. The overall mapping function applied to a high-fill-factor beam ($R = 0.9$, $I = 0.1$) gives a

Fig. 3-37. Unfocused beam intensity profile at lens (fill factor = 0.45).

Fig. 3-38. Focused beam intensity profile at target surface (whole-beam $B = 1$).

softer-tailed profile ($r = 0.63$, $I = 0.405$) wrapped on the target. Fortunately, softer-tailed profiles give higher uniformity. However, softtailed profiles must be well wrapped around the target, causing less normality and resulting loss in power. Although the present design gives good illumination and is quite efficient, experimental variation of these parameters on Shiva will determine the optimum illumination geometry. The $f/1.62$ aplanatic Shiva focusing lens has a small, probably beneficial effect on mapping and should not experience damage by caustic foci.

W. C. O'Neal

J. A. Monjes

Mechanical Support Structure

The Shiva laser system is a large neodymium:glass laser target-irradiation facility being constructed to perform laser fusion experiments. Very simply, the plan for Shiva is to irradiate a microscopic DT target pellet with 20 laser beams arriving simultaneously at the target along 20 different axes. This requires very precise alignment and high stability to maintain alignment. The 20 laser chains, composed of amplifiers, spatial filters, polarizers, rotators, and mirrors, must be arranged in an optimum geometry and stably held.

We have designed a high-stability space frame to accomplish this. The frame will support some 600 individual component assemblies while maintaining a tolerance of $\pm 4\text{-}\mu\text{rad}$ rotation between any two points over a period of 100 s. This stable support requires a design approach different from that normally used in conventional machine-support structures. The usual loads must be considered, but the dominant considera-

tions in this case are vibrational and thermal disturbances. The sizing of structural elements to minimize motion requires that we strive for maximum stiffness, sufficient size and mass for high thermal inertia, and minimum weight to keep resonant frequencies high. The frame must provide structural rigidity and good access for maintenance. It must also be simple enough to allow good air flow around the frame and components for dust and heat control. Finally, the design must be cost effective.

Shiva Support System. After considering several alternatives, we decided to make the structure in two sections, as shown in Fig. 3-39. One section will be an H-shaped laser-support frame for the oscillator, amplifiers, polarizers, rotators, splitters, and folding mirrors. The other will be a five-segment icosahedral target support for the target chamber, turning mirrors, and possibly radial amplifiers, as shown in Fig. 3-40. These sections will be physically separated by a shielding wall. The amplifier section will be 40 m long, 12 m

wide, and 7.6 m high. The target section will be approximately $15 \times 15 \times 15$ m.

The frame will be hard-mounted to the floor without vibration isolation. Although spring-mounting would be useful because it attenuates vibration, it is not attractive because the laser- and target-support structures would have to be one single inflexible unit, $8 \times 12 \times 70$ m. This configuration is extremely difficult to achieve, especially because shielding is required between the laser and target sections. Other disadvantages exist, including the cost of such large springs.

The basic construction material will be 6×6 in. square tubing with 4×4 in. square tubular diagonals, made of 0.25-in.-thick steel. This allows fabrication of clean, simple welded joints and flat surfaces for mounting hardware; it also presents the most uniform rigid cross section, with no possibility of flange or web buckling. The square tubing will form the basic structural unit: an open grid box, $1.2 \times 1.2 \times 1.2$ m, with short spans to provide maximum stability. This unit

Fig. 3-39. Shiva high-stability space frame. The laser chains are located in linear array along the walls of the H-shaped laser space frame. An intricate system of turning mirrors will convert the linear array to a spherical one for irradiation of the target in the target chamber.

Fig. 3-40. Engineering model of target chamber space frame. Once the beams reach the space frame they follow complicated reflection paths to the target. This model was constructed to verify engineering drawings and determine precisely where structural members had to be cut to avoid interference with the beams.

also allows ample space for channeling cables and pipes and for the flow of room air. One important advantage of this type of structure is the ease with which it can be modified.

Laser components will be cantilevered from the outside vertical faces of the structure by stiff brackets at

each end, as shown in Fig. 3-41. The brackets 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 magnet pulses. They support the components in a manner that will allow alignment repeatability during installation and

replacement. The components will have tamper-proof and lockable alignment adjustments, which will be used for gross alignment and will allow the amplifiers to be rotated easily to a number of positions around the beam axis. This method of support is simple and allows good air flow around components for dust and heat control. The air system is designed to limit dust particles and maintain the Shiva system environment to a Class 10,000 clean room. The structure design depends on the building air system for thermal control.

Components will normally be accessible for inspection and light maintenance through a system of movable and elevator platforms or, in the target-room frame, by catwalks and stairways. Major maintenance will require the removal of a whole unit by an overhead crane and special handling equipment; the unit will then be serviced in a separate clean room.

Power cables and gas pipes will be routed through ports in the building floor, distributed under the raised floor, and fed up to each component through the open-grid structure of the space frame.

System Stability. The main sources of motion in the structure are acoustic vibration, stress relief, load deflection, ground vibrations, and thermal distortions. The building that houses the laser is being designed to minimize acoustical noise, and little disturbing input is expected. Residual stresses from welding will be relieved by mechanically vibrating the structure in a low-frequency range during and after welding. Load deflection is taken care of during component installation by adjusting the brackets.

Determining ground-vibration effects requires considerable calculational effort. The dynamic analysis code SAP IV was used, with ground vibrations mea-

Fig. 3-41. Prototype of a component cradle. The components attach to the space frame by cradle mounts. Shown is a small section of the space frame with a beta amplifier supported by a pair of cradles. The components move laterally from their clamped position on foldout J-bars. Alignment fixtures used for x-y positioning are removed once the component has been aligned and locked.

Fig. 3-42. Elevation cross section of building floor and frames, showing the amplification of input vibrations. To determine the motion of the space frame, the floor and supporting columns were investigated as a unit, as were the two support frames. The input motion, traveling through the ground, is amplified by each unit. The laser frame sitting on the support columns has a higher amplification than the target frame.

sured near a similar building at the site as input. The initial calculations involved the concrete laser bay floor on which the amplifier frame will be mounted. Because the amplifier frame will consist of a number of repeated identical sections, a small portion of the frame was considered by defining boundaries by appropriate symmetry or asymmetry conditions. Calculations showed magnification of peak ground displacements ranging from 1.7 to 2.0 at the frame, as shown in Fig. 3-42. Computer graphics routines were used to visualize the low vibration modes of the amplifier frame and to choose the most appropriate locations to add diagonals for extra stiffness.

The target frame does not have such a convenient form. It is basically cylindrical in shape with the only symmetry involving five equal sections around the center of the cylinder. Because SAP IV requires that the boundary conditions be defined in Cartesian coordinates, the problem became too large to handle. Several initial attempts to get around this problem were unsuccessful. Finally, each distinct section of the frame (involving many members) was represented by a simple beam. The required stiffness characteristics of such a beam were determined by treating the corresponding section of the frame as a cantilever with a point load or moment applied at the end. The code was then used to

determine the resulting deflection or rotation so that the appropriate bending and shear stiffnesses can be calculated. This technique was used to model the complete frame without having too many frame members.

Calculated values of the motions of the floor and of the two structures, as listed in Table 3-9, indicate a maximum motion vertically of 0.45 μm in the laser bay. Horizontal motion of the laser bay floor is negligible because of its ties with other parts of the building. Static calculations of the target structure indicates vertical motion to be very small; hence, dynamic vertical displacement is estimated to be insignificant.

Machine-induced vibrations from equipment in the building, which can be transmitted to components, has been analyzed to determine primary frequencies that will enter the space frame. It is necessary to know both the natural frequencies and the driving frequencies to determine resonances. The natural frequencies were determined by use of the SAP IV code, and are given in Table 3-9. The results show that input peaks do not correspond with natural frequencies to any great extent, but the results do indicate a need to physically test the frame for possible resonance conditions.

Thermal stability is achieved by choosing structural elements of a suitable size and mass to be compatible with the building environment. Air-temperature stabil-

ity at any point in the laser bay, including the allowable drift of the mean temperature, is specified to be less than $\pm 0.5^{\circ}\text{C}$ peak to peak, with a period not exceeding 15 min; the floor-to-ceiling differential will be less than 1°C . The room has vertical air flow, providing a complete air change once every 20 s. Frame motions resulting from these conditions will not hamper laser operations.

The effect of environmental temperature changes is decreased by the thermal inertia of the structure. When the air temperature varies 1°C with a 15-min period, the steel temperature varies with the same period, but with a time lag and an amplitude of only 0.0159°C . This temperature variation causes a negligible, sinusoidally varying strain of 0.4×10^{-6} and a stress of 82.7 kPa.

Supports for the space frame are designed to accommodate thermal growth without strain, during periods when the air conditioning system is not operating. Roller-bearing supports will allow the frame to move in an accurately guided manner from a fixed point.

Conclusion. The support frame for the Shiva laser components is being shop fabricated in large sections concurrently with building construction. The size of these prefabricated sections is determined by handling and space restrictions. They will be welded together for final assembly in the laser building. The total weight of the steel is 272,155 kg, with 13,600 weld joints and a total of 8535 m of weld.

Construction of the building and the support frame is scheduled for completion in the autumn of 1976.

C. A. Hurley
J. O. Myall

Power Conditioning

The most cost-effective circuits available to perform the Shiva power-conditioning task are the result of a substantial evolutionary design process that has included periodic reviews by independent contractors. The reliability of these systems has been demonstrated and repeatedly improved through the operations of the

Janus, Cyclops, and Argus lasers. The individual circuit components and modifications to them are discussed in this report under the Argus and Shiva bank-optimization sections. This section deals with the grouping and "staging" of these components into a total Shiva system and the system-level cost trades that were associated with component selection.

At the onset of this effort, systems goals outside of minimum cost were defined. These had the effect of setting constraints on the overall design. The following is a partial statement of these overall goals.

- The system shall be designed with a life of 10^5 20-kV discharge cycles before onset of failures because of wearout mechanisms. This allows for a 6-mo debug period of 6 days per week, 2 shifts per day, and 10 discharges per hour, and an operational period of 9.5 years at 6 days per week, 2 shifts per day, 1 discharge cycle per hour, plus an additional 10 discharges per day for troubleshooting. This constraint places an upper bound on the charge time allowed and the time at voltage prior to a discharge cycle.

- All systems components with the exception of the master oscillator shall be designed to operate at 20 kV nominal. This inherently reduces the number of generic problems to be encountered, the inventory and spares requirements, and the design and qualification costs.

- The system shall be designed to operate safely at a 25-kV redline without regard to life degradation. This provides for 56% excess energy capability to be delivered to the laser in the event that getting that last joule into target means demonstrating "sufficient thermonuclear burn" or "scientific breakeven" even though the pumping is inefficient and off the nominal design points.

- Gross system gain control will be obtained using the preamplifiers directly after the master oscillator. This has the effect of reducing the operating range of voltages over which a majority of the amplifiers operate and allows for reduction in the peak overshoot triggering voltage that will be seen by the bulk of the amplifiers in the system. All circuits in the Shiva chain are designed to guarantee triggering of the lamps when the supply voltage is set to 19 kV minimum.

Table 3-9. Structure motions and frequencies resulting from vibration

	Vertical motion		Horizontal motion	
	Frequency (Hz)	displacement (μm)	Frequency (Hz)	displacement (μm)
Laser bay floor	12-17	0.22	10	—
Laser structure	22-40	0.24	7-37	0.26
Target structure	—	—	5-40	0.18

Table 3-10. The Shiva electrical components associated with the optical components of Fig. 3-28. Each switch is a series pair of size-D ignitrons capable of 40-kV standoff and 70-C charge transfer for 10^5 discharges. The power supplies are 25-kV, 100-kVA voltage-doubling units (there is also an additional redundant supply in the system). The capacitors are 20-kV dual-bushing capacitors with a castor-oil Kraft-paper dielectric system

Component	Lamps per head	Circuits per comp.	Total system comp.	Total switches	Total circuits per switch	Total power supplies	Total switches per supply	Energy per comp. (kJ)	Capacitors per circuit	Charge time	Total capacitors required	Total system energy (MJ)
Master oscillator	2	1	1	—	—	—	—	0.019	1	—	—	—
α rod amplifiers	6	1	22	2	2 & 20	2	1	14.5	5 (14.5 μ F)	10.75, 1.08 & 0.54	110 (14.5 μ F)	0.319
β rod amplifiers	12	2	26	6	1 & 20	6	1	29.0	5 (14.5 μ F)	21.5 & 1.08	250 (14.5 μ F)	0.754
β amplifier	16	8	60	15	32	3	5	150	7 (14.5 μ F)	110.79	3,360 (14.5 μ F)	9.000
β Faraday rotator	—	1	20	1	20	1	1	21	7 (15 μ F)	15.05	100 (14.5 μ F)	0.420
γ amplifier	24	12	20	20	12	20	1	200	1 (14.5 μ F) 3 (23 μ F)	7.4	240 (14.5 μ F) 720 (25 μ F)	4.000
δ rotator	—	1(2)	20	2	10	1	2	88	30(3)	65.37	600 (14.5 μ F)	1.760
δ amplifier	32	16	20	10	32	22	5	260	6 (14.5 μ F)	96.0	1920 (14.5 μ F)	5.200
Total	2080 (44 in.)	—	Total circuits (4) 1040 44 in. lamps 74 35-cm lamps 40 rotators 1154	56	—	35	—	—	—	—	—	21.453

Table 3-10 shows the system characteristics corresponding to the laser system elements shown in Fig. 3-28. Figure 3-43 shows the total system layout; each power supply and ignitron is configured in conformance with the requirements of Table 3-10. In arriving at this staging and overall system layout, each element of the circuit has been separately considered. The considerations that contributed to the choices of major components are discussed below.

Power-Supply and Switch-Staging-Design Considerations. Because the fixed costs for large capacitor-charging power supplies are high in relationship to the marginal cost for increasing their power rating, the most cost-effective system is one in which the largest number of capacitors possible are charged simultaneously. However, power-supply staging is constrained by additional requirements. One require-

ment is to provide individual gain control of each arm for at least two positions in the chain. A second requirement is that each separate amplifier section—for example, the alpha amplifiers taken as a whole—is required to have individual gain control. This concept allows each major section of the laser to be operated independently of the others so that optimum performance between amplifier stages may be obtained. Balancing between arms is accomplished with individual amplifier control at the next-to-the-last stage for major gain variations, and fine tuning is accomplished by individual control of the Pockels cells at the beginning of the chains.

In addition, the length of time required to charge the capacitors affects this lifetime. A charge time of 2 min is not unreasonable, although existing systems at LLL have all been sized with a 1-min charge time. Existing

staging uses a 2-min charge time for the beta amplifiers and the booster stage. All other charge times in the system are less than 1 min. The incremental cost to decrease the charge time to 1 min using the existing 100-kVA supplies estimated at \$93,000, or 14% of the power supply budget.

Because of the high fixed cost for each individual power supply, as noted above, all power supplies in the

system will be of one common type. Although on some of the lightly loaded stages of the system this is definitely overkill, the savings that could be obtained by going to a smaller supply are not sufficient to warrant the maintenance and inventory costs associated with maintaining two types of supplies. In addition, the use of common supply throughout the system will allow for one standby supply to provide a redundant capability

Fig. 3-43. Block diagram of the Shiva-system electrical power architecture, showing the configuration of the lamp circuits in relation to the series ignitron switches and the system power supplies. The number of ignitrons per power supply and circuits per ignitron for each type of optical component may be obtained from Table 3-11.

through switching for all power supplies within the system. Staging the power supplies in this manner has reduced cost to about 70% of the original budgetary estimates.

The switch staging reflects three design considerations. The first is a total charge transfer to 70 C per discharge cycle, which is compatible with a 10^5 -discharge-cycle lifetime. The second consideration is that the total impedance offered by the switch to each individual lamp circuit should not contribute more than one-third to the circuit loss. The third consideration is that an integral number of amplifiers should be discharged from one switch. This ensures that the lamps in the head will always be subjected to the same magnetic forces during operational and troubleshooting discharge cycles. Again, as in the case of the power supply, one common type of switch will be used throughout the system to minimize maintenance, inventories, and types of generic problems encountered.

Capacitors. The options available for the capacitors that have not yet been purchased are shown in Table 3-11. Option 4 has been chosen. This option provides for a system that requires the least capital outlay, has a reasonable decision time to fire the laser at voltage, and utilizes all previously purchased 14.5- μ F capacitors.

The choice of a 23- μ F high-density capacitor over other alternatives is discussed in the Shiva bank-optimization section. Very-high-density cans, which would provide additional cost and space savings, were eliminated from consideration because they have not been qualified in the envelope that optimally fits within the basement.

Energy-Storage Capacitor Racks. The producibility and cost-improvement study conducted by Maxwell Laboratories concluded that it would be more cost effective for LLL to buy commercially available storage racks for the capacitor banks than to continue producing welded racks to our prints. In line with this recommendation, a specification has been produced to buy these racks. This specification incorporates the Laboratory's safety requirements and requirements unique to the laser facility.

The capacitor racks as specified (MEL 75-001268A) are 2.0 m long. The width of the unit when loaded with capacitors excluding bus work and studs on the capacitors is 1.7 m. The height of the rack when loaded with capacitors and allowing for a 6-cm air gap is 3.8 m. This size rack was chosen as the basic module because it provides for the maximum number of cans per PFN network in the length provided by one

Table 3-11. Many capacitor tradeoffs have been made in the course of selection of energy storage capacitors. The tradeoff shown here is constrained by a 10^5 -shot life requirement, a given space envelope, a 25-kV charge-voltage limit, and a compatibility requirement with the 6000 14.5- μ F capacitors previously purchased. The charge time shown is a resulting constraint on the control system

Option	Configuration ^a	Cost	Rework required for 32-arm system with ϵ 's	Decision time at voltage available (s)
1	β circuits 7 cans at 14.5 μ F γ, δ circuits 6 cans at 14.5 μ F	\$443,000 (14.5 μ F)	All γ and δ circuits	>10
2	β circuits 7 cans at 14.5 μ F γ, δ circuits 1 can at 14.5 μ F 3 cans at 23 μ F	\$596,000 (23 μ F)	No rework required	~5
3	β circuits 1 can at 23 μ F 5 cans at 14.5 μ F γ circuits 6 cans at 14.5 μ F δ circuits 1 can at 14.5 μ F 3 cans at 23 μ F	\$510,000 (23 μ F)	All γ amplifiers	~5
4	β circuits 7 cans at 14.5 μ F γ circuits 1 can at 14.5 μ F 3 cans at 23 μ F δ circuits 6 cans at 14.5 μ F	\$30,000 (14.5 μ F) \$255,000 (23 μ F) \$285,000 (total)	All δ amplifiers	~5

^aRod amplifiers and Faraday-rotator circuits all use 14.5- μ F cans and are constant across all configurations.

Table 3-12. Cost comparison between the house-designed capacitor storage rack presently in use throughout the program and the rack system selected for Shiva

	Cantilever rack			Racks now used in existing systems	
	6-can circuit	7-can circuit	8-can circuit	5-high 6-can circuit	6-high ^a 6-can circuit
One rack - \$ per cap	13.20	11.30	9.90	18.90	
Five running racks - \$ per cap	9.30	9.60	8.40	18.90	
Floor space one rack - ft ²	0.52	0.45	0.39	0.47(0.42 ^b)	0.39(0.35 ^b)
Floor space five running racks - ft ²	0.39	0.40	0.35	0.47(0.42 ^b)	0.39(0.35 ^b)

^aMust be externally braced at additional cost to handle earthquake loading.

^bNumbers in parentheses are for free-standing racks without regard to building constraints. An adjustment to this number has been made to account for the inefficiencies introduced by the columns in Building 391. This adjustment is not required for the cantilever rack because the columns are straddled by the racks.

running shelf. The vertical dimension was limited by the clear space provided in Building 391. These basic units may be assembled in multiples of this basic length for any arbitrary length. When this is done, one vertical upright may be eliminated for each basic section of rack added—that is, a 5-unit rack 10 m long only requires six vertical uprights. Table 3-12 shows cost and floor-space comparisons for the racks previously in use compared with the cantilevered racks that have been ordered. The relative inflexibility of the racks in existing systems for handling circuits with different numbers of cans per PFN was an unnecessary constraint.

As shown in Fig. 3-44 the five-unit rack provides an optimum energy storage layout in Building 391. In this layout, two aisles of 90 cm and one forklift aisle running normal to the banks are provided. A 90-cm aisle is provided between banks. Using these racks in this layout sacrifices no space on account of building columns in Building 391. Figure 3-44 also shows the space available for potential Shiva upgrades.

**P. Rupert
W. Gagnon**

Control-System Architecture

Shiva has a very wide range of control requirements varying from simple manual operator controls through sophisticated computer processing and display. In defining the control system, the control design tasks have been clustered in several functional groups, vertically integrated from the sensor through the control room. The names of these tasks and the specific functions addressed within each one are shown in Fig. 3-45.

There will be several control stations in the central control room, corresponding almost one-for-one with the blocks of Fig. 3-45. Each will be functionally

separate in early stages of Shiva operation but will be integrated under a central processing unit at a later time. The central control will be concerned with inter-shot data from all control subsystems and will support the display systems and other computer peripherals.

Power-Conditioning Controls

The power-conditioning effort is responsible for transformation, storage and delivery of the 20 MJ of energy required to pump the Shiva laser. This extends from the 13.8-kV utility lines to the flashlamps and encompasses all high-voltage equipment and its control.

Power-conditioning controls fit into the overall Shiva control system as a separate functional entity. This control system located in the control room will communicate with a master system as shown in Fig. 3-45 but will be capable of stand-alone operation. The system will provide those functions necessary to control the power-conditioning system and to diagnose its failures. The system will provide for man-machine interface, which allows both direct manual intervention and control, and semiautomatic operation with manual supervision. A brief description of the basic functions of the system is given below.

PILC. Before and after a firing sequence, all the flashlamps will be checked to ensure integrity. This function is performed by a pulsed ionization lamp check (PILC). Each set of flashlamps common to one ignitron switch assembly is ionized. The current, detected in the return leg of each lamp circuit, sets a latch that is subsequently polled and then reset by the control system. If any lamp circuit indicates that it has not ionized, a further check of the system monitor and latching device is commanded from the control system. If this self-test function indicates that the PILC

Fig. 3-45. Shiva control and data monitoring requirements are clustered into independent functional groups that can be separately designed, checked out, and operated. Common architectural techniques allow total system integration to provide overall control, sequencing, and analysis as well as the sharing of the more expensive peripheral equipment.

monitoring system itself is functioning properly, the shot is aborted and the offending amplifier-lamp circuit combination replaced.

Power Supply Control. The power supplies in the system have been laid out with the objective of providing individual gain control of the various stages and of each arm. The supplies can be adjusted to the nearest 10 V to control the energy delivered to each stage of the system. Data from a previous shot are evaluated to assure that equal illumination of the target from all 20 beams was obtained and that a proper buildup of intensity as the beam propagates through the amplifier chain did occur. These data, which are collected by the beam quality diagnostics, are then used to modify the stored energy for each section of the laser through an adjustment of the power supply voltage for that stage.

An additional requirement on the power supply controls arises from the variation in load on the various supplies. To maximize capacitor life, all supplies should reach charge voltage at the same time. This requires sequential initiation of the charging sequence.

The power supply controls also monitor the power supply output current during the charge cycle. If a continuous short-circuit current is observed, it is usually indicative of a capacitor that has failed by shorting. By monitoring this current for the first 300 ms of charging, the short condition can be detected and the charging sequence stopped to prevent further damage to the PFN.

Bank at Voltage. Prior to shot initiation, the 1154 bank at-voltage monitors will be verified. These indications are used to assure that all circuits have come to voltage and that the flashlamp pumping of the amplifiers and the magnetic stresses between the flashlamps within the amplifiers are uniform. The at-voltage monitor will reveal an open charge resistor, internally arcing capacitors, or a fuse that may have been partially degraded during a prior shot and subsequently opened during the current charge cycle.

Shot Initiation. The power conditioning control system triggers the rotators, flashlamps, and Pockels cells. Each of the major amplifier types and the rotators

- ☐ Banks required for 20-arm system
- ☒ Additional banks required for 32-arm system

Fig. 3-44. The Bldg. 391 basement has ample space for the baseline Shiva system. Upgrades presently in the planning stage will require full utilization of this space as well as re-location of shops presently located in the wings of the building.

require initiation at a different time to arrive at peak gain and correct rotation in coincidence. The differences in timing occur because of different lifetimes of laser dopants in the various amplifiers and the desire to keep the ringing frequency of the rotators low to improve capacitor life. Six initiation times with delays on the order of tens to hundreds of microseconds between each triggering signal are planned. The initiation of the Pockels cells will be accomplished with laser-pulse-driven spark-gap switches.

Waveform Monitoring. To detect problems before they become hard failures detectable by the PLC, bank at-voltage monitors, or power supply current monitors, a subset of the total current waveforms in the system will be monitored and compared against a referenced waveform during each shot. The circuits monitored will be changed from shot to shot so that all circuits will be monitored over a 20 shot sequence. This form of detection will identify lamps that have been contaminated from a small leak, charging resistors and connections that have opened but are still making connection during the shots by arcing, and section opens and shorts within the capacitors.

Redundancy. Because the total number of components within the Shiva system represents an order of magnitude increase over the existing laser systems, special attention has been given to implementing redundancy in all portions of the system where a substantial increase in reliability can be obtained at minimum cost. As a result, the power-conditioning control system must provide for redundancy management so that failures in the system will be apparent to the operators during the actual performance of a shot and then indicated upon the conclusion of the experiment. In particular, the system will be capable of dealing with failures in the power supplies, in the crowbar system, and in the ignitron initiation systems without interruption of the normal shot sequence.

Fast Automatic Gain Control (AGC). Provisions are being made within the power-conditioning control system to allow a fast AGC function to be performed by controlling the output voltages of the Pockels cells during the pumping pulse of the flashlamps. System components directly associated with the Pockels-cell charging are being chosen so not to preclude the ability to perform this control. If such a control becomes necessary, it will be provided by a separate hardware logic system that will take data from the amplifier system, determine the required transmission of each alpha Pockels cell, and adjust this voltage within the 100 μ s before pulse propagation.

Safety and Facilities. In addition to the foregoing power-conditioning controls, a separate safety and facilities-control system has been identified. All safety interlocks will be handled on a hardwire basis and will

prevent the initiation of a charge or fire sequence when not satisfied. Indication of these interlocks will be provided in the control room. In addition, building temperatures, nitrogen pressures and flows, and other facility items will be monitored by this system.

P. R. Rupert

Alignment and Electrooptics Controls

The alignment and electrooptics controls system controls all beam-handling equipment necessary for transporting the optical pulses from the oscillators through the many parallel laser paths onto the fusion fuel pellet. This includes the control of the alignment systems and the Faraday rotators, Pockels cells, and shutters.

The total alignment-control system is designed into the overall Shiva control system as an independently functioning control subsystem interfaced with the master system as shown in Fig. 3-46. The alignment-control system will provide the functions necessary to control, monitor, and record alignment component performances within the control room. The system will provide both manual intervention and control, and semiautomatic operations. The portion and function of the alignment-control system being designed by Aerojet is shown inside dotted lines in Fig. 3-46. A full minicomputer-based control processor is required to meet the following functional requirements of this total system.

Focus Lens Control and Monitoring. The final 20 focus lenses will be controlled in X, Y, Z motions to micrometer accuracies and their actual positions at shot time monitored and recorded. Delta X, Y, Z motions to move from the surrogate target "best point and focus" position to a predetermined list of real target spot positions will be provided and correlated with final pointing-mirror delta motions. Mechanical-gearing backlash compensation may be necessary. Interpolation to the best focus point between operator-selected front and back out-of-focus points is needed, and provision for the future addition of digital processing of focus image information will be included.

Final Pointing-Mirror Control. The 20 final pointing mirrors with fractional microradian accuracies in θ and ϕ will be controlled and their operation monitored, both in a manual mode and by enabling closed-loop control on selected chains at the proper time. Correlation with real target delta positions by the focus lens must be provided. A local control panel in the high bay will provide simple manual control and monitoring function to "bring up" the operation of the gimbals, servo network, and PFC sensor described below.

In summary, the functional requirements of the total alignment-control system are established to the point that a general-purpose computer-based control system is clearly warranted. A preliminary detailed plan for the system has been developed and substantial work toward this goal has begun. Concurrently with this effort, control functions that are critical to the initial debugging phases will be handled by local hardware-implemented control panels with computer interfaces.

F. W. Holloway

Chain Diagnostics and Control

The purpose of the chain diagnostics and control system is to diagnose beam focusability, to collect housekeeping and performance data from each shot, and to warn of dangerous or damaging situations as soon as possible. The quantities of interest related to focusability are wavefront distortion, radial beam profile, ΣB , and ΔB . While the ultimate desire is to be able to characterize the spatial and temporal properties of the beam at the target surface, these quantities will initially be measured along the laser chain. For example, a collection of calibrated photodiodes distributed between each group of amplifiers along each chain will be used to provide a plot showing gain, power, intensity, and B integral as a function of position along the laser. One such plot was shown in Fig. 3-29. An actual overlay of this with actual data after each shot will identify potential problems.

Wherever feasible, it is desirable to automate the collection of diagnostic image data by interfacing the sensors directly with the analysis equipment, bypassing the manual loading, unloading, processing, and transportation of photographic film. However, the extraction of high-resolution data from photodetectors illuminated by coherent $1.06\text{-}\mu\text{m}$ illumination poses severe technical challenges. Nonetheless, elimination of film handling, processing, and stocking problems offers immense potential rewards in speed of obtaining and using diagnostics data.

Per-Shot Diagnostics. The following set of beam parameters will be measured and controlled or used as control inputs on each laser shot.

Energy Output and Distribution Along Each Chain. A high-quality calorimeter at each chain output combined with photodiodes distributed along each chain will provide this information. The calorimeter will be interfaced through a continuously sampling A/D converter and the diodes interfaced through sample-and-hold units followed by A/D converters.

Temporal Pulse Width. The presently used ultrahigh-speed streak camera with self-scanned photodiode array used for optical-to-electrical conversion

will be used to measure the pulse duration at the oscillator and at the target chamber. However, a transient digitizer will replace the diode array to eliminate the need for intermediate storage on photographic film. Triggering of the streaking cameras will be accomplished by the oscillator pulse with a spark-gap switch.

Prepulse. The present technique for monitoring prepulse is a self-calibrating oscilloscope/photographic film display. A CPU-controlled transient digitizer would alleviate the need for film. Although this technique is not fast enough to provide the desirable real-time abort of a particular shot when a prepulse does occur, the ease of data handling makes this the preferred monitoring technique.

Low-Power Intensity Profile At the Target Surface. The sensing and correction of the illumination pattern on the surface of the target is in a conceptual design and evaluation phase. It is desirable to display the low-power beam-intensity profile on the target for use by an operator in manual control of the aberration corrector subsystem. This might be accomplished by the PFC sensor. The aberration corrector shown in Fig. 3-47 requires eight control-point inputs, some cross-coupled to introduce corrective predistortion of the wavefront early in each laser chain to compensate for astigmatism, coma, and spherical aberration.

Adjustment of an aberration corrector may be required when optical elements of a laser chain are moved, refinished, or thermally distorted. To accomplish remote manual control of the correctors, actuator motors associated with each motion of each aberration generator are multiplexed onto a set of motor controllers, and control is effected from the control room by an operator observing the intensity profile at the target. It should be noted that a time-integrated high-power beam-intensity profile might also be obtainable from the PFC sensor Vidicon.

Periodic Diagnostics. The previously mentioned diagnostics and their controls have been those of interest on or before every full-power laser shot. Periodically, other diagnostics will be used during setup of new experiments and components and in regular system maintenance. Because fast throughput of these data does not have the high priority of shot data, some of these diagnostics may be taken on photographic film. Solid-state imaging readouts will be used when the data require repetitive rapid observations.

Pulse Synchronization. The pulse synchronization will measure the round-trip transit time of any desired laser chain to an accuracy of 10 ps (3 mm). This accuracy in simultaneity of light arrival from all arms is necessary to satisfy temporal uniformity of illumination of the target pellet. Because resynchronization should be required only infrequently, it will be a manual adjustment.

Both images in target plane

Before correction

After correction

Fig. 3-47. Aberration corrector control is by observation of PFC Vidicon output and remote manual operation of lens-control motors.

Amplified Spontaneous Emission (ASE). ASE will be measured by firing a no-target, no-pulse shot using a sensitive calorimeter in conjunction with its integrating photodiode and a fast photodiode, both feeding transient digitizers. It is expected that ASE level verification will require only infrequent measurement.

Near- and Far-Field, Spatial- and Temporal-Pulse Beam Profile. Photographic film is used on present laser systems for time-integrated beam profiles and for recording the streak-camera output of a time-swept, spatially fixed slice through the beam. Several development projects are under way with the intent of using solid-state photodiode arrays, charge-coupled-device arrays, or silicon-target Vidicons to provide time-integrated X-Y intensity data. There are efforts under way to produce time- and space-resolved intensity data for diagnostics purposes. These will require

the support of reasonably sophisticated computer interfacing, deconvolution software, and display techniques.

J. W. Davis

Target Data Acquisition

The Shiva target diagnostics data acquisition subsystem shown in Fig. 3-48 and discussed further in Sec. 8.4.5 on target diagnostics, is conceived to be an upgrade of the Argus data-acquisition system. A PDP-11/55 is envisioned as being the heart of a CAMAC data-acquisition system so that hardware and software compatibility between the Janus, Argus, and Shiva target diagnostic systems can be realized. With this plan in mind, this subsystem can be duplicated

Fig. 3-48. The Shiva target diagnostic and control system consists of a PDP-11/55 minicomputer with minimal peripherals. The CAMAC interface standards will be used for most target diagnostics. Archival and analysis of the data will be done in conjunction with the Shiva control, analysis, and monitoring computer.

from Argus and make use of a year's operational experience.

Most data from the experiment will be handled through the use of transient digitizers, sample-and-hold plus A/D, and both linear and area digital-processing techniques (CCD's, CID's, Reticons). Both the CAMAC byte-serial and branch highways are envisioned to handle the anticipated higher data rates and longer physical distances to the target area in Shiva. Fiber-optic communication with automatic crate-bypassing techniques in case of crate failure is planned.

This subsystem will be able to run as a stand-alone system to control the target-data acquisition and acquire and store data. The real-time analysis and applications programs that are on the same system on Argus will be part of the overall Shiva control/monitoring/analysis machine. Archiving the data is done by magnetic tape on the SCAM (Supervisory Control, Analysis, and Monitoring) system, allowing access to the last laser event as well as other events through the SCAM system; this will allow a more powerful system to be fielded because the peripherals and data can be shared by all subsystems.

J. R. Greenwood

Shiva Upgrade

Recent advances in glass laser systems technology and laser components have greatly improved the prospect for achieving hundreds of terrawatts from an Nd:glass laser. Since this laser power will be sufficient to obtain scientific breakeven and prove much of laser fusion physics at near full-scale reactor yield levels in the near future, the feasibility of upgrading Shiva is being examined.

More Laser Chains. The design of multiple beam illumination schemes capable in theory of achieving a very high degree of intensity uniformity (approximately $\pm 2\%$) on the target allow higher-beam-count laser systems to be considered. To realize such an ideal illumination, optimally profiled, gain-controlled, aberration-free beams must be precisely aligned onto the fusion target. Such beam profiles have been computer-optimized to achieve good propagation characteristics in the laser, good transformation properties in the final focusing lens system, and good illumination on the target. A multiple-lens aberration corrector has been demonstrated to be effective in prototype tests and is now undergoing further development and testing. An automatic alignment system described previously is in the final stages of detailed design and will be prototyped in 1976 before installation on Shiva in 1977. Automatic-gain-control concepts for Shiva are in the conceptual design phase. These developments will

allow the Shiva beam count to be increased from 20 up to about 42 beams, which will fill the capacity of the present Shiva supporting structure and building.

Longer Laser Chains. The idealized effect of spatial filters in attenuating the growth of small-scale beam breakup is illustrated in Fig. 3-49. At each spatial filter the small-scale aberrations and intensity ripples are stripped from the beam. In fact, because spatial frequencies associated with the beam profile must be preserved, even the ideal pinhole spatial filter will not remove all the small-scale spatial variations. The experimental test of the effectiveness of the cascaded filters will be determined this year on Argus, which has six spatial filters. If proved effective, the use of multiple spatial filters will allow the length of laser chains and thus the output aperture size to be increased to the point at which whole-beam nonlinear distortions become prohibitive. With a 30-cm stage added to the Shiva chain, the output it can be increased by a factor of 1.5 to 2.0 at a cost of about 4 to 7 rad of whole-beam distortion.

Higher-Performance Laser Chains. The development of new laser materials and higher-damage-threshold thin-film optical coatings is described in Sec. 4.3.2. The improvement in overall laser-system power performance by decreasing the nonlinear refractive index in the laser and passive optical materials ranges from about 1.4 and 1.8 for phosphate and fluorophosphate glass to about 2.7 for beryllium fluoride glass. The relative figures of merit of several materials for a variety of applications in the laser system are listed in Table 3-13. The status of the development of these materials is given in Table 3-14. In general, some phosphate and fluorophosphate materials are within 1 year of being commercially available, and the more advanced compositions of the fluoroberyllate glasses should be available within 3 years.

The operation of the laser chains at higher energy-fluence levels will require the development of higher-damage-threshold coatings as listed in Table 3-15. Those required for full utilization—that is, high-power long-pulse operation of a phosphate/fluorophosphate laser system—are almost within the state of the art today, but the coatings needed for use with a fluoroberyllate laser system will require significant further development.

Summary. The options of increasing the number, length, and performance of laser chains have been preliminarily examined technically and first-cut cost estimates made. The performance-per-cost curves for silicate, phosphate/fluorophosphate, and fluoroberyllate materials are shown in Fig. 3-50. The corresponding performance data are tabulated in Table 3-16. These numbers will be refined during 1976, but several observations can be made at this time with confidence.

Table 3-13. Figures of merit computed from the stimulated-emission cross section σ , the refractive index n , the nonlinear refractive coefficient n_2 , and the Verdet constant V are shown for the advanced materials with respect to the silicate glasses used in Shiva. The improvement in system performance will be about 1.8 with phosphate/fluorophosphate materials and about 2.7 with fluoroberyllate glass

Component	Figure of merit	Host material				
		Silicate glass	Phosphate glass	Fluorophosphate glass	Fluoroberyllate glass	Fluoride crystal
Laser rod (pump limited)	$\frac{\sigma n}{n_2}$	1.0	1.8	1.9	3.1	—
Laser disk (pump limited)	$\frac{\sigma n^2}{n_2}$	1.0	1.7	1.8	2.7	—
Laser disk (parasitic limited)	$\frac{n^2}{n_2}$	1.0	1.4	1.8	2.7	—
Window	$\frac{n}{n_2}$	1.0	1.3	1.7	2.7	2.0
Lens	$\frac{n(n-1)}{n_2}$	1.0	1.3	1.7	2.2	1.7
Rotator	$\frac{Vn}{n_2}$	1.0	0.5	1.2	2.1	5.0

Fig. 3-49. Spatial filters. As the laser beam propagates through the various optical components, any intensity variations self-focus and intensify. This breaking up of the beam grows exponentially. However, the amplitude and phase aberrations will not focus through the spatial-filter pinhole and are stripped from the beam.

Table 3-14. Materials-development status

Use and material	Examples	Maximum melt diameter	Status	Commercial availability
Laser rod and disk				
Silicate	ED-2, LSG-91H	30 cm	Production	Now
Phosphate	EV-1, LHG-6	20 cm	Development	0-1 yr
Fluorophosphate	LI-G-10	1 cm X 10 cm	Research	1 yr
Fluoroberyllate			Research	2-3 yr
Lens and substrate				
Silicate	BK-7	30 cm	Production	Now
Fluorophosphate	FK-51	30 cm	Development	1 yr
Fluoride crystal	CaF ₂	15 cm	Development	1 yr
Fluoroberyllate			Research	2-3 yr
Faraday rotator				
Terbium silicate	EY-1, FR-5	30 cm	Production	Now
Cerium phosphate	FR-4	30 cm	Production	Now
Terbium fluoride crystals		1 cm ³	Research	2 yr

First, the achievement of several-hundred-terawatt-level performance with Nd:glass laser systems will be possible in the very near future. Second, the laser-system technology developments that will be implemented on Shiva are obviously necessary for the upgraded system and will profit from the experience and refinements Shiva will generate. Finally, the advantage of high-performance optical materials and coatings is very great, for both the Shiva upgrade and for all

future laser fusion systems, which will always require these materials for beam control and transport optics. The development of these materials and coatings must be energetically pursued toward the specific requirements of the advanced systems.

T. J. Gilmartin
W. F. Hagen

Table 3-15. Damage level requirements allowing a factor-of-2 safety margin at peak intensity

	Pulse length (ns)	Antireflection (J/cm ²)	High reflection (J/cm ²)	Polarizer (J/cm ²)	Substrate (J/cm ²)
Past experience	0.1	2	2	3	15
	1	6	6	9	47
Best today	0.1	4-6	4-9	4-7	30
	1	12-18	12-28	12-22	100
Upgrade requirements:					
Fluorophosphate system	0.1	3.5	3.5	3.5	5
	1	21	21	21	30
Fluoroberyllate system	0.1	5	5	5	7
	1	32	32	32	40

Table 3-16. Higher performance of the Shiva upgrade can be achieved (1) by using lower n_2 optical materials such as fluorophosphate and fluoroberyllate glasses, (2) by adding 20-cm-aperture δ and 30-cm-aperture ϵ amplifiers, and (3) by increasing the number of laser chains. The power levels shown can be further increased by about 1.5-1.7X by overfilling laser apertures at the expense of illumination uniformity

Configuration	Staging	Performance (TW) for each characteristic laser material		
		Silicate	Fluorophosphate	Fluoroberyllate
20 chains	Shiva	27	54	80
	Shiva + ϵ	44	88	132
	Shiva + δ + ϵ	60	120	180
32 chains	Shiva	43	86	130
	Shiva + ϵ	70	140	210
	Shiva + δ + ϵ	96	192	288
42 chains	Shiva	57	113	170
	Shiva + ϵ	93	186	279
	Shiva + δ + ϵ	126	252	378

Fig. 3-50. Shiva upgrade options. The increase in laser-system performance per incremental cost is a strong function of the optical material used, ranging from \$420,000/TW with silicate glass to \$170,000/TW for fluoroberyllate glass. The use of the more advanced materials will greatly improve the Shiva-upgrade system performance without significantly changing the overall cost.

3.2.5 ASSEMBLY AND CLEAN-ROOM OPERATION

Contamination-Free Disk Amplifiers

During 1975 several new disk amplifier designs and new clean assembly procedures were tested. The B75N 8.5-cm-aperture disk amplifier was prototyped and tested for 1000 firings with acceptable gain degradation and damage levels. This successful design was generated for the Argus experiment and the seven amplifiers for that system were assembled and installed. Dirt-generating operations such as scraping, sliding, screw fastening, etc., were eliminated from the assembly procedure. Stainless steel is used for all metal parts in the pump cavity. Buffing with aluminum oxide and electropolishing was employed to eliminate particulate contamination on those metal surfaces. Springs replaced screws in all pump cavity assemblies and in all

but external applications in the frame and lamp housing. Figure 3-51 shows the B75N during assembly and the finished product, in Fig. 3-52.

The larger, 20-cm-aperture C75L amplifier (Fig. 3-53) was designed using the same concepts employed in the B75N, but with the additional requirement of containing around the laser disk a liquid-edge-coating material such as a saturated water solution of zinc iodide. This necessitated a much more complex disk-holder assembly shown in Fig. 3-54. Several elastomer seal materials were evaluated. The final choice rests between Scotchcast 221 (3M) and L-100 (Du Pont) polyurethanes. Tests indicate that L-100 should be most satisfactory, but full-scale amplifier tests are still pending to confirm that choice. Several C75L amplifiers with both good liquid seals and an acceptable

Fig. 3-51. B75N disk amplifier during a final assembly operation. Disk cavity materials are stainless steel as is the main frame. Clean assembly procedures preclude the use of threaded fasteners inside the amplifier. The optical aperture is 8.5 cm.

Fig. 3-52. The completed B75N amplifier has five filters on both inlet and exit gas ports. Lamp cable entrances are gas sealed. Nitrogen-gas coolant flow pressurizes the amplifier to reduce inward migration of particulate contaminants.

Fig. 3-53. The C75L amplifier has a 20-cm aperture. It employs liquid-edge coated disks. Other design features are like the B75N.

Fig. 3-54. The disk holder for the C75L amplifier uses a conical-elliptical seal surface between its male and female parts. This allows disk thickness change (repairs) without remachining the holders. L-100 polyurethane O-ring seals are necessary to survive edge-seal chemical attack and flashlamp irradiation.

level of disk distortion have been assembled. The principal difficulty in this assembly arises from the contact pressure needed to achieve a seal; this causes strains and aberrations in the disk because the metal parts and O-ring groove dimensions do not match the one-eighth wave dimensional tolerance of the laser disk. The importance of developing a reliable, high-quality solid edge coat for large disks can be appreciated from the time consumed and difficulties encountered in getting satisfactory liquid-edge-coat assemblies.

Laboratory Environment

It is not easy to quantify the material or condition of contamination materials. It is vital to the successful use of disk amplifiers that the amplifiers be immaculately clean. Particles of foreign material as small as $5\ \mu\text{m}$ are of concern, and it has been demonstrated that beam obscurations caused by particles or damage sites $50\ \mu\text{m}$ or larger on the disks can cause serious glass damage and the loss of wavefront uniformity necessary to successful target compression. A considerable effort has been devoted to improving cleaning procedures and evaluating the end result of the many different cleaning processes employed. In addition, the laboratory envi-

ronment is maintained at a high level of cleanliness. Table 3-17 gives an evaluation of the environment in the vertical-laminar-flow room (VLF) and in the Bldg. 381 high bay.

Particle-settling rates were measured and the particles counted according to ASTM F-24, F-25 with the following modified procedure. Clean $0.45\text{-}\mu\text{m}$ membrane filters were placed in several locations in the VLF room, the Bldg. 381 high bay and the Janus and Cyclops laboratories. The results are shown in Table 3-18 for particles $>5\ \mu\text{m}$.

The membrane filters were placed in plastic Petri dishes and allowed to stand open for 72 hr. This method of collecting particles has not been approved by ASTM because of its lack of repeatability, but it does give a reasonably good indication of the settling rate of particles from the atmosphere. The results also approach more closely the actual information desired—that is, how many particles accumulate on surfaces. As long as the debris stays in the air, the count per unit volume is not of concern. As can be seen from Tables 3-17 and 3-18, the VLF room is at least an order of magnitude cleaner than the high bay, and the high bay is about four times cleaner than either of the laboratories containing the currently operating systems.

Table 3-17. Clean-room evaluation, showing the degree to which our two assembly areas conform to recommended federal standards

	LLF vertical-laminar-flow room	LLL Bldg. 381 high bay	Federal standard 209B	
			Class 100	Class 10,000
Humidity	30-47%	30-47%	$40\% \pm 5\%$	Same
Temperature ($^{\circ}\text{F}$)	70-73	70-73	72 recommended	Same
Air-cleanliness level (particles/ ft^3)	0.5 (typical)	1240 (typical)	<100	<10,000
Particle-size measured (μm)	>0.5	>0.5	>0.5	>0.5 ($<65/\text{ft}^3$ for $>5.0\ \mu\text{m}$)
Pressure: room to adjacent areas	Not measured	Not measured	0.05 in water	
Air flow from filters	150 ft/min from HEPA filters		90 ft/min	
Air flow exiting room	Doors closed: 400 ft/min Doors open: 300 ft/min			
Room air changes	15 changes/min 4 s/change		0.33 changes/min 3 min/change	
Pressure drop across HEPA filters	Generally 0.5-0.6 in. water; filters are changed when this reaches approximately 1.5 in. water			

Table 3-18. Number of particles greater than 5 μm in diameter settling from room air in a 24-hr collection period

VLF room	$<2/\text{cm}^2$
Bldg. 381 high bay	$16/\text{cm}^2$
Janus laboratory	$54\text{-}59/\text{cm}^2$
Cyclops laboratory	$54\text{-}59/\text{cm}^2$

Clean-Room Equipment Analysis

Gloves. After reviewing outgassing problems associated with clothing and bagging materials used in the clean room, it was decided that the currently used clean-room vinyl gloves be used only for handling dry articles and that they not be washed in a solvent before use. Large quantities of plasticizer are used in the manufacture of vinyl gloves. This is dissolved away by organic solvents and transfers to any surface that the gloves contact. There is also a second problem when cleaning laser disks, in that the acetone or trichloroethane slowly dissolves and swells vinyl gloves. Polyethylene is relatively unaffected by acetone and after some cleanliness testing has been found to be at least as clean, from a particulate standpoint, as vinyl gloves. Unfortunately, polyethylene gloves are far less flexible than vinyl gloves. The particulate cleanliness of gloves ultrasonically cleaned in Freon for 2 min (particles $>5 \mu\text{m}$) is as follows:

Vinyl	25-170/ cm^2
Polyethylene	27/ cm^2

Solvents. A large variety of fluids are regularly used for cleaning without a great deal of concern for their cleanliness. Although it was generally realized that a dirty solvent may actually leave the object being cleaned dirtier than before cleaning, there had been no nondissolved residual (NDR) monitoring taking place. Fluids are now being NDR analyzed by membrane filtering and manual particle counting as per SAE ARP-598 or ASTM F-25. A Royco automatic fluid-particle counter, which will greatly decrease the time necessary to count particles in a given sample of fluid, is being purchased and will be operating early in 1976.

To indicate the contaminant problem, consider allowing 60 drops of acetone to evaporate from a 20 cm^2 laser disk. Sixty drops is approximately 0.9 ml. If the

acetone is a Class 4 fluid as per NASA 1638 standard, approximately 2 particles/ cm^2 larger than 5 μm are left on the surface. This quantity of particles would take at least 24 hr to accumulate by settling in the VLF room.

Most of the solvents used in the clean room were examined for NDR particles. Table 3-19 indicates the results of these tests. Note that below 500/ cm^2 we are concerned with levels less than 1 ppm contamination. An interesting comparison is the ratio of particles per volume in air to particles per volume in these relatively clean fluids. Comparing a Class 4 fluid to a Class 10,000 clean room, we find that the fluid is 21,000 times dirtier than the air.

To clean solvents to the lowest NDR level, several pressurized liquid-dispensing containers fitted with membrane-filtering nozzles are now in use. A 0.5- μm filter is used in these nozzles.

Ultrasonic Cleaning. A review of the literature shows that small particles can be attached to laser parts by quite high forces in relation to the particle weight. Typical forces holding 20- μm particles in place exceed 0.5 dynes. This represents a force 1.2×10^4 times the weight of the particle. Ultrasonic cleaning has been the principal technique used to remove these particles.

Ultrasonic cleaning is a method of cleaning in which sound energy is imparted to a fluid, causing the formation of vapor-cavitation bubbles that collapse to produce very high local pressures, creating a scrubbing action. In quantitative tests performed to determine the particulate cleanliness of surfaces before and after ultrasonic cleaning, metallic surfaces were found to retain substantial particulate material even after lengthy ultrasonic cleaning times. For this reason, other techniques such as flushing with a high-pressure water jet are being investigated.

To determine if any of the four cleaners located in the Bldg. 381 clean room were superior to one another in cleaning ability, a series of tests were performed in a correctly operating ultrasonic cleaner using a thin

aluminum-foil test strip. The foil should be pitted, dented, and torn after 1 min when immersed in water with a small amount of detergent. The percent of metal removed is a relative measure of damage. Most ultrasonic devices fail the foil test with solvents because cavitation levels are substantially lower in solvents than in water.

All four units were tested with Freon and water as the primary solvent and with a glass beaker filled with either Freon or water placed in the primary solvent. The fluid-coupling experiments were used to determine the power loss through the glass container. With Freon, all units performed equally poorly, causing no damage. With water, units 1, 2, and 3 were excellent. Unit 4 was not tested with water. While water was observed to couple enough energy to a beaker of Freon to cause some foil damage, the converse was not usually observed.

To simulate an actual cleaning situation, a black dye was obtained and spread on microscope slides and dried on a hot plate. The dye is water soluble, so tests were performed only in Freon. Ultrasonic units 1, 2, and 3 removed almost all of the dye in less than 1 min. Unit 4, the 40-gal unit, had no effect on the stained glass. After examination it was determined that four of the eight transducer power amplifiers were not operating. After repairing the ultrasonic cleaner the dye test was repeated in room-temperature Freon. The test again failed. The unit was then returned to the manufacturer and the transducers and amplifiers were replaced.

Solvent heating and power input were considered as alternate measures of cleaning-unit efficiency. All energy input to a sonic transducers appears as heat in the fluid. It would be very convenient if only the cavitation energy appeared as thermal energy, but unfortunately if the transducer is less than 100% efficient (more likely they are 50% efficient), the lost energy

also appears as heat. In all the units a uniform 12-19% of the line-cord input power appeared as thermal heating when using Freon. This is contrary to the dye test in which unit 4 failed to remove the dye. Several references mention a value of energy input per unit transducer area that is necessary to cause cavitation. For all four units the critical value of 2.15 W/in.² is exceeded if the calculation is based on input power, but the values are insufficient if dissipated thermal energy is used. The conclusion is that neither heating rate nor input power can definitively discriminate between units that clean well or poorly.

To directly measure the particulate or NDR cleaning ability of several ultrasonic units a series of machine-screw cleaning tests was performed. Machine screws have a large portion of their surface area in the form of feathered edges and should resemble the worst-possible machined surface. Ten to twenty 5-40 × 1/2-in. machine screws were sonically cleaned in Freon for a variety of cleaning times from 1 to 84 min. The total number of particles removed was normalized to the apparent surface area of the screws. Particle counting was performed by passing the Freon through a 0.45- μ m membrane filter and then microscopically counting all those particles larger than 5 μ m. It was immediately apparent that as many as 3000 particles/cm² could be removed in 1 min of ultrasonic cleaning. This quantity would take 4 months to accumulate if left standing in the Bldg. 381 high bay. Even more surprising is the fact that a second ultrasonic cleaning (1 min) will also remove 2000-3000 particles/cm². Particles continue to be removed for as long as cleaning was continued—84 min. Even after 84 min, 700 particles/cm² could be removed in 1 min. If the cumulative number of particles removed is plotted against cleaning time, we can see that the total particles removed seems to reach an asymptote after about 100 min as shown in Fig. 3-55.

Table 3-19. Nondissolved residual particles (per cm³ >5 ml) in solvents

	Actual solvents used	NASA 1638-class solvents
Tap water	101	5
Distilled water	26	3
Ethyl alcohol	24	3
Freon TF	22-36	4
Membrane-filtered Freon	3	0
Freon from ultrasonic cleaner #4	24	3
Deionized water	15	3

Fig. 3-55. Ultrasonic cleaning time. A collection of small machine screws was subjected to prolonged ultrasonic cleaning. After 60 min of cleaning, particles were still being removed. Even after 84 min, 700 particles/cm² could be removed in 1 min of further exposure.

Conclusions and Recommendations

The major source of contaminants has not yet been identified. Considering the high average surface contamination levels measured (typically 5000 particles/cm² >5 μm) and the very clean air conditions

in the VLF room, it can generally be concluded that particles settling from the environment are not the major source of contaminants that can be flushed from surfaces. Solvent contaminant levels are in some cases higher than desirable, but even the evaporation of these solvents cannot account for the relatively high levels of surface contamination measured.

A significant problem lies in the currently used ultrasonic cleaners. Without exception, all four ultrasonic cleaners do not appear to be operating adequately to reliably remove small particulate matter (>5 μm). Cleaning tests using a variety of laser-amplifier parts show that after as long as 100 min of ultrasonic cleaning significant quantities of particles can still be removed (typically 500 particles/cm² >5 μm). Several cleaning tests of parts that were about to be assembled indicate that these relatively high particle levels exist on both disassembled and ready-to-be-installed parts.

The basic problem of removing particles from surfaces will be studied more extensively to determine the best method for removing these particles. Techniques using gas and fluid jet flushes will be tried. The procedure of preflashing parts in the intense light of flashlamps will also be tested. The problem of automating the cleaning steps will be examined to reduce the time necessary to reassemble amplifiers and to improve the repeatability in cleaning.

W. S. Neef, Jr.
I. Stowers

References

1. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975); *Laser-Fusion Program Semiannual Report—January-June 1973*, Lawrence Livermore Laboratory, Rept. UCRL-50021-73-1 (1973); *Laser-Fusion Program Semiannual Report—July-December 1973*, Lawrence Livermore Laboratory, Rept. UCRL-50021-73-2 (1974).
2. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), pp. 35-42.
3. G. J. Linford, H. H. Chau, J. A. Glaze, C. B. Layne, and F. Rainer, "Pump-Induced Optical Distortions in Disk Amplifier Modules: Holographic and Interferometric Measurements," *Appl. Opt.* **14**, 3057 (1975).
4. Ref. 2, p. 242.
5. Ref. 2, pp. 178-200.
6. Ref. 2, pp. 52-54 and 84-88.
7. Ref. 2, pp. 203-206.
8. Ref. 2, pp. 197-199.
9. Ref. 2, pp. 135-138.
10. Ref. 2, p. 37.
11. Ref. 2, pp. 54-56.
12. Ref. 2, pp. 151-155.
13. W. Fountain, LLNL internal memorandum.
14. Ref. 2, p. 56.
15. Ref. 2, pp. 68-88.
16. Ref. 2, pp. 79-83.
17. J. W. Shearer, *A Survey of the Physics of Plasma Heating by Laser Light*, Lawrence Livermore Laboratory, Rept. UCID-15745 (1970), p. 19.

4. GLASS LASER DEVELOPMENT

Section Editors: W. D. Fountain
M. J. Weber

4. GLASS LASER DEVELOPMENT

Component Development

- Developed an improved passively mode-locked oscillator (PMO).
- Developed on all electronic single-pulse selector (switchout).
- Developed metallic apodizing apertures.
- Developed 5-cm aperture, fast Pockels cells.
- Developed a uniform, high-gain, 40-mm aperture rod amplifier.
- Developed cost-effective high-energy spatial filters.
- Demonstrated feasibility of two concepts of ASE shutters for protecting targets.
- Developed the B-75 and C-75 clean disk amplifiers.
- Fabricated a prototype of very clean disk amplifiers (β , γ , δ).
- Implemented an effective and continuing laser technology transfer program for the benefit of private industry.

Laser Physics

- Spectroscopic studies have provided guidelines for selecting new laser glass compositions.
- Damage studies have provided a reproducible data base for 100-ps-pulse damage.
- n_2 measurements and analysis have lead to a model which predicts n_2 in new glass.
- Propagation studies have resulted in an accurate analytic model of nonlinear beam distortion and elucidated limits for small-scale beam breakup in lasers.
- Coherent pulse stacking has been demonstrated. This leads to techniques for providing shaped laser pulses from simple oscillator pulses.

4. GLASS LASER DEVELOPMENT

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4. GLASS LASER DEVELOPMENT

4.1 Overview

In the previous section we discussed system design and assembly, one of the three specific project areas in the glass laser program. In this section we discuss the other two project areas: component design and engineering, and laser physics.

Component Design and Engineering

The component development portion of the glass laser program is devoted to improving the performance and reliability of laser components, to meet the increasingly demanding requirements of the program. Over the past year excellent progress has been made in the design of amplifiers, spatial filters, electrical-pulse power systems, and lenses. Some examples of this work are shown in Fig. 4-1. The amplifier work has

been motivated by the requirement for laser amplifiers having very high gain and low-noise sources so as to minimize nonlinear beam-focusing problems in laser systems. Because a large fraction of the total system cost is in the electrical energy storage subsystem, cost reduction efforts have been concentrated there. The recent installation of the Argus energy storage bank at a cost of \$0.22/joule indicates that the Shiva capacitor bank can be installed well within budget.

Laser Physics

During 1975 our efforts to improve the performance of high-peak-power glass lasers shifted in emphasis from the study of individual components and idealized propagation conditions to problems associated with the

Fig. 4-1. Components designed for the Argus laser system—clockwise from upper left: 2.5-cm rod amplifier, 8.5-cm disk amplifier (B75N), spatial-filter telescope, and 4-cm rod amplifier.

Table 4-1. New laser materials

	Shiva	Shiva Upgrade	Increase in power handling capability
Laser rod:	Silicate glass	Phosphate glass	2.2
Laser disk:	Silicate glass	Fluorophosphate glass	2.1
Lens:	Borosilicate glass	CaF ₂ crystal	1.8
Faraday rotator:	Terbium glass	Terbium fluorides	~2.4

entire laser chain. It became clear that perturbation growth occurs at the same rate in complex laser systems¹ as in simple plane glass systems,² although with different spatial frequencies. Since this perturbation growth or "self-focusing" results in catastrophic beam deterioration and laser damage, we must seek to minimize it.

Self-focusing in laser systems can be described mathematically as follows:

$$N = N_0 \exp \left[\text{const} \frac{n_2}{\lambda n} \int I dl \right]. \quad (1)$$

The perturbation growth level N can be minimized by reducing all of the free parameters in Eq. (1). Except

for λ , which is fixed at $1.06 \mu\text{m}$, and the constant term, all terms are minimized consistent with cost constraints, using the following procedures:

1. Reduce the initial noise amplitude, N_0 , by maintaining very clean surfaces and by spatial filtering.
2. Reduce n_2/n , the ratio of the nonlinear index of refraction to the linear index of refraction, by using new laser materials (see Table 4-1).
3. Reduce the glass path, l , by using high-gain amplifiers and thin components.
4. Control the peak power intensity, I , by optimizing the laser staging.
5. Sequentially reduce the perturbation level, N , to a new N_0 value by spatial filtering (see Fig. 4-2).

All of these techniques are being used to maximize the performance of the LLL laser systems.

Into Spatial Filter

Exit from Spatial Filter

Fig. 4-2. Effect of a spatial filter in the Cyclops chain. Note reduction in beam perturbation after filtering.

The improvements in physics understanding have led to improved system modeling and component design. Improved models, in turn, have enabled us to concentrate our attention on physics and engineering problems whose solution would yield large performance/cost benefits. Over the past three years,

this interplay between physics, engineering, and "production" has been very effective. Results in terms of impressive large-system performance will be apparent during the coming year.

J. F. Holzrichter

4.2 Components

The year 1975 was generally a period of evolutionary, rather than revolutionary, development in the components area. However, LLL's achievements in this area have been important steps toward attaining the laser fusion program's goals. Our accomplishments have included the following:

1. Incremental improvement in the passively mode-locked oscillator (PMO) design.
2. Development of an improved single-pulse selector (switchout).
3. Development of improved apodizing apertures.
4. Development of improved fast Pockels cells.
5. Improved designs for large-aperture Pockels cells.
6. Development of a uniform-high-gain, 40-mm-aperture rod amplifier.
7. Development of cost-effective high-energy spatial filters.

8. Proof-of-concept demonstrations for two methods of protecting the target from amplified spontaneous emission, ASE; also called superradiance or superfluorescence) with ASE shutters.

9. Development of a clean disk amplifier type (B75, C75), and fabrication of the prototype of another very clean improved amplifier type (β, γ, δ).

10. Continued progress toward strain-free, index-matched solid edge claddings for amplifier disks.

11. Implemented an effective and continuing laser technology transfer program for the benefit of the commercial (industrial) community.

These and other accomplishments are expanded upon in the body of this section.

W.D. Fountain

4.2.1 OSCILLATOR DEVELOPMENT

The Shiva laser system envisioned as the next major step in the laser fusion program will require an initial radiation source that provides, reliably, a pulse with a carefully tailored temporal shape. To this end we have been investigating various techniques for reliable short-pulse generation. The current approaches for short-pulse generation include passive mode locking, use of a fast external switch, active mode locking and injection locking, and combinations of active and passive mode locking. The required short-pulse properties of greatest importance are (1) a pulse energy of roughly 1 mJ with $\pm 5\%$ amplitude stability, and (2) a pulse duration that is variable, at least directly, between ≤ 50 ps and ≥ 1.5 ns with $\pm 5\%$ duration stability. The adequacy of the various generation techniques is judged in terms of these requirements. Passive mode locking has the advantage that it can easily produce pulses of the shortest duration. The essential disadvantage of this technique is that the statistical nature of the fluores-

cence noise, from which the short pulse grows, is reflected in the final pulse. The use of an external switch to cut a short pulse out of a longer pulse is the simplest, most reliable, and best understood technique available. However, the minimum pulse duration is limited to about 200 ps by transit time of the high voltage pulse across the Pockels cell crystal.

Actively mode-locked oscillators (AMO's) now appear to be the most promising approach to satisfy all of the short-pulse requirements. However, current mode-locked oscillators produce pulse energies of about 10 nJ. Consequently two methods of increasing the pulse energy are being examined. Work on Q-switching a pulsed, quasi-cw, mode-locked oscillator by D. Kuizenga at the Stanford Research Institute is being supported by LLL under subcontract 1547503, which is a follow-on to LLL subcontract 5241805 with Stanford University. In addition, work is in progress at LLL to explore the properties of injection-locked oscillators.

A minor redesign of the resonant cavity of the existing passively mode-locked oscillator (PMO) was performed in order to lower the power density at most of the intracavity components.

The dual-modulation oscillator (DMO), which uses an intracavity electrooptic modulator together with a dye cell, was reported preliminarily in the 1974 Annual Report. It has been characterized and its performance is excellent, with the very important exception of what we have termed the "breakup" problem, which renders it unusable at this time. This problem is evidenced by the tendency of the DMO to emit a train of modulated pulses or pulse bursts, with each burst being on the order of 250 ps in duration, when the pulse duration is lowered below about 250 ps. This problem is caused by intracrystal electrical reflections in the Pockels cell, which cause the optical transmission and hence the pulse to be modulated, which modulations are enhanced by the bleachable dye. We are currently working on improved fast Pockels cells (Sec. 4.2.2), but all DMO work has been stopped pending success in this endeavor.

4.2.2 SPECIAL COMPONENTS

An Electronic Single-Pulse Selector

Optically triggered spark gaps can be extremely fast, simple switching devices when the optical energy far exceeds threshold. However, they are plagued by erratic operation and large jitter when they are required to function as threshold detectors as well. An all-electronic single-pulse switchout system has been designed to avoid these problems. It uses an avalanche transistor chain to trigger a Krytron switch. Threshold detection is performed in the comparator of the electronic switchout by a tunnel diode which has a switching time under 100 ps and a threshold which is very well defined. The signal to the comparator is obtained from an ITT F4018 vacuum photodiode, driven by a few tenths of a percent of the energy from the mode-locked train. An optical delay line between the beam splitter (for the photodiode) and the Pockels cell ensures that the optical pulse that is switched out is the one that triggered the system. Thus the gated pulse must exceed a certain adjustable minimum energy.

Figure 4-3 is a block diagram of the Janus electronic switchout system. An avalanche stack of nine 2N3700 transistors generates a 1.5-kV pulse which triggers the Krytrons. Their delay can be decreased to about 5 ns by pulsing the keep-alive current to a high value (above 1 mA) at the time the oscillator lamps fire. By adjusting the pulsed keep-alive currents, the 7-kV gating pulse to the Pockels cell can be varied both in position and

The DMO task accomplished the following:

1. "Clean" 250-ps (and longer) pulses, with no dye.
2. With dye, pulses as short as 25 ps (but in a format unusable for target-shooting).
3. No failure to mode-lock (no missing trains).
4. No double or multiple pulse *trains* (i.e., barring the "breakup" problem).
5. Excellent stability of the shape and amplitude of the pulse-train envelope.
6. Interpulse noise better than -43 dB.
7. Output pulse arrival predictable to <1 ns.

This approach did not address, and would not (even if successful) have improved, the shot-to-shot variations in pulse *duration* observed with the PMO.

W. H. Lowdermilk
J. E. Murray
W. D. Fountain
B. C. Johnson

duration. The total delay from optical trigger to switchout is about 25 ns, 10 ns of which is due to the avalanche transistor stack and 6-8 ns of which is due to the comparator. This system is presently operational on the Janus laser.

D. W. Phillion
R. Bolt

Precision Apodizing Apertures

Beam-shaping or "apodizing" apertures are vital components for the successful operation of high-power laser systems.³⁻⁶ In systems such as those being developed for laser fusion experiments at LLL, the optimum whole-beam spatial profile represents a sensitive tradeoff among three conflicting requirements: (1) efficient energy extraction from the laser, (2) propagation through the amplifier chain with minimal beam breakup from linear (diffraction) and nonlinear effects, and (3) distribution of the beam near the far field at small laser-fusion targets. In order to achieve a balance among these requirements, it is mandatory to utilize optical elements that can exercise precise control of the radial intensity profile of the laser beam.

The previous Annual Report⁴ described in detail a "rotating mask" processing technique that is used to produce photographic apodizing apertures with accu-

Fig. 4-3. All-electronic single-pulse selector for Janus laser system uses an avalanche transistor chain to trigger a Krypton switch.

rately predetermined spatial transmission profiles. These photographic-plate apertures have been successfully implemented on all the large laser-amplifier systems (Janus, Cyclops, Argus) presently in operation, where they have demonstrated the capability of providing the optimum whole-beam spatial profile for these systems. As was discussed in the 1974 Annual Report, the presently preferred profile is the "filleted quadratic"; such an aperture profile is shown in Fig. 4-4.

Over the past year, the "rotating mask" technique has been applied to the production of vacuum-deposited metallic-coated apodizing apertures (MCAA's). The MCAA's have several advantages over the photographic-plate apertures presently being used. First, the MCAA's are fabricated using high-optical-quality substrates, resulting in optical elements with much less optical phase distortion than obtained with the relatively poor-optical-quality photographic plates. Second, since the metallic coatings can be placed on substrates that have been antireflection-coated, the

Fig. 4-4. Radial optical-density profile of the "filleted quadratic" type produced by photographic-plate apodizing apertures used on large laser systems (Janus, Cyclops, Argus) presently in operation.

MCAA's, unlike the photographic plates, do not require a special liquid gate mounting holder for index matching. As a result, MCAA's are considerably simpler to use, align, and replace. A possible additional advantage is that the MCAA elements use reflection as well as absorption to reject unwanted energy from the input beam. Reflective elements are less prone to adverse effects resulting from heating by absorbed laser energy, and can also be conveniently used to provide the reflected optical signal to alignment (e.g., quadrant detector) or other offline diagnostics.

An example of a typical MCAA is shown in Fig. 4-5. The metallic coating consists of a radially varying thickness of Inconel 604 alloy, vacuum-deposited onto the substrate. By maintaining tight quality control over all phases of processing, and carefully calibrating the metal vapor deposition cycle, we can produce virtually any desired transmission characteristic on the final aperture.

Detailed spatial and spectral transmission and optical microdensitometer measurements confirm that the "rotating mask" MCAA devices can produce the spatial transmission characteristics required for our laser systems. Wavefront distortion measurements and extensive damage testing show the apertures to be of sufficiently high optical quality and durability to be suitable for long-term system use. The optical densities, D , achieved in the aperture cutoff region typically exceed 5, which indicates that they will reduce residual Fresnel diffraction ripples (approximately equal to $2 \times 10^{-D/2}$) to less than 1%.

B. C. Johnson

Fig. 4-5. Metallic-coated apodizing apertures (MCAA's) have better optical properties and are simpler to use, align, and replace than photographic-plate apodizing apertures.

Fig. 4-6. Lasermetrics Model 1081 Pockels cell uses a KD*P crystal in the cylindrical ring electrode configuration. This is typical of advanced-design Pockels cells developed by several different commercial suppliers in cooperation with LLL.

Pockels Cells

Pockels cells (PC's) have found a wide range of useful applications in the LLL laser program. They are presently used for optical gating and switching and may more generally be used for phase and amplitude control of laser light. Laboratory efforts over the past year in this area have been concentrated on two principal projects: (1) the development of small-aperture

(<1-cm) fast-responding PC's for switching applications, and (2) design and construction of large-aperture (>2.5-cm) PC's for use in optical isolators in the larger laser systems, such as Cyclops, Argus, and Shiva.

Fast-switching PC's are generally used in optical gates to select a single pulse from a mode-locked pulse train, or as intracavity Q-switch/modulators to control the generation of short mode-locked pulses in laser oscillators. Our primary efforts in this area have been to improve device performance through increased optical quality and contrast (on/off) ratios, to lower device capacitance for faster device risetime, and to obtain good impedance-matching in the devices to permit efficient electrical coupling into the devices, particularly at high frequencies (>1 GHz). As a result of collaborative efforts, several commercial vendors have responded to our requirements with devices that represent substantial advances over the previous technology. A typical example of one of these new devices is shown in the photograph of Fig. 4-6. The active material in the device is a KD*P (KD_2PO_4) crystal of the cylindrical ring electrode configuration.⁷ Electrically, the device acts as a 50- Ω feedthrough transmission line, and is well-matched to the 50- Ω coaxial cable and connectors used to connect the cell to the driving circuitry. In operation, the PC is connected to a high-voltage driving source, and placed between crossed polarizers in the beam path. When the halfwave-voltage pulse (~ 7 kV at $1.06\text{ }\mu\text{m}$) is applied to the device, the PC turns "on" (transmits an optical pulse), and it turns "off" as soon as the voltage is removed. The contrast ratio of the device shown has been measured to be $>10^4:1$ at 1064-nm wavelength, and its optical transmission risetime is about 150 ps or less.

A general area where PC's have programmatic impact is optical isolation. The PC is an electronically controllable bidirectional isolator, rejecting unwanted radiation propagating in both forward and backward directions when in its normal "off" state. It is turned "on" only to allow the desired pulse to propagate through the chain.

The photograph of Fig. 4-7 shows the results of recent commercial developments in large-aperture KD*P PC isolator devices. The smaller unit has a 2.5-cm clear aperture and the larger device has a successfully employed on Cyclops to suppress amplified spontaneous emission and to protect the system front end from back-reflected radiation. The 3.5-cm device is scheduled for implementation on Janus early in 1976. Both these devices have exhibited excellent performance characteristics, with contrast ratios $>500:1$ and optical transmission risetimes <10 ns. These devices represent state-of-the-art developments in large-aperture PC's. One serious impediment to the

development of large-aperture (i.e., >2.5 -cm) PC's has been the unavailability of sufficiently large crystals of the required optical quality. Recently, progress has been made in crystal growing capabilities, as evidenced by the above-mentioned 3.5-cm devices and 10-cm doubling crystals which have been grown and are now being polished.

A computer-aided, iterative design procedure has been developed to optimize the performance of large-aperture PC isolators, subject to a number of constraints including cost. Cylindrical, 0° z-cut KDP (KH_2PO_4) and KD*P (KD_2PO_4) were chosen as the active crystals because they are the only two materials currently available of sufficient size and optical quality and having a high optical-damage threshold. The electric field and potential distribution in and around the active crystal are calculated by the computer code JASON,⁸ which solves the Poisson equation for the cylindrical geometry employed. A number of iterative steps are used, with systematic variations of a number of geometrical parameters, such as crystal aspect

(length/diameter) ratio and electrode position. The geometry used in the design model is illustrated in Fig. 4-8.

Calculations show that the voltage difference, V_T , between the crystal faces is radius-dependent, and a strong functional of crystal and electrode geometries. Since the transmission of the device between crossed polarizers is given by

$$T(r) = T_{\max} \sin^2 \left[\frac{\pi}{2} \frac{V_T(r)}{V_{\lambda/2}} \right],$$

where $V_{\lambda/2}$ is the halfwave voltage, it is important to keep variations in V_T as small as possible.

A number of experiments on smaller KD*P samples and devices were conducted to provide additional design data. The nonlinear index of KD*P was measured— $n_2(\text{KD*P}) = (1.0 \pm 0.3) \times 10^{-13}$ esu—because it is important to determine the amount of "beam breakup" contributed by a given length of material. Direct-current and pulsed (~ 50 -ns) high-

Fig. 4-7. Recently developed large-aperture KD*P Pockels cell isolators. Unit on left has a clear aperture of 2.5 cm; one on right, 3.5 cm.

Fig. 4-8. Geometry of large-aperture Pockels cell isolator modeled by JASON computer code.

Fig. 4-9. Results of high-voltage breakdown tests to establish the surface breakdown threshold of KD*P.

Fig. 4-10. Results of a typical design calculation are a curve of transmission as a function of radius.

voltage breakdown tests have been conducted to establish the surface breakdown threshold of KD*P. These results are summarized in Fig. 4-9. Finally, detailed transmission, capacitance, and contrast-ratio measurements were used to compare and normalize the predictions of the design model. The results of a representative design calculation, expressed in the form of a transmission-vs-radius curve together with the parameters used, are shown in Fig. 4-10.

Using this approach, it has been possible to design large-aperture (>2.5 -cm) Pockels cells with length-to-diameter ratios less than or equal to unity, with transmission nonuniformities $<10\%$ across the aperture, and with risetimes as short as 5 ns.

B. C. Johnson
M. A. Summers

4.2.3 ROD AMPLIFIERS

The current development of Nd:glass laser rod amplifiers is motivated by the need to provide suitable drivers for the large-aperture (>9 -cm) disk amplifiers in Argus and Shiva. Our primary goals have been to achieve (1) high gain coefficients, (2) excellent gain uniformity ($\pm 5\%$ or better) across the amplifier aperture, (3) a significant reduction in beam obscurations (caused by damage sites, bubbles, and other defects), (4) minimal phase shifts due to birefringence, and (5) control over both parasitics and amplified spontaneous emission (ASE). The reasons for the goals are: (1) high gain coefficients permit the minimizing of whole-beam nonlinear phase shift contributions of the rod amplifiers, (2) a homogeneous gain distribution does not affect the apodization of the transmitted laser beam, (3) reduction or elimination of beam obscurations helps control small-scale catastrophic self-focusing and reduces scattering, (4) minimizing stress birefringence in the glass laser rods reduces the amplifier insertion losses (and therefore increases the net gain coefficient) and, what is more important, minimizes the variations in beam intensity produced by birefringence after the beam propagates through an isolation polarizer, and (5) parasitic oscillations and ASE produce stray $1.06\text{-}\mu\text{m}$ radiation which can be amplified along a laser chain into a flux sufficient to deteriorate or destroy a fragile laser-fusion target before the main laser pulse arrives.

The current state of solid-state laser technology permits predictions of laser rod amplifier performance to be made based upon the quantum-mechanical and optical properties of the laser glasses, details of the pumping cavity, rod length, rod diameter, and flash-lamp construction. Both analog and digital methods are used to optimize the rod amplifier designs in accordance with the above-mentioned design goals. Ray-tracing codes used for pumping cavity simulations are ZAP and MIR (3D and 2D Monte Carlo codes, respectively).

Our present rod-amplifier designs are based upon silicate laser glasses ($n = 1.556$, $n_2 = 1.4 \times 10^{-13}$ esu), so that the principal design parameters pertinent for laser rods are Nd doping, rod length, and rod diameter. If the product of the laser rod diameter, D , and the doping, ρ , of the bulk material is kept constant at 4-cm , then relatively homogeneous gain distributions can be achieved by placing the rod in a rather simple pump cavity designed to overcome the exponential attenuation of the pump light as it passes through the outer regions of the laser rod. If uniform gain is a requirement, then rod amplifiers exceeding 5-cm aperture require very low Nd dopings and hence sacrifice gain coefficient and excitation efficiency.

Optimization of the pumping cavity involves the

variation of 12 bank and pumping-cavity parameters. The tedious aspect of this optimization process is relieved somewhat by the existence of fixed values (such as silver reflectors and 300 Torr lamp pressure) and a few extant "rules-of-thumb" whose choices are based on substantial experimental data. The remaining parameter space was probed using the smaller, 2D, ray-tracing code (MIR). It was found to be feasible to optimize the nonfixed cavity parameters one at a time. Prototype pumping cavities were constructed to check the normalization of the computer codes. The predictions of both MIR and ZAP were found to be substantially in error unless empirical normalizations were applied.

Fig. 4-11. Spatial variation of gain coefficient, $\alpha(r)$, for a 4-cm-diam rod amplifier fitted with 6-lobe and 12-lobe silvered reflectors containing 6 and 12 flash-lamps respectively. Freshly prepared ZnCl_2 immersion fluid, Sm-doped shield glass, 300-Torr 13-mm flashlamps, input energy 12 kJ. Two different azimuthal angles are represented: $\phi = 0^\circ$ (corresponding to a scan along a line connecting two lamps and the rod's centerline), and $\phi = 30^\circ$ (corresponding to a scan along a line bisecting two lamps and intersecting the rod's centerline).

Fig. 4-12. Schematic of lateral cross section of 4-cm-diam rod amplifier equipped with 6-lobe silvered, crenulated reflectors.

A 4-cm-diameter rod amplifier was designed using the above techniques. Prototype reflectors with 4, 6, and 12 lamps were constructed using both aluminum and silver surfaces. The gain distributions obtained for the 6-lobe and the 12-lobe silvered reflectors are shown in Fig. 4-11. As indicated in the figure, the focusing ability of the 12-lobe reflector was inadequate to provide a uniform gain distribution in the 0.8%-Nd-doped 4-cm rod, and hence the 6-lobe reflector was required

to achieve a homogeneous gain distribution.

Beam obscurations and static birefringence in the 4-cm rods were controlled by stringent optical specifications on the laser rods (bubbles <0.1 mm, birefringence ≤ 0.7 nm/cm). Parasitics were controlled in the 4-cm rod amplifier by surrounding the rod with a samarium-doped (selectively absorbing radiation at $1.06 \mu\text{m}$) shield glass filled with a nearly index-matched ($n = 1.52$), nearly saturated aqueous solution

Fig. 4-13. Completed 4-cm rod amplifier (corresponding to Fig. 4-12) now installed in Cyclops and being tested in Argus.

of ZnCl_2 immersion fluid. As shown in Fig. 4-12, the diameter of the shield glass was chosen to be n times the diameter of the laser rod where n is the glass's index of refraction. This insured that most of the flashlamp light refracted into the ZnCl_2 immersion fluid was coupled into the laser rod. For an index-matched immersion fluid, the diameter of the shield glass should be 6.2 cm.

The immersion-fluid/shield-glass design permits the viscous (25-P) index-matching fluid to be flowed to a heat-exchanger/reservoir, thereby cooling the laser rod. Use of lower-index immersion fluids (such as diluted ZnCl_2 or H_2O solutions) caused the gain at the edge of the rod amplifier to roll off because of parasitics. This

is an undesirable situation, since it permits the parasitic "whisper modes" to oscillate within the volume filled by the totally reflected rays, thereby generating an additional source of $1.06\text{-}\mu\text{m}$ radiation to feed ASE problems already inherent in the "front end" of a laser chain.

At year's end, a 4-cm rod amplifier (see Fig. 4-13) was installed (nearly replacing two "A" disk amplifiers) in the Cyclops laser system, and two others were delivered to the Argus system for tests.

G. J. Linford
S. Yarema

4.2.4 HIGH-ENERGY SPATIAL FILTERS

The 1974 Annual Report presented the initial design and performance of a prototype vacuum spatial filter that was implemented and characterized on Cyclops. This year's goal was to design and provide cost-effective spatial filters for Argus.

A number of parameters must be considered in actually designing and building a spatial filter. One of these is the pinhole design. For optimal filtering, the pinhole diameter should be reduced as much as possible without infringing on the part of the beam one wishes to transmit. Several limitations occur. First of all, the beam as a whole may contain some optical distortions and hence will not focus to an ideal diffraction-limited spot inside the spatial filter. Secondly, because of whole-beam self-focusing in the system components, the distance from the input lens to the position of the focus will change slightly as the intensity of the pulse first rises and then falls. Finally, the pinhole itself may be damaged by the energy that it is intercepting. Damage to the pinhole can be minimized by using a pinhole

geometry that provides a large surface area on which the filtered energy impacts. This is to be compared with a pinhole which has a flat surface normal to the beam. The choice of material is also important. We use diamond, so that much of the energy is refracted or reflected rather than absorbed.

Another important consideration is the design of the lenses. Unless precise lens tilt adjustments, which are quite expensive, are to be provided, it is essential to use a coma-free lens design. Further, spherical aberration can be avoided only if the cube of the f-number of the lens is much greater than about $17D$, where D is the diameter in millimeters of the clear aperture, or if one of the surfaces of the lens is aspherized. Lenses free of both coma and spherical distortion are termed "aplanatic"; we find that the cost differential for precision aplanats is much less than the cost differential for precision five-axis adjustments. The Argus spatial filters (Fig. 4-14) generally have x,y,z adjustments for each of the pinhole and the exit lenses, no adjustments

Fig. 4-14. One of the spatial filters built for the Argus laser system.

for the entrance lens, and relatively coarse x, y, θ, ϕ adjustments for each of the two spatial filter support legs (the beam propagates along z).

Another design consideration is the choice of the vacuum system. If the spatial filter is not evacuated, the high intensity of the focused beam ionizes the atmosphere and produces a plasma sufficiently opaque that very little of the beam energy is transmitted. The operating pressure in the Cyclops filter is approximately 10^{-5} Torr. It may be possible to obtain satisfactory operation with a somewhat softer vacuum, but this is not yet established. On the Cyclops spatial filter, the

vacuum system is a mercury diffusion pump which does a good job but is bulky and requires constant attention. The Argus spatial filters are initially evacuated with a portable roughing system and then pumped down to final pressure and held there using small ion pumps, which are expected to have a lifetime of several years in this application; however, 100% redundancy has been provided in pumps and pump controllers.

W. D. Fountain
E. S. Bliss

4.2.5 DISK LASER AMPLIFIERS

The design and development of disk amplifiers has been an effort receiving major attention at LLL since 1972. Details regarding crucial disk-amplifier design issues, general design goals, parasitic oscillation control, fluorescent depumping effects, and acceptable construction materials have been extensively treated in earlier reports.⁹⁻¹² Only the present status of solutions to these diverse problems will be reviewed here.

The design goals for disk amplifiers intended for use in laser fusion applications parallel those discussed above for glass rod amplifiers, with several important additions peculiar to disk amplifiers. These disk amplifier design goals include:

1. High gain coefficients.
2. Excellent gain uniformity.
3. Elimination of beam obscurations.
4. High degree of cleanliness in assembly.
5. Minimal birefringence.
6. Cost effectiveness with high reliability.
7. Excellent optical figure.
8. Minimization of both parasitics and amplified spontaneous emission.

Since the optical surfaces of disk amplifiers are exposed to direct flashlamp illumination, they are susceptible to damage and progressive deterioration if contaminants are present within the disk laser amplifier. As a consequence of this, extreme cleanliness and proper materials must be employed in order to avoid damaging or degrading the optical surfaces of the laser disks. In our most recent disk-amplifier design, the B-75, this has been accomplished by enclosing the laser disks within a protective transparent cylindrical shield, utilizing Class 100 clean-room assembly facilities, employing suitable construction materials, eliminating fasteners that generate undesirable metal particles, and, in general, using scrupulous cleaning

methods during the clean-room assembly procedure. The resulting high degree of cleanliness is maintained during the operation of the amplifier by tightly gasketed seals, tubes enclosing the interamplifier beam paths, pure N_2 purge gas, and appropriate filters for interdicting the propagation of particulates through common or connected gas passages.

The inner assembly of the prototype of the B-75 disk laser amplifier is shown in Fig. 4-15. (See also Fig. 3-51.) Note that the disk holders are not machined (as in earlier designs) but instead are hydroformed from sheet 304 stainless steel. This design eliminates internal threaded parts and features tightly fitting split shields and separate gas purge supplies for the inner (disk) cavity and the exterior (flashlamp) pumping cavity.

The efficacy of the foregoing disk-amplifier design rationale has been verified by performing gain and life tests on a B-75 disk amplifier prototype. These tests were conducted with suitable optical diagnostics to monitor the amplifier gain and the number, sizes, and distributions of disk obscurations *in situ* for each individual laser disk.

The monitoring of disk obscurations was accomplished by the use of an external focusing optical system configured to focus successively on each individual laser disk mounted inside the B-75 amplifier. The collimated, coherent illumination at a wavelength of $0.633 \mu m$ was provided by a 50-mW cw He-Ne laser equipped with an intracavity etalon and a spatial filter to provide a uniform, nearly single-frequency laser source. The nominal depth of focus of the optical system was adjusted to focus (approximately) between both parallel faces of an individual laser disk oriented at Brewster's angle. Since all six laser disks are simultaneously in the diagnostic laser beam, obscurations on the five other disks are identifiable as exfocal images

Fig. 4-15. Inner assembly of the prototype of the B-75 disk amplifier.

whose characteristics permit a relatively accurate assessment of the actual sizes of the out-of-focus obscurations. Thus, for an obscuration of diameter ρ located a distance z (where $\rho^2/\lambda < z$) from the object focal plane of the diagnostic apparatus, the diameter, D , of the first null in the far-field intensity distribution is given by

$$D = M \left[\frac{2.44\lambda}{\rho} \left(z - \frac{\rho^2}{\lambda} \right) + \rho \right], \quad (1)$$

where M is the (lateral) magnification of the diagnostic optical system.

As reported previously,¹³ obscurations are not acceptable in high-radiance laser amplifiers since (1) they increase scattering (for very small obscurations); (2) the intensity fluctuations they produce may be amplified by nonlinear effects (according to the Bespalov-Talanov theory), producing a badly self-focused laser beam; (3)

they may produce further damage (and obscurations) when subjected to the intense pumping radiation from the flashlamps.

Gain measurements and passive optical insertion losses were made using a cw Nd:YAG laser oscillating at 1.0642 μm . In addition, a pulsed (~ 100 -ns pulsewidth) Nd:YAG laser designed to oscillate selectively at 1.052, 1.061, and 1.064 μm was used to expand the spectral range of the gain measurements (necessary for the phosphate glass examined). Life and gain tests over more than 1000 shots were made on each of two types of "B"-size laser disks:

1. Owens/Illinois ED-2, 3% doping with Er^{3+} edge coating.
2. Hoya LHG-6 phosphate glass with BSDL-5 edge coating.

The measured gain coefficients for these glasses during the 1000+ shots are plotted in Figs. 4-16 and

Fig. 4-16. Measured small-signal gain coefficients (at 1.064 μm) of ED-2 glass B-disks in the prototype B-75 amplifier during life testing.

4-17. As shown in Fig. 4-17, pulse gain data were taken for the LHG-6 disks at 1.052 and 1.061 μm . Both cw and pulsed gains were measured for the LHG-6 in the B-75 disk amplifier at 1.064 μm , with identical values being obtained.

Detailed examinations of the B-75 diagnostic photographs and individual photomicrographs revealed that relatively few (<20) disk obscurations/damage sites were of metallic origin. Additional vitreous obscurations from the Pyrex shield (in the ED-2 disk experiment) and from the BSD-5 edge coating (in the LHG-6 disk experiment) were found. Corrective measures were subsequently taken to control the production of the vitreous obscurations.

In general, the B-75 disk amplifier prototype survived the two life tests in excellent condition. The stability of the measured optical gains and the general resistance of the metallic amplifier elements to pump-induced deterioration were sufficient to permit operation of analogous B-75 amplifiers "on-line" in a laser system for thousands of shots before normal amplifier maintenance would be required. The single-pass, small-signal, cw-measured gain of the B-75 was 3.73 for ED-2 glass measured at 1.064 μm , using an input energy of 135 kJ. This value is somewhat less than the typical single-pass gains obtained for earlier "B" amplifiers, but the substantial increase in amplifier cleanliness and durability offset the slight reduction in amplifier gain.

The design of the Shiva β -disk amplifier was completed in 1975 and the drawing package was prepared for solicitation of quotes for 66 amplifier units to serve as the principal disk amplifier for the 20-beam Shiva

laser system (three β -disk amplifiers per arm plus spares). The β -disk amplifier features a one-piece fused silica shield glass, eliminates the massive rails found in the B-75 disk amplifier by welding the individual hydroformed disk holders into a relatively lightweight structure, and utilizes disks slightly larger than the "B" disks used in the B-75 amplifier. Some consideration is being given to the use of nickel instead of 304 stainless steel alloy; the former probably produces larger wear particles, but the iron component of the latter dissolves in the glass and hence produces larger obscurations for the same particle size. As in the B-75 disk amplifier discussed above, separate N_2 purge supplies are fed into the flashlamp (exterior) and disk (interior) cavities. Somewhat better sealing between these two gas systems is possible with the β -disk amplifier design owing to the use of the one-piece shield glass.

The β -disk amplifier is designed to have a pulsed 0.1-ns pulse length gain of 3.8 at an input energy of 135 kJ. It has been found that the gain of the β -disk amplifier is in excess of that obtained for the B-75 owing to the reduction of internal obstructions (such as the massive rails) in the disk cavity.

Eight three-disk C-75 amplifiers were being constructed for use on the Argus laser system at the end of the year. These disk amplifiers feature a liquid index-matching system which is designed to minimize the optical feedback from the periphery of the "C" disks. The liquid-clad disk holders feature a triple-O-ring design which contains an index-matching liquid of

Fig. 4-17. Measured small-signal gain coefficients of LHG-6 glass B-disks in the prototype B-75 amplifier during life testing.

nearly saturated aqueous ZnI_2 circulated between the disk holders and a constant temperature reservoir. An extrinsic absorber (chrome black) was deposited on the inside of the disk holders to absorb the 1.062 and 1.34 μm fluorescent radiation passing through the disk/ ZnI_2 interface. Since gain coefficients as high as 0.08/cm are desired (corresponding to an αD product of 3.0), the fraction of the incident fluorescent light returned to the laser disk must be less than 2% if significant depumping effects are to be avoided. Accordingly, the Argus "C-75" liquid-clad disk holders are designed to use a ZnI_2 index-matching immersion liquid carrying a suitable intrinsic absorber (such as NiCl_2) to assure that the absorption of the 1.062- and 1.34- μm radiation will be sufficient.

Significant advances in obtaining solid index-matching edge coatings for laser disks were achieved during 1975. The use of solid edge coatings on laser disks has hitherto been acceptable only for disks up to "B" size (9-cm aperture), since the typical refractive index of solid edge coatings until recently has been approximately 1.71 (compared to the bulk laser glass index of approximately 1.556). This relatively large mismatch of refractive indices permits spurious reflections to take place at the glass/edge-coating interface and permits total internal reflections to occur at steep angles of incidence. This is not acceptable for laser disks of 20-cm aperture (such as the "C" and "8" sizes for Cyclops and Shiva respectively) since these index mismatches reduce the obtainable gain coefficients by 15-20%.

Successful melts of candidate edge-coating glasses were made at BMI during the year. Hoya has also developed an index-matching glass for LSG-91H. We plan to test several "C"-size (20-cm aperture) disks coated with the index-matched solid edge coating to determine if direct substitution for the liquid-clad system (described above) is acceptable.

**G. J. Linford, W. D. Fountain, W.F. Hagen,
W. Neef, P. Holl, D. Bupp, N. Patlovich,
K. Ker, W. Crothers**

Design of Breakup-Limited Disk Laser Amplifiers

This section outlines the method used to design a series of laser amplifiers of different sizes and gains on the basis of the properties of the laser glass used in them. The amplifiers are optimal in the sense that they produce a given performance factor X (ratio of output power to breakup integral) and gain G for the least possible cost.

Comparison of various designs requires a method of comparison. The X factor of an amplifier is:

$$X = \frac{\alpha n^2 d^2}{316n_2(1 - 1/G)},$$

where α is the average gain coefficient in the disks, n is the refractive index, d is the beam diameter, n_2 is the nonlinear refractive index, and G is the gain. We can write this as

$$X = \frac{X_\infty}{(1 - 1/G)},$$

where X_∞ is a factor which gives the performance of the disks independently of how many there are (i.e., independently of the gain). Thus, the appropriate measure of performance is

$$X_\infty = \frac{\alpha n^2 d^2}{316n_2}.$$

We refer to X_∞ as the "ultimate performance factor." Since we are interested in cost-effective designs, we also need a gain-independent measure of cost. This is the gain-specific cost

$$S = \frac{\$}{\ln G}.$$

Clearly, if we double the number of disks (or amplifiers) it will double both the cost and the logarithm of the gain, so S will be unchanged (this is slightly wrong for low gains due to end effects).

Optimum amplifiers will have, for any given gain, the highest possible X_∞ value, since this will lead to the highest X and thus best performance. Likewise, minimizing S with any fixed G leads to the lowest possible cost. Thus, X_∞ and S are the variables we should consider when optimizing amplifiers.

Let us first consider optimizing the performance of amplifier disks of a fixed beam diameter d . Since it is not practical to construct disk amplifiers with many different combinations of pump pulse duration, disk doping, disk thickness, and bank energy, we utilize a model of the pumping process to simulate the laser behavior. The model has been carefully checked against copious experimental data available from the LLL laser hardware. It contains the following elements:

1. Flashlamp driving circuit simulation.
2. Optical power flow in the laser cavity.
3. Absorption properties of the laser glass.
4. Decay of inversion in the glass.
5. Enhanced loss due to fluorescence amplification.
6. Inversion upper limits due to bulk and face parasitic oscillations.

The output of the model is the maximum disk gain achieved for the specified pumping conditions.

To optimize the pump duration and doping with fixed bank and disk thickness, the model is used repeatedly while the discharge circuit parameters are changed to modify the pump duration, and the glass absorption and decay are changed to follow the doping. The result is a contour map of the gain as a function of doping and pump duration (Fig. 4-18). Since X_∞ is

Fig. 4-18. Repeated simulations with different dopings and drive pulse widths produce a contour plot from which one can choose combinations of values for these parameters that produce the highest gain. Hatched area lies within 2% of optimum.

Fig. 4-19. Curves of average gain coefficient as a function of disk thickness and bank energy. Each point has been optimized for doping and pump pulse duration.

maximized at the peak of this plot while the cost is not changed by the doping or pump duration, the best place to operate is at the peak. With large bank energy, lamp life may be reduced to the point where we must operate with longer pulses; in this case, the appropriate operating point is at the maximum gain reached to the right of the pulse duration corresponding to minimum acceptable life.

We now choose the optimum bank energy and disk thickness. Here we must strike a balance between increasing performance and increasing cost as the bank gets larger. This is done by finding the highest gain attained for a variety of disk thicknesses and bank energies (Fig. 4-19). From these, we can calculate the corresponding X_∞ values. Knowing the cost of the disks, lamps, and head hardware, and the cost per joule of energy storage, we can also find the S value at each point. This allows us to plot contours of constant S on a chart of X_∞ versus bank energy W (Fig. 4-20). Each such contour reaches a maximum X_∞ value at some bank energy (and disk thickness). This is the best performance available for the given S . We now have the information needed to plot a curve of lowest S available from this diameter as a function of X_∞ (Fig. 4-21). We can choose a wide variety of performance factors; as performance rises, the optimum disks become thinner and the bank becomes larger.

The final step of our amplifier design optimization method is to carry out the above process for a number of different beam diameters. The result is the set of curves illustrated in Fig. 4-22. For any performance, there is a diameter which gives the lowest cost. We

Fig. 4-20. Curves for several S -values as a function of bank energy and X_∞ . The most cost-effective amplifier is the one giving the largest possible X_∞ at any fixed S . These optimal values are indicated by dots on the curves.

then work back to find the thickness, bank energy, doping, and pump duration which led to the optimum.

To summarize, we start with required X and G values for an amplifier. We calculate

$$X_{\infty} = X(1 - i/G)$$

and then determine the best diameter amplifier from Fig. 4-22. This then yields the other disk parameters (thickness, bank, doping, pump duration). From the gain G_1 of one disk, we determine the number of disks needed

$$N = \frac{\ln G}{\ln G_1}$$

and the cost of the amplifier

$$S = S \ln G.$$

The optima found in this way turned out to be rather flat. This means that considerable variation from the absolute optimum is permissible without great cost penalty. Thus, variations may be made for engineering convenience without worrying about serious degradation of the laser performance.

Finally, since the glass properties required (pump light absorption and decay as a function of doping, peak cross section, linear and nonlinear refractive indices) may be found from a set of small samples of varying doping, we can design a complete set of laser amplifiers and thus complete optimum laser systems from these samples. This capability is of great importance in the selection and evaluation of new laser materials.

J. B. Trenholme

Fig. 4-21. Minimum cost required to produce desired performance for a given amplifier diameter. As the performance increases, the disks become thinner and the bank larger.

Fig. 4-22. A set of curves like the one in Fig. 4-21, but for different beam diameters, allows us to choose the best diameter for any performance level.

Optimum Constant-Energy Laser Pump Pulse Shape

What is the best shape of the pump pulse into the flashlamps that pump a Nd:glass laser? More generally, what is the optimum power pulse to maximize the peak value of an exponentially decaying process, given some relation between input power and pump rate?

The answer to this question is simply found once we realize that the *pump pulse should end at the time of peak gain*, since any power put in after this should have been put in before the peak, where it could have done some good (Fig. 4-23).

The converse is that the peak gain comes at the end of the pulse. Thus we know the time of peak gain, and may reduce the problem to a isoperimetric variational problem.

Suppose, then, that we have a fixed amount of energy W in a storage device. We meter it out in some power waveform $P(t)$, where

$$W = \int_{-\infty}^{\infty} P(t) dt.$$

The power is converted by some instantaneous efficiency $f(P)$ into the pumping rate of an exponentially decaying process A :

$$\frac{\partial A}{\partial t} = f(P) - \frac{A}{\tau}.$$

The process decay time is τ . If we define the end of the pump pulse as $t = 0$, the maximum value of A comes at this time and is

$$A_m = \int_{-\infty}^0 e^{t/\tau} f(P) dt.$$

Maximizing A_m with W constant is just a variational problem with a Lagrange multiplier. The resulting Euler-Lagrange equation is

$$\frac{\partial}{\partial P} [e^{t/\tau} f(P) + \lambda P] = \frac{d}{dt} \frac{\partial}{\partial P'} [e^{t/\tau} f(P) + \lambda P] .$$

Since P' does not appear, the right-hand side is zero and we have

$$\frac{\partial f}{\partial P} = -\lambda e^{-t/\tau} .$$

For flashlamps driving lasers, we have

$$V \propto j^{1/2}$$

and so

$$P \propto j^{3/2} .$$

Fig. 4-23. Pumping that continues past the time of peak laser gain (upper plot) is wasted. Therefore pump pulse should end at time of peak gain (lower plot).

The efficiency of transfer is

$$\eta(j) \propto j^{-Q}$$

with $Q \approx 0.8$, so

$$\eta(P) \propto \frac{1}{j^Q} \propto \frac{1}{(P^{2/3})^Q} \approx \frac{1}{\sqrt{P}}$$

and thus

$$f(P) = P\eta(P) \approx \sqrt{P} .$$

The Euler-Lagrange equation becomes

$$\left(1 - \frac{2Q}{3}\right) P^{-2Q/3} = -\lambda e^{-t/\tau}$$

or

$$P = \left[\left(\frac{\frac{2Q}{3} - 1}{\lambda} \right) e^{t/\tau} \right]^{3/2Q} .$$

We evaluate the Lagrange multiplier λ by doing the W integral. We find

$$W = \left(\frac{\frac{2Q}{3} - 1}{\lambda} \right)^{3/2Q} \times \frac{2Q\tau}{3}$$

so that

$$P = \frac{3W}{2Q\tau} e^{3t/2Q\tau}$$

is the optimal drive pulse. For $Q = 0.75$, this is

$$P = \frac{2W}{\tau} e^{2t/\tau} .$$

Thus the optimal laser drive pulse is a rising exponential, with a risetime about twice as fast as the laser decay time (Fig. 4-24).

Because such a pulse is hard to generate with simple, reliable circuits, we will probably stick with our present pulse. However, we now know the best we can do and thus can see just how much we give up to get reliability.

J. B. Trenholme

The design of focusing optics for illumination of the laser fusion target poses a problem with unique features, from the standpoint of optical design. We are generally considering fast optics with numerical aperture values ranging from 0.3 to 0.7 ($f/1.6$ to $f/0.7$). Imaging characteristics such as field curvature and distortion are of far less consequence than spherical aberration and coma, while chromatic aberration is generally of no concern at all. The lenses and lens-mirror combinations are essentially energy delivery systems, rather than imaging systems, and the figures of merit for their performance are not the classical criteria of lens design.

Additional constraints are imposed on focusing optics for laser fusion by the requirement of handling very high power densities. First of all, to ensure survival of the lens, the power density within the lens must be kept below the normal damage threshold of the lens material. Bulk threshold values are very high, on the order of 10 J/cm^2 in a 100-ps pulse, but the damage threshold at coated surfaces is less by nearly an order of magnitude. The lens surfaces must be coated—first, to prevent significant losses due to Fresnel reflection, which can amount to 15% per surface at the steep angles encountered in fast lenses. In addition, this reflection is polarization-dependent, so that an uncoated singlet lens can produce up to 22.5% azimuthal asymmetry in the transmitted light. Secondly, surfaces must be AR-coated (i.e., antireflection-coated) to prevent the formation of “ghost” images, which are intense caustics arising within the lens material as a result of multiple reflections with focusing from the lens surfaces.

In addition to the damage problem, lenses must be designed to minimize the amount of nonlinear index

effect introduced in the lens itself. A measure of this effect is the beam breakup integral,

$$B = \frac{2\pi n_2}{\lambda n_0} \int d\ell \langle E^2 \rangle, \quad (1)$$

where n_0 is the index of the material, λ is the vacuum wavelength of the light, the index change due to nonlinearity is $\delta n = n_2 \langle E^2 \rangle$, and the integral is taken along the optical path.

The desire to keep the B-integral at a minimum renders the use of multiple-element lenses unsuitable for high power optics. Extra elements mean extra edge thickness, and the intensity within the elements closest to the focus increases markedly. The lenses designed at Livermore for fusion illumination are all singlets and doublets. This, in turn, means that aspheric surfaces must be used to remove spherical aberration.

There are three principal tools used in the design of fusion illumination optics at Lawrence Livermore Laboratory. These are ACCOS V, a commercial lens-design program obtained under license from Scientific Calculations, Inc., for use on the LLL computer system; GHOST, a program for the analysis of ghost focusing, written at LLL; and DIRECT, a point design program for aspheric lenses, developed at LLL. In the following pages, the use of these design aids will be described, and an example will be given of their application to the design of a doublet with numerical aperture of 0.7.

ACCOS V

There are several large-scale lens design and evaluation programs available from commercial sources, either through commercial time-sharing services or for installation under a licensing agreement. Each of these codes has specific advantages, depending on the nature of the design problem. After a survey of LLL lens design needs and the special problems of laser lens design, it was decided to purchase and install ACCOS V, a proprietary program of Scientific Calculations, Inc., on the LLL computer system. It was necessary to modify the code to be compatible with the LLL operating system, and this modification was carried out by Terry Gong of the Computations Department.

ACCOS V can be used either for lens design or evaluation. In the design mode, an objective function is defined, either in terms of classical aberrations or in terms of ray positions on a specified surface. Since the mapping of rays from the entrance pupil (incident beam) to the target surface determines the mapping of intensity onto the target, ACCOS V can be used di-

Fig. 4-24. Optimal laser pump power curve is a rising exponential that ends at time of peak gain and has a risetime about twice as fast as the laser decay time.

rectly to design lenses to accomplish a specific intensity mapping. This feature is of great utility in the design of energy transfer optics.

For any set of values of the lens parameters, such as radii of curvature, thickness, and aspheric coefficients, a set of values of the design variables, such as ray positions on target, or classical aberrations, can be evaluated. The sum of the squares of the amount by which these variables differ from their desired values represents the residual error in the system. The program attempts to minimize the residual error by variation of the lens parameters, using a damped, least-squares minimization routine. The operator has control of the values of the damping constants, and the relative weights of the design variables, as well as the choice of the relative weights assigned to the lens parameters.

In the lens evaluation mode, ACCOS V will trace rays through the lens system, and report either ray parameters, such as position and angle at any surface, or classical aberrations of the system. Paraxial diffraction calculations and spot diagrams can also be generated.

ACCOS V is widely used in the optics industry, and is generally available through a commercial time-sharing service. Results obtained at LLL using ACCOS V can thus be transferred quickly to other institutions involved in optical design or fabrication.

Direct Design Methods

Given a lens design problem, for example the design of a fast aspheric doublet of a given numerical aperture, the code ACCOS V can be used to arrive very quickly at a good approximation to the design. Due to its flexibility and interactive nature, ACCOS V is especially useful for surveying the parameter space, in order to obtain the best set of design features. The principal difficulty encountered in its use, however, is the actual evaluation of the aspheric surface used in the system. In general, only one surface in a system of two or three elements is designed to be aspheric, exclusive of ellipsoidal mirrors. The introduction of multiple aspheric surfaces greatly complicates the fabrication and testing of the lens.

In ACCOS V, an aspheric surface is defined in the form

$$z(y) = \frac{Cy^2}{1 + [1 - (1 + K)C^2y^2]^{1/2}} + Dy^4 + Ey^6 + Fy^8 + Gy^{10}, \quad (2)$$

where y is the ray height (radius), z is the distance from the surface to the tangent plane, C is the vertex curvature, K is the "conic constant," related to the eccen-

tricity of the surface by $K = -e^2$, and D through G are coefficients of the polynomial correction to the best conic section approximation. The code varies the coefficients, including C and K , to obtain the best performance of the system.

If we consider a cylindrical, symmetrical focusing system, the best theoretical performance is perfect. In such a system, all ray paths from the object point to the image point should be exactly equal in optical length. This condition of equal optical paths defines the single aspheric surface in the system exactly. This principle is taken as the basis of our direct design method. It can be generalized as follows. We can specify the desired transformation of the system under design in terms of a set of ray positions on a sphere. The radius of the sphere may go to infinity to represent a plane target.

Referring to Fig. 4-25, let us consider two adjacent rays incident on the sphere at angles to the optical axis, θ_1 and θ_2 , respectively. Let their points of intersection with the sphere be ϕ_1 and ϕ_2 , respectively. Since the rays must be normal to the phase surface, the incremental difference in optical path between the two rays must satisfy

$$\frac{\Delta S}{R\Delta\phi} = \sin(\bar{\phi} - \bar{\theta}), \quad (3)$$

where R is the radius of curvature of the sphere, and the overline indicates that ϕ and θ are averaged between the values for ray 1 and ray 2. As the surface becomes a plane, the phase equation becomes

Fig. 4-25. Optical path requirement for direct design calculations.

$$\frac{\Delta S}{\Delta r} = -\sin \bar{\theta}, \quad (4)$$

where r is the radial coordinate along the plane.

For a set of rays emanating from a point source, the total optical path, defined as the product of refractive index and physical path length, from the source to the target sphere must satisfy Eq. (3). As the radius of the sphere shrinks to zero, Eq. (3) reduces to the condition of equal paths. The integration is started along the optical axis, where the ray path and optical path are known.

The program DIRECT, written in Fortran IV for the CDC 7600 at LLL, calculates the aspheric surface, point by point, for a given transformation of ray heights in the entrance plane (the object distance is assumed to be infinite) onto ray positions on the target sphere. The aspheric surface is assumed to be the external surface (i.e., closest to the object), but this assumption is not essential. Versions of DIRECT for interior aspheric surfaces have been written for the HP 9830 and demonstrated to be satisfactory.

Starting at the optical axis, a set of rays is traced from the target sphere to the aspheric surface, with the angle at which the ray is launched being estimated from the geometry. Two successive values are taken, and the amount by which the optical path is in error is evaluated at each of the two starting values for the ray. Newton's method is then used to improve the value of the starting angle until the optical path condition is satisfied. Typically, 10 iterations are required to reduce the optical path error to less than 10^{-6} mm.

Input to DIRECT consists of the specification of all surfaces in the system except the aspheric external surface. All thicknesses, indices, etc. are given. The output can take various forms. A point-by-point definition of the aspheric surface can be made. It is more useful to specify the aspheric in terms of the conic plus polynomial given in Eq. (2). Accordingly, the vertex curvature is determined by fitting the first three points of the aspheric. The envelope conic is then determined, fixing the conic constant so that the conic section passes exactly through the outermost point of the surface. The difference is then spline-differentiated, and the derivative is fitted to a polynomial in y with powers 3, 5, 7, and 9. The resultant polynomial is then integrated up one degree to obtain an expression of the form of Eq. (2).

This procedure is followed because ray-trace codes like ACCOS V differentiate the surface to calculate refraction. Even with the above procedure, it is generally necessary to iterate ACCOS V one or two times about the solution provided by DIRECT. In this way, convergence is rapidly obtained, and difficult aspherics can efficiently be derived without prolonged iteration.

It should be stressed that DIRECT is a point design code, meant to be used with a survey tool like ACCOS V to obtain the best design of focusing optics.

The GHOST Focusing Code

In focusing lenses used with high power lasers, damage may occur due to aberrated multiple-reflection foci (ghost focusing). An example of such damage is illustrated in Fig. 4-26, which shows off-axis caustic formation in an $f/1$ singlet lens.

Geometrically, a ghost focus is a point where refracted and reflected light is focused to an internal spot or ring. Due to diffraction and aberration, however, a caustic is actually a surface. These caustic surfaces arise primarily in fast aspheric lenses, but they may also occur in a system of slow elements, due to multiple reflections between elements.

The potential damage to laser components from ghost focusing necessitates careful design of lenses, but no known method existed to calculate these effects; therefore, GHOST was written. GHOST is a Fortran IV program running on the CDC 7600's under the LLL time-sharing system. Designed by John Trenholme and written by Ed Goodwin, GHOST analyzes an optical system for caustic regions. The optical system description and the running parameters are read from an input file which can easily be generated by teleprinter interaction with the program. The results from running GHOST are output to the teleprinter and to a graphical (CRT) data file to be plotted or displayed later.

GHOST is a two-dimensional, radially symmetric, optical ray-trace code. The program tracks pairs of rays very close together and assumes that caustic regions occur wherever pair crossings occur, or wherever optical-axis crossings occur.

Each surface in the system is described by two conic parameters and (for aspherics) up to five polynomial coefficients. A quick-guess table for each surface (generated from input) provides bracketing radial and axial coordinates. A modified King method then iterates to the correct intersection solution.¹⁴

Once the exact intersection with a surface is determined, the surface normal is calculated and Snell's law is applied. The intensities of both the reflected and refracted legs are found on the basis of a specified reflection algorithm (Fresnel, constant, or tabular), and the most intense leg is stacked for later tracing.

A ray-pair trace may be terminated ("killed") if its intensity falls below a specified cutoff value. Otherwise, pairs are followed until they exit the system at either end, until they exit a maximum radius, until they strike a center hole, or, optionally, until they cross to form a caustic within the material.

The intensity in the caustic region is calculated from

Fig. 4-26. $f/1$ lens with internal damage due to off-axis caustic formation (a) and close-up of damage (b).

scalar diffraction theory in one of two ways. The intensity at an axial caustic is given by

$$I_c = \frac{I R_0}{\lambda} \frac{dR}{dZ},$$

where I is the present intensity of a ray pair after Fresnel surface interactions, R_0 is the initial radius of the pair, and λ is the wavelength of the light. The expression dR/dZ must be determined by examination from the output plot; it is the ratio of differences between initial radii and final Z distance along the axis for two adjacent caustic points.

Off-axis caustics are calculated from the expression

$$I_c = 5.28 \frac{I R_0}{R} \left(\frac{\rho_0}{\lambda} \right)^{1.3} \left[\frac{dR}{dS} \left(\frac{\rho}{\rho_0} \right)^{1.3} \right],$$

where I , R_0 , and λ are as above, R is the radius of a caustic point, and ρ_0 is a user-supplied reference radius of curvature. GHOST does not calculate the actual radius of curvature of a caustic surface (ρ), nor the distance between adjacent points of a caustic. Therefore, the user should guess at ρ_0 and later determine the value of the expression in brackets to calculate the true caustic strength relative to the beam center. Examination and measurement of a plot will provide the three necessary parameters.

The input file contains a mathematical description of the lens system being analyzed and running instructions for the task or tasks to be performed. An example of an input file is shown in Fig. 4-27.

In the above example, the first surface begins at $Z = 0$. It is an aspheric surface which curves to the right. The next material is glass, bounded on the right by a spherical surface which curves leftward. The final material is always an infinitely thick vacuum.

The 21 lines describing the first task in the above example define five ray pairs which are incident on the first surface from the left at equal radial intervals. The incident light is parallel. The output picture is requested to show nearly the entire system with lines tracing the ray paths, and triangular symbols appearing at caustic points. The symbols are scaled in size to the logarithm of intensity.

The second task in the example is different in only three respects. One hundred ray pairs, symbols and numbers instead of lines, and a smaller magnified portion of the picture are requested.

An example of output from GHOST is shown in Fig. 4-28. To conserve space, the first part of the plot file output (a repeat of the system specs) was not reproduced. Three pages are generated for each task. Notice the picture of the first task with four of the five ray-pairs multiply reflected inside the lens. Three of

(a)

(b)

Fig. 4-28. Graphic output for GHOST. (a) Task 1 output, multiple internal reflections. Caustic points are represented by triangles. (b) Task 2 output, detail of caustic. See text for explanation of symbols.

Design of Cyclops Doublet Lens with Numerical Aperture of 0.7

As an example of the application of the GHOST code in the design process in conjunction with ACCOS V, we consider the problem of designing a 200-mm-diam doublet lens having a numerical aperture of 0.7, for use with ellipsoidal clamshell mirrors on the Cyclops system. A series of doublets was designed, with the first surface (entrance surface) aspheric. The shape factor of the spherical element, defined as

$$q = \frac{C_1 + C_2}{C_1 - C_2}$$

where C is the vertex curvature of the surface, was varied from $q = 0$ to $q = 3.0$. GHOST output for three representative lenses is shown in Figs. 4-29, 4-30, and 4-31. For each lens, GHOST was run for light incident from the laser and for light reflected from the target. It is seen from the "forward" runs (light incident from the laser) that increasing the shape factor of the second lens reduces the occurrence of caustics in the second lens, and pushes the caustics in the first lens to larger radii. The "backward" runs (light reflected from the target) show the opposite effect. As the shape factor increases, the caustic region near the space between the two elements grows more extensive.

It was decided to alleviate the latter problem by increasing the spacing between the lenses. This spacing had been held at 1 mm in the first set of designs. It was increased to 7 mm in the second set. Two designs were run, with shape factors of $q = 1.92$ and $q = 2.98$. The GHOST output for B1($q = 1.92$) is shown in Fig. 4-32. The "backward" run indeed shows that the caustic between the lenses now falls entirely in the airspace. The forward run, however, shows a severe caustic intersecting the surface nearest the target, which was felt to be unacceptable from damage considerations.

Design B3, with $q = 3$, taken as an acceptable compromise. The GHOST output is shown in Fig. 4-33. The caustic in the first element for "forward" incidence and the one in the second element for "backward" incidence are about of equal intensity. Each is well removed from any surface. The interlens caustic is contained in the 7-mm airspace. This lens is designed to have a 5-mm-diam hole along the axis, to alleviate any on-axis caustics.

The final question regarding the performance of this lens is the illumination pattern generated on the pellet, using the Thomas clamshells. In Fig. 4-34 we see the effect of varying the target position at the clamshell focus. A target radius of $100 \mu\text{m}$ was assumed. The distribution of illumination on the target was calculated for various displacements of the target center from the

(a)

(b)

Fig. 4-29. GHOST output for Cyclops doublet A2 with $q = 1.0$ for second element. (a) Light incident from laser. (b) Light reflected from target.

(a)

(b)

Fig. 4-30. GHOST output for Cyclops doublet A4 with $q = 1.7$ for second element. (a) Light incident from laser. (b) Light reflected from target.

Fig. 4-31. GHOST output for Cyclops doublet A1 with $q = 3.0$ for second element. (a) Light incident from laser. (b) Light reflected from target.

Fig. 4-32. GHOST output for Cyclops doublet B1 with $q = 1.9$ for second element. (a) Light incident from laser. (b) Light reflected from target.

clamshell focus. The input-beam intensity profile was assumed to be a filleted quadratic of the form

$$I = I_0 (1 - (r/0.9)^2) \quad (0 < r < 0.81),$$

$$I = I_0 ((1 - r)/0.4359)^2 \quad (0.81 < r < 1.0),$$

Fig. 4-33. GHOST output for Cyclops doublet B3 with $q = 3.0$ for second element. (a) Light incident from laser. (b) Light reflected from target.

where r is the fractional radius in the entrance aperture. It is seen from Fig. 4-34 that at a displacement of $50 \mu\text{m}$ from focus the illumination is uniform to $\pm 10\%$, and even more uniform over the range of angles from 0 to 65° . In Fig. 4-35 we see the deviation from normal incidence as a function of polar angle on the pellet. We see that nowhere does the deviation from normality exceed 30° . This deviation from normality could be reduced by use of a beam profile with a higher fill factor like the $n = 5$ super-Gaussian used on the Janus system. However, estimates indicate that deviations up to 30° are acceptable, and may lead to enhanced absorption.

A. J. Glass

Fig. 4-34. Intensity distribution on $100\text{-}\mu\text{m}$ target. Target displacement from the focus is 40, 45, 50, and $55 \mu\text{m}$.

Fig. 4-35. Deviation from normal incidence vs polar angle on $100\text{-}\mu\text{m}$ target. Target displacement from focus is $50 \mu\text{m}$.

Nonlinear Index Contribution in Lenses

The contribution to the B-integral for a system arising from the optical path through focusing lenses can be readily calculated from a knowledge of the lens design. We employ the ray matrix technique. For a thick lens, with vertex radii of curvature R_1 and R_2 , respectively, and thickness t , the ray matrix can be written

$$\begin{pmatrix} r \\ u \end{pmatrix} = \begin{bmatrix} 1 - mt/R_1 & t/n \\ -1/f & 1 + mt/R_2 \end{bmatrix} \begin{pmatrix} r_0 \\ u_0 \end{pmatrix}, \quad (1)$$

where

$$\begin{aligned} r_0 &= \text{ray height incident on the lens,} \\ u_0 &= \text{ray slope incident on the lens,} \\ r &= \text{ray height emerging from the lens,} \\ u &= \text{ray slope emerging from the lens,} \\ n &= \text{lens index,} \\ m &= (n - 1)/n, \\ f^{-1} &= (n - 1)(1/R_1 - 1/R_2) + (n - 1)^2 t/nR_1R_2. \end{aligned}$$

Within the flux tube bounded by the ray initially at r_0 , the intensity through the lens is given by

$$I = I_0 r_0^2 \frac{1}{[r_0 + z(u_0/n - mr_0/R_1)]^2}. \quad (2)$$

Thus the B-integral through the lens can be written

$$B = \left(\frac{2\pi\gamma I_0}{\lambda n} \right) \int_0^t \frac{dz}{[1 + z(u_0/nr_0 - m/R_1)]^2} \quad (3)$$

or

$$B = \left(\frac{2\pi\gamma I_0}{\lambda n} \right) \frac{t}{1 + t(u_0/nr_0 - m/R_1)}. \quad (4)$$

We further note that the incident ray slope is $u_0 = r_0/S$, where S is object distance, or distance to the center of curvature of the incident beam. Equation (4) assumes the form

$$B = \left(\frac{2\pi\gamma I_0}{\lambda n} \right) \left[\frac{1}{\tau} + \frac{1}{nS} - \frac{(n-1)}{nR_1} \right]^{-1}. \quad (5)$$

Thus, knowing the "vergence" of the incident beam and the vertex radius of curvature of the first surface, we can determine the B. The quantity in brackets in Eq. (5) is the equivalent thickness of the lens, referenced to the input flux density,

$$t_{eq}^{-1} = \frac{1}{t} + \frac{1}{nS} - \frac{(n-1)}{nR_1} \quad (6)$$

Let us consider a lens, as previously specified, followed by an air space of length d . The ray matrix is

$$\begin{pmatrix} r \\ u \end{pmatrix} = \begin{bmatrix} 1 - mt/R_1 - d/f & t/n + d + dmt/R_2 \\ -1/f & 1 + mt/R_2 \end{bmatrix} \begin{pmatrix} r_0 \\ u_0 \end{pmatrix} \quad (7)$$

After the airspace, the ray height is

$$r_2 = r_0 \left\{ (1 - mt/R_1 - d/f) + [t/n + (1 + mt/R_2)d]/S \right\}, \quad (8)$$

and the ray slope is

$$u_2 = r_0 [-1/f + (1 + mt/R_2)/S]. \quad (9)$$

The effective vergence at this plane is given by

$$S_2 = \frac{r_2}{u_2} = d + (t/t_{eq})[-1/f + (1 + mt/R_2)/S], \quad (10)$$

where t_{eq} is as previously defined in Eq. (6). If we define an equivalent focal length of the lens as

$$f_{eq}^{-1} = \frac{1}{f} - \frac{1}{S} - \frac{(n-1)t}{nR_2S}, \quad (11)$$

we can write

$$S_2 = d - (t/t_{eq})f_{eq} \quad (12)$$

and

$$r_2 = r_0 [t/t_{eq} - d/f_{eq}], \quad (13)$$

so that the intensity at plane 2 is just

$$I_2 = I_0 F, \quad (14)$$

where the intensification factor is

$$F = [t/t_{eq} - d/f_{eq}]^{-2}. \quad (15)$$

The B-integral for a second element can be calculated by inserting I_2 and S_2 into Eq. (5).

For collimated light incident at the first surface, $1/S = 0$, so

$$t_{eq}^{-1} = 1/t - (n-1)/nR_1, \quad (16)$$

$$f_{eq} = f, \quad (17)$$

$$I_2 = \frac{I_0}{[1 - (n-1)t/nR_1 - d/f]^2}, \quad (18)$$

and

$$S_2 = d - f [1 - (n-1)t/nR_1]. \quad (19)$$

To illustrate the calculation, let us analyze the Janus doublet.¹⁵ For the first element (in mm)

$$R_1 = 51.21, \quad n = 1.507$$

$$R_2 = -123.37,$$

$$t = 24.2,$$

$$f = 74.87 = f_{eq},$$

$$t_{eq} = 28.77,$$

$$d = 1.30,$$

$$S_2 = -61.68,$$

$$I_2 = I_0/(0.824)^2 = 1.474 I_0.$$

For the second element,

$$R_1 = 83.69,$$

$$R_2 = -123.37,$$

$$t = 21.0,$$

$$t_{eq} = 30.45.$$

Thus the B-integral of the doublet is

$$\begin{aligned} & \left(\frac{2\pi\gamma I_0}{\lambda n} \right) [28.77 + 30.45 (1.474)] \\ & = \left(\frac{2\pi\gamma I_0}{\lambda n} \right) [73.65]. \end{aligned} \quad (20)$$

The B-integral can also be obtained directly from a paraxial ray trace, in the form

$$B = \left(\frac{2\pi\gamma I_0}{\lambda n} \right) \left[y_1^2 \left(\frac{t_{12}}{y_1 y_2} + \frac{t_{34}}{y_3 y_4} + \dots \right) \right],$$

where t_{ij} is the thickness between lens surfaces i and j , and y_i is the paraxial ray height at surface i .

For comparing lens designs, it is useful to have a lens figure of merit. A little thought shows that the performance factor of the lens

$$X = \frac{P}{B} \quad (21)$$

scales as the lens diameter. Since I goes as D^2 where D is the beam diameter, B decreases as D for constant P . Therefore the factor

$$L = \frac{X}{D} \quad (22)$$

will depend only on the lens design, and not on its size. The L factor is defined for a uniform input beam, so that

$$P = I_0 \frac{\pi D^2}{4}. \quad (23)$$

We have seen that the B-integral for a lens or lens combination can be computed directly from the vertex radii and thicknesses, or by performing a ray trace. The L -factor can be written as

$$L = \frac{nD}{316 n_2 \sum_i (t_{eq})_i F}, \quad (24)$$

where the t_{eq} 's are computed for each of the lenses in the system, and F is the intensification factor, or, equivalently, as

$$L = \frac{nd}{316 n_2 y_1^2 \left(\frac{t_{12}}{y_1 y_2} + \frac{t_{34}}{y_3 y_4} + \frac{t_{56}}{y_5 y_6} + \dots \right)}. \quad (25)$$

For the Janus lens, we find that

$$L = 4.6 \text{ GW/neper-mm}; \quad (26)$$

with a diameter of 85 mm, the X-factor is

$$X = 390 \text{ GW/neper}. \quad (27)$$

A. J. Glass
J. B. Trenholme

Argus Power-Conditioning System

Bank Staging Philosophy. The underlying design philosophy for the Argus laser's power-conditioning system has been to keep the energy storage in modular form and to charge, switch, and trigger the maximum number of these modules consistent with system constraints, component ratings, and desired system flexibility. This is simply an extension of the approach taken in the design of the Janus and Cyclops B and C disk-amplifier energy storage configuration shown in Fig. 4-36. Each capacitor-inductor-fuse combination in the parallel arms of this configuration forms an isolated energy-storage module, which is tailored to provide optimal triggering and drive to a series pair of 44-in.-arc-length xenon flashlamps. These modules are charged and switched as one large common block of energy storage, which results in reduced complexity, increased reliability, and reduced cost. In the Argus system, this arrangement has been applied to the energy storage required for the various Faraday rotators and rod amplifiers as well as the B and C disk amplifiers.

There are several operational and component restrictions—in addition to the general considerations of cost, reliability, and flexibility—placed on the power-conditioning staging philosophy applied to the Argus laser system. The primary restrictions are:

1. The need to balance arm-to-arm gain variations through capacitor-bank voltage adjustments.
2. Differences in nominal amplifier and Faraday-rotator operating voltages.
3. Differences in timing requirements.
4. Peak current and charge transfer limitations of size D ignitron switches (150 kA and 70 C respectively).
5. Maintaining an integral number of laser amplifiers on a single switching device. (This eliminates the possibility of increased magnetic force being placed on the quartz envelope of the flashlamps in the event of a switch misfire.)

The final power-conditioning staging as shown in block diagram form in Fig. 4-37 reflects these restrictions. Although this diagram is complex it illustrates the functional relationship between the optical elements and power-conditioning elements of the system.

An examination of the typical operating voltages and nominal timing requirements of the various laser devices given in Table 4-2 indicates that the system must have a minimum of six triggering devices and six power supplies. This minimum number of power supplies increases, however, with the addition of arm-to-arm gain adjustability.

The first 2.5-cm rod amplifier in each arm following the first beam split is charged from individual power supplies to provide *initial* arm-to-arm gain balancing. The remaining 2.5-cm and 4.0-cm rod amplifiers are charged from a common 5-kV, 5-kVA power supply. Although not shown in Fig. 4-37, *all* 2.5-cm and 4.0-cm rod-amplifier ionization networks are driven with a single supply-switch combination.

The *final* arm-to-arm gain adjustment is provided by individual C-disk-amplifier power supplies in each of the four arms following the second beam split. Note that the power supply has been sized (100 kVA) to charge all four C disk amplifiers in a given arm—the maximum block of energy storage modules within the constraint of the final gain adjustment capability. Additionally, the peak current and charge transfer of each high-voltage switch are near the switch rating (120 kA, 55 C).

The eight B disk amplifiers spanning all four arms are charged from a common power supply and switched by two high-voltage switches. It is interesting to note that the power-supply and high-voltage-switch loadings for the B disk amplifiers are identical to those of the C disk amplifier configuration. Since the timing requirements of all the B and C disk amplifiers are the same, a common triggering device is used.

The four B Faraday rotators in the system are charged from a common 5-kV, 5-kVA power supply and switched by a single size-D ignitron. In much the same fashion, the eight C Faraday rotators are charged from a single 27-kV, 100-kVA power supply. How-

Fig. 4-36. Power-conditioning and switching system.

Fig. 4-37. Power-conditioning system for the Argus laser.

Table 4-2. Typical operating voltages and nominal timing requirements of various laser devices

Device	No. in system	Nominal operating voltage (kV)	Energy storage required (kJ)	Timing requirement (osc. pulse occurs at $T = 0$) (μ s)
1.25-cm rod amp.	2	3.3	12	-520
2.5-cm rod amp.	6	5	18	-580
4.0-cm rod amp.	2	5	24	-580
A* rotator	2	4	6	-820
B rotator	4	5	48	-450
C rotator	8	18	720	-800
B disk amp.	8	20	1152	-550
C disk amp.	16	20	4608	-550
			Total = 6588	

ever, four high-voltage switches are required to keep the charge transfer per switch below the 70-C rating, since the rotator energy-storage configuration, as shown in Fig. 4-38, forms a moderately high-Q RLC circuit. A typical current waveform of this circuit is given in Fig. 4-39. The number of high-voltage switches could have been reduced if a diode clamp had been used in each rotator circuit to prevent the circuit from ringing; however, 20-kV, 20-kA diode stacks cost almost as much as the complete high-voltage switch.

The ringing nature of both the B and C Faraday

rotators also required that the energy storage modules be fused in smaller increments (B rotators) or that parallel fuses be added to the modules (C rotators). Although the peak currents of the rotator circuits are within the capabilities of the high-voltage fuse, the total integrated energy deposited in the fuse during a normal shot would cause the fuse to open.

There is a small (A*) Faraday rotator after the second and third 2.5-cm rod amplifiers in each arm following the initial beam split. The two A* rotators in

Fig. 4-38. Energy storage system for the eight C Faraday rotators in the Argus laser.

Fig. 4-39. Typical current waveform for the circuit of Fig. 4-38.

each arm are driven in series from a single capacitor bank; they are charged by separate 5-kV, 1-kVA power supplies to allow for precise rotation adjustments. Since the power-supply and energy-storage requirements are small, the cost of this additional flexibility is insignificant compared to total power-conditioning costs (approx 0.2%).

The power conditioning staging as described above requires 12 power supplies for the major optical elements. These are required to be in two voltage ranges and three power sizes (1) 5 kV, 1 kVA, (2) 5 kV, 5 kVA, (3) 27 kV, 100 kVA. The control and operation of all power supplies are identical. The small power supplies (5 kV) are rack-mounted and are simply exchanged with a spare unit in the event of a failure. The

large power supplies (100 kVA) must be repaired in place. However, a spare supply has been built into the system and may be "wired in" within a few hours in the event of a catastrophic failure of one of the operational units. The total power-supply complement is shown in Fig. 4-40.

There are some interesting aspects of the staging which are worth noting. First, the switch loading for all the B and C amplifier switches is identical to that successfully used in Cyclops for the past two years. Second, in keeping with the final constraint listed above, each switching device handles an integral number of laser amplifiers. Third, there is an inherent symmetry to the staging which is esthetically pleasing (to the designer) and simple to remember (for the

Fig. 4-40. Total power-supply complement for the Argus laser system.

operator).

Whenever a single power supply is connected to more than one switch, either resistor, fuse, or fuse-and-diode isolation networks have been used to isolate the switches from each other and to protect the power supply in the event of an internal failure. Without this isolation, the switches would be tied in parallel by the common power supply output line. In the event of a switch misfire, the other switch (or switches) would attempt to handle twice its normal load.

Pulsed Ionization Lamp Check (PILC). Perhaps one of the most sorely needed additions to the present operational laser systems is a means of determining flashlamp integrity before or after the firing of any or all of the laser systems' flashlamps. If a full-energy shot is made with a broken lamp in any of the disk amplifiers, there exists a definite possibility of additional flashlamp breakage, damage to expensive laser disks, and general amplifier damage due to high energy arcs. Also, if a flashlamp has simply "gone to air" and fails to fire, the quartz envelopes of adjacent flashlamps are subjected to increased magnetic forces, which tends to increase their failure rate. In addition, failure of a flashlamp to fire may cause sufficient arm-to-arm gain change or degradation of beam quality due to nonuniform pumping to ruin the shot altogether. This failure is otherwise nondestructive and is detectable by monitoring the flashlamp current or voltage during the shot. Experience has shown, however, that the voltage and current waveforms taken during a shot in which the flashlamp breaks are identical to those taken during a shot in which the flashlamp does not break.

Some alternate means of checking flashlamp integrity was needed, and accordingly the Argus laser system has been fitted with a simple, cost-effective, low-energy flashlamp ionization scheme known as PILC—pulsed ionization lamp check. In addition to flashlamp failures, this scheme will detect many capacitor-bank problems such as open cables, fuses, and inductors, and positive-plate-to-case capacitor shorts.

A simplified circuit diagram of the PILC scheme is shown in Fig. 4-41. Basically, its operation is as follows. The PILC capacitor bank, C, is charged to a nominal 20 kV and then switched into the main capacitor bank of a disk amplifier through a single coaxial cable to the main-bank ignitron switch. The pulse shaping inductors, L, in each of the capacitor bank modules *force current sharing among the various flashlamp circuits*. The main bank capacitors, C₂, present essentially a short circuit to the PILC current. The PILC bank capacitors, C, and the pulse forming inductors, L, form resonant charging networks which charge

the load cable capacitance and flashlamp capacitance to approximately 1.5 times the PILC bank voltage, thus ionizing the flashlamps. This is essentially the same as the main bank triggering characteristic. A typical voltage waveform is shown in Fig. 4-42. A current pulse around 100 μ s wide and 200 A in amplitude flows through the ionized flashlamp. This pulse is then detected by a 100:1 current transformer in the shield return lead of the series flashlamp pair. A typical detector waveform into a 1- Ω load is shown in Fig. 4-43. If a flashlamp is broken or otherwise fails to ionize, there will be no detector output signal. The arc which will occur in the event of a broken flashlamp will contain less than 1% of the energy of a main bank shot.

One might note that the PILC circuit ionizes the flashlamps in the opposite direction from the main bank circuit. Thus the current transformer may serve the dual function of monitoring the main-bank discharge current as well as the PILC current simply by using current steering diodes on the current transformer output.

At-Voltage System. The at-voltage system is used to indicate whether each energy-storage module has been charged to the desired voltage during any given charge cycle. The basic voltage sensing arrangement is shown in Fig. 4-44, which illustrates a disk-amplifier energy storage module in more detail. Relay K-1 is a small, current-sensitive relay which activates with a nominal 860- μ A coil current. Resistor R₁ is chosen such that this nominal current flows through the coil when the capacitor voltage reaches approximately 80% of the typical disk-amplifier operating voltage. The contacts of relay K-1 are used to indicate the voltage status of that particular energy-storage module.

The at-voltage system as installed is of very limited value on the disk-amplifier energy storage modules. The only definite piece of information gained is the condition of the bank module high-voltage fuse. Also, this information is gained only after the capacitor banks have been charged. However, with an operational PILC system, the fuse status is known before charging. There are several bank-module failure modes which PILC will not detect, two of which a reconfigured at-voltage circuit would detect. One is a plate-to-plate capacitor short, and the other is an open charge resistor. The first failure will cause the second failure, either when the short occurs, or during the next charge cycle. The reconfigured at-voltage sensor will be a differential voltage divider which looks directly across the capacitor.

W. L. Gagnon
G. R. Allen

Fig. 4-41. Circuit of the pulsed ionization lamp check (PILC) system.

Fig. 4-42. Typical voltage waveform for PILC circuit.

200 A/div
50 μ s/div
PILC bank voltage = 15 kV

Fig. 4-43. Typical PILC detector waveform.

Fig. 4-44. Voltage-sensing arrangement used in a voltage system.

Flashlamp Testing Program

Component Test Facility. Early this year a 10,000 sq ft facility (Bldg. 611) for component testing was activated. Included in this facility is a semiclean

area for new lamp acceptance and infant mortality testing, and numerous bank systems capable of powering laser amplifier tests on a full-energy, 24-hour basis. A major part of this facility is dedicated to flashlamp acceptance and life testing. Over 1300 lamps have been

processed through this facility. In addition, long-term life tests have been run on almost all components used in the power conditioning systems.

Flashlamp Acceptance Testing. We have continued to modify our inspection and test procedures as we learn more about failure modes for lamps. Our experience to date indicates that improper handling and testing of lamps can be a significant cause of failures. Consequently, we have carefully developed and optimized every step of the lamp acceptance, testing, storage, and installation procedures. A flow diagram for the entire process is shown in Fig. 4-45. Each step is described and illustrated as follows:

1. New lamps are unpacked and logged in by serial number. They are also given a quick visual inspection for gross problems.
2. The lamps are placed in special trays which serve as both storage racks and handling trays.
3. Next, a sample of each lot of lamps is subjected to a dimensional inspection.
4. Each lamp is then placed on a ground plane with anode and cathode heads tied together. A 60-kV, 1-min

hi-pot test between the joined heads and the ground plane is then performed.

5. Lamps which pass the hi-pot test are fired 50 times in a nitrogen atmosphere at 40% of the free-air explosion energy. This test stresses the lamps to twice the normal energy level and will generally cause those with weak envelopes or cracked seals to explode. Also, this energy level and the resulting envelope stresses will cause small wall-cracks to enlarge enough to be detected by microscopic examination.

6. At this point the lamps are put into storage until required for installation in a laser amplifier.

7. When extracted from storage, the oldest lamps are taken first. Each lamp is then inspected under a 7-power binocular microscope for cracks.

8. The lamps are given a final cleaning and installed in the reflector assembly.

9. The entire reflector assembly is mounted in a test chamber and fired 20 times at 20% of free-air explosion energy in a nitrogen atmosphere.

10. The tested assembly is then enclosed in a special antistatic double bag and moved to the clean room

Fig. 4-45. Flow diagram showing I.I. procedures for flashlamp acceptance, testing, storage, and installation.

for final installation in the laser amplifier.

Lamp Wall Materials. Flashlamps used in our disk amplifiers have a bore of 15 mm and an arc length of 1.1 m. They are filled with xenon to a pressure of 300 Torr.

The general idea is to arrange the lamps spatially, and excite them electrically, in such a manner that the highest possible gain per disk can be realized. This approach minimizes the total length of glass in the laser beam path and thus reduces the effects of beam breakup and whole-beam self-focusing to a minimum. There are several important constraints: (1) Too short an excitation pulse causes the lamps to turn opaque and reabsorb a significant percentage of the light energy. (2) Too long a pulse is inefficient, because the stored energy in

the disk self-decays at a rate faster than the lamps can replace it. (3) The circuitry used to produce the pumping pulse should, by necessity, be simple, cost-effective, and reliable.

Within the guidelines of the above objectives and constraints, the present lamp-reflector configurations and the single-mesh electrical circuit are near optimum. Another important consideration is lamp wall material and its effect on the output spectrum of the lamp. We have tested lamps with wall materials of clear fused quartz, titanium-doped quartz, and cerium-doped quartz. In Fig. 4-46, we show the measured transmission spectra from clear fused quartz walls and cerium-doped quartz walls, along with the major pump bands for neodymium. One can see that the cerium-doped

Fig. 4-46. Spectra from xenon flashlamps with walls of clear fused quartz and cerium-doped quartz. Pumping bands for neodymium are superimposed.

Fig. 4-47. Damage to laser amplifier caused by exploding flashlamp.

quartz walls cut off rather sharply in the uv range, but still have considerable output over most of the main pump bands for neodymium. Reduced output in the uv region is highly important, because much of the damage occurring to the optics in the laser amplifiers results from the ultraviolet interaction with small dust and metal particles.

Flashlamp Failure Studies. Our lamp acceptance and infant mortality testing program has been effective in revealing almost all the possible lamp-failure modes. However, until fairly recently, the cause of one particular type of wall failure had remained unexplained. This failure mode manifested itself as a relatively clean shear across the diameter of the lamp and generally occurred while the lamps were out of use. While such a failure is relatively infrequent, the amount of damage caused by an exploding lamp in a laser amplifier is extensive (Fig. 4-47). We viewed this particular failure mode as a potentially dangerous one, with a high

probability of causing an explosion in a fully loaded amplifier.

The failures appeared to be related to small cracks in the wall material which grew in size over a fairly long period of time. A study contract was awarded to ILC Technology to determine the cause of these failures. In the course of this study, more than 500 lamps were examined at each of four different points in the production cycle. Of these, 9 lamps failed and 13 more were identified as potential failures. The mechanism for failure was determined to be longitudinal, exterior surface cracks in the quartz walls. These cracks are produced from "fire-checking" (see below) and can occur at any point in the production cycle of either the raw quartz or the complete flashlamp. Most of the failures in the study occurred as a result of joining the cathode assembly to the quartz envelope.

In Fig. 4-48a,b are shown longitudinal cracks which eventually produced failures, and in Fig. 4-48c,d other

(a) Longitudinal crack, 7X

(b) Crack growth, 7X

(c) Circumferential crack, 7X

(d) Slanting crack, 7X

Fig. 4-48. Cracks in quartz walk of flashlamps. Longitudinal cracks in (a) and (b) eventually produced lamp failure; other types of cracks shown in (c) and (d) did not produce failure.

types of cracks which did not result in failures.

From this study, we have concluded the following:

1. Longitudinal surface cracks produced by localized heating of the envelope (fire-checking) will result in lamp failure.

2. This failure mode can be detected by microscopic inspection of lamp envelopes.

3. Quality control procedures should be revised to include two 25-shot acceptance test segments with microscopic inspection for surface cracks before and

after testing. In addition, there should be a seven-day waiting period after testing and before final inspection.

We have recently instituted these changes in our testing schedule and have uncovered a number of possible failures of this nature.

Flashlamp Life Testing. During the last two years, we have gathered a considerable amount of long-term life data for flashlamps. In addition to the data gathered from test amplifiers undergoing long-term runs in the component test area, a large amount of failure informa-

Table 4-3. Results of lamp testing done in laser amplifiers at the component test facility

Head shots	Unit shots	Number of failures	Comments
1,000	20,000	1	Lamp broke at 55 shots
10,000	200,000	2	A clean break at 856 shots A braze failure at 949 shots
1,000	20,000	0	
10,000	200,000	0	
1,000	20,000	1	Base insulation failure at 35 shots
1,000	20,000	0	
23,373 ^a	373,968 ^a	3	Envelope failure at 11 shots Braze joint at 3,994 shots Blowup at 23,373 shots ¹
11,000	175,000	0	
20,000	320,000	0	
Totals	1,348,968	5	

^aAfter 12,417 head shots the energy was doubled by adding two capacitors and charging to 25 kV.

tion is available from the operating experimental laser facilities. These long-term data are summarized in Tables 4-3 and 4-4.

Table 4-3 covers the results of testing performed on lamps in laser amplifiers at the component test facility. Table 4-4 summarizes the failure experience of lamps in our operating lasers. Both cases represent approximately two years of testing and operation. In summary, the results indicate 26 failures in 1.7×10^6 unit shots.

However, almost all of this data was gathered before we detected the basic cause of envelope failures. If envelope failures (which we are now confident can be detected during acceptance testing) are removed from Tables 4-3 and 4-4, we could estimate failures at less than 24 for 1,671,871 unit shots.

W. L. Cagnon
A. Pemberton

Table 4-4. Lamp failure experience in LLL's operating lasers in the laser program

Laser or facility	Unit shots	Number of failures	Comments
Argus	38,204	2	Shorted base and lamp to an
Cyclops	97,512	10	Most were lamp to an
Janus	54,000	4	One blowup, 3 lamps to an
175	65,920	1	Lead failed outside base
611 (shell testing)	80,640	0	
Burn-in	20,000	2	One blowup, 1 lamp to an
Totals	356,276	19	

Shutters for Control of Amplified Spontaneous Emission

There are a number of possible methods under consideration to reduce amplified spontaneous emission (ASE) in long laser chains. These include: fast Pockels cells, fast Faraday rotators, rotating-disk shutters, and fast moving-foil shutters. Fast Pockels cells are adequate for use at the front end, near the oscillator, where beam diameters are in the 10-to-20-mm range. If a large-diameter shutter is required, a fast Faraday rotator is a possible solution. We have designed a fast "C" size (20-cm) rotator with a fill time of less than 5 μ s. This solution has the disadvantage of adding glass path length in the beam line and thus contributing to the beam breakup and whole-beam self-focusing problems.

Rotating-disk and moving-foil shutters can be located at the focal point of spatial filters at the target end of the chain. This solution adds no glass to the beam path and allows one to deal with beam diameters of 1 mm or less.

Rotating Shutter Design. A pair of "C" size spatial filter housing with rotating disk shutters (Fig. 4-49) have been built and tested. An aluminum disk 8 in. in diameter is coupled to the shaft of an 8000-rpm hysteresis synchronous motor. A hole at the outer edge of the disk lies at the focal point of the spatial filter and provides an opening time of roughly 10 μ s.

In a multi-arm laser, it is necessary to synchronize a number of these rotating disks. Figure 4-50 is a block diagram of the electrical system for a pair of rotating shutters. A 400-Hz oscillator supplies the basic frequency drive to both motors through a phase resolver and transistor power amplifier in each leg. The 8-pole, 400-Hz hysteresis synchronous motors rotate at 8000 rpm. Each motor has an ac tachometer coupled to the rear shaft. A phase detector compares the outputs of the two tachometers and drives a dc motor attached to one phase resolver until the two disks are in phase coincidence. A trigger pulse is then generated which enables the laser oscillator to initiate a pulse at the same time the shutter hole crosses the beam line. The control and amplifier chassis are shown in Fig. 4-51.

W. L. Gagnon
G. R. Allen

Optimization of Shiva Power-Conditioning System

During the past year, a considerable effort has been directed toward optimizing the power conditioning system for the Shiva laser.¹⁶ We have continued to develop the bank technology which has been applied to the

Fig. 4-49. One of the two rotating-disk shutter assemblies of C size that have been built and tested.

Janus, Cyclops, and Argus lasers. In addition, two study contracts were instituted with Maxwell and Physics International.¹⁷ These contracts had two specific goals. The first goal was to obtain an independent technical review of the overall design. The second goal was to review the design in terms of cost, performance, deliverability, and manufacturability. These studies proved to be productive. No basic flaws were discovered in the baseline design; however, considerable cost savings were realized. A review of the results of these studies is included in this section.

Shiva Bank Optimization. Amplifier modeling has been carried out to determine optimum designs and to stage the Shiva system. In order to understand detailed circuit-design parameters, such as transient voltage levels and the required insulation and creep distances for a given circuit, a detailed analysis of a specific circuit model was required. Such a model can also be used for detailed analysis of flashlamp triggering waveforms, study of various circuit faults, and making parametric variations on the various system components over limited ranges from their nominal values.

Figure 4-52 shows the circuit model. This is a typical circuit used to drive two flashlamps in a Beta amplifier. In this case, the flashlamps are each 44 in. long and 15 mm in diameter. They are filled with 300 Torr of xenon. Single components are indicated by the dashed lines; for instance, a cable is composed of a lumped capacitance, a lumped inductance, a center-conductor resistance, and a shield resistance (center-conductor and shield resistances are treated separately in order to allow study of various grounding schemes and associated faults). Values associated with the switch are adjusted depending upon the number of

individual circuits which are paralleled on one switch. Figure 4-53 shows the physical configuration.

An LLL-modified version of SCEPTRE, which is a high-level language designed for electrical networks, was used to do the modeling. This language also allows the solution of nonlinear first-order differential equations. This feature has been used to obtain total charge through switches, energy actually delivered to the lamps, peak energy stored in the magnetic field of the rotators, and a relative measure of gain. The model is flexible, and provisions have been made to change cable lengths, number of parallel circuits per switch, and lamp parameters such as diameter, length, and pressure. A second model using two such circuits, with the second one scaled to represent 31 parallel circuits, has been constructed to determine fault interaction between circuits.

The use of SCEPTRE requires an equivalent resistance and inductance for the lamps. Since the lamp does not exhibit linear properties in voltage and cur-

rent, these values are separately calculated as a subroutine and passed to SCEPTRE as constants at each point of integration. The voltage across the lamp was taken as $V = K_0 |i|^{1/2} + d(Li/dt)$. The first term of this equation is well known and has been given by Markiewicz and Emmett.¹⁸ The second term is a time-dependent inductance which is used to approximate the inductance of the lamp during arc growth; an inductance of the form $L = L_0 \exp(-t/\tau)$, where both L_0 and τ are picked to match empirical data from a given lamp configuration, gives adequate extrapolation to new ring-up conditions for all test cases measured to date. These measurements have included test cases at different lamp energies, different basic time constants ($\sqrt{LC}$), and different lamp diameters, lengths, and pressures. Thus the equivalent resistance term calculated for each integration step is $R = K_0^2 / |V_{lamp}| - (L_0/\tau) \exp(-t/\tau)$, and the equivalent inductance term is as given above. The equations in this form provide a transition from an inductance-dominated circuit to a

Fig. 4-50. Electrical system for a pair of rotating shutters like the one shown in Fig. 4-49.

Fig. 4-51. Control and amplifier chassis for rotating-disk shutter system.

resistance-dominated circuit in a time comparable to the time required for a disturbance to propagate in xenon from the center of the bore to the lamp wall at the local speed of sound (approximately $50 \mu\text{s}$). Figure 4-54 shows a comparison between the model's predicted output and the actual output of a flashlamp circuit.

In order to study faults, a good model of the fuse was required. Initially we tried a model which just opened after a given energy had been dissipated in a fixed resistance. This model proved to be inaccurate when compared with actual fuses being blown into a fault. A subroutine was then written which increased the resistance of the wire as the temperature increased due to power dissipation in the fuse. In this subroutine, when the melting point of the fuse is reached, the melted material is assumed to be absorbed or forced into the salt and removed from the conductor. During this time, resistance is held constant as a function of temperature but increased due to the reduction in effective diameter of the wire. This process is allowed to

continue until the fuse resistance is in excess of $10^{15} \Omega$.

While this model is adequate for all fuse occurrences which include the system inductor as a current-limiting device, it is probably not adequate for mega-ampere faults which occur ahead of the inductor. This conclusion is based on the fact that a great deal of literature is available on mega-ampere fuse actions, and agreement between theory and experiment is no better than about 30%. If improvement of this model is required to study faults of this nature, a first step will be to include the effects of the variable inductance presented by the fuse wire (as a function of the diameter).

As a side note, the Franklin fuse which is presently used seems to be an exceptionally good design since it is quite repeatable with regard to the energy at which it opens. There are three wires internal to the fuse, running in parallel, and initially positioned in such a way as to enhance the probability of developing a kink instability which would aid in opening the fuse.

In order to determine the effect on amplifier output of parametric variations from the nominal circuit val-

Fig. 4-52. Typical circuit used to drive two flashlamps in a Beta amplifier.

Fig. 4-53. Physical configuration of the circuit of Fig. 4-52.

Fig. 4-54. Comparison of model-predicted and measured output of a flashlamp circuit.

ues, a representation of the gain was required. First-order amplifier gain is given by $G = e^{\alpha \ell}$, where α is the gain coefficient and ℓ is the amplifier path length. The α in this equation may be determined from a simple rate equation $\dot{\alpha} = (\text{const}) \eta(j) P(t) - \alpha/\tau$, where the constant is empirically determined for a given amplifier and reflector geometry, η is some function of the current density, P is the power delivered to the system at any time, and τ is the time constant of the glass. Several different forms of η which conform to various physical models of the arc and of reabsorption processes occurring within the amplifier cavity have been used to empirically match the measured gains. Trenholme's empirical fit of the form $\eta \approx (j)^{-0.5}$ seems to work best. This has been used to study various multiple-mesh configurations as well as to anticipate

Fig. 4-55. Comparison of model-predicted and measured amplifier gain as a function of time.

what gain changes will be realized from various energy inputs to given circuits. Figure 4-55 shows a comparison between the model output and the gain of an amplifier as a function of time.

Another use of the gain equation has been to evaluate the effect of pumping the amplifier with the optimal pulse shape derived by Trenholme and shown in Fig. 4-56. This is a rising exponential with a time constant about half the fluorescent time decay. An improvement in gain coefficient of up to 16% may be obtained for a constant input energy if this pulse shape is used instead of the single-mesh circuit. If the peak gain is held constant, a 26% decrease in pump energy may be achieved with this same pulse shape. This analysis puts bounds on the increase in efficiency and cost effectiveness which may be obtained by any form of pulse shaping.

Lamp triggering is an area of extreme interest which has been investigated using the model. Ionization of the flashlamps is accomplished by producing a momentarily high voltage from one lamp electrode to ground (reflector). After breakdown occurs at that electrode, a streamer arc propagates along the lamp wall to the opposite electrode. At this point, the full lamp volume begins to ionize. This process of triggering takes place during the first 5 to 50 μ s of the pulse.

A series of lamp triggering tests was run on the Beta amplifier design with a separately grounded reflector. Preliminary analysis of the data shows that with a dV/dt as small as 500 V/s, the lamps trigger at a mean of 14 kV with a sigma value of approximately 3 kV. All lamps had triggered within a 2-sigma value of the 14 kV. On the basis of this data the minimum initial overshoot for any circuit is set to 26 kV by selecting appropriate values for damping resistors. This limits the overshoot voltage and reduces stress on the lamp base, which is the weakest link in the dielectric system. The values shown in Fig. 4-52 are typical design values and produce the required overshoot at the flashlamp while holding the peak bushing-to-case voltage and the peak capacitor-case-to-ground voltage to less than 10 kV.

In order to specify the capacitor-to-rack spacing, several fault cases were investigated with the model. The normal working voltage of the case is a short-duration pulse of 10 kV (assuming a 25-kV initial charge). The worst-case pulse voltage under a fault is the 25 kV; however, if a damping resistor opened and a bushing-to-case fault had occurred on a preceding shot (neither of which necessarily would be noticed since the lamps would still function at a higher stress level), 25 kV could be reached during the next charge cycle. Thus, a 25-kV dielectric spacing has been provided. This is typical of the analysis which is being carried out for all anticipated fault conditions.

Fig. 4-56. Optimum shape of pump pulse.

Another interesting fault case analyzed with the model is the opening of the damping resistor across the inductor. This was done on a version of the model which approximated a β amplifier circuit with 90 ft of cable between the lamp and the capacitors and 22 ft of cable between the capacitors and the switch. In this case the initial triggering voltage across the lamp went to 48 kV with a charge voltage on the capacitors of 20 kV. This was unexpected; however, experiments conducted with a test amplifier verified the result.

The model has also been used to verify that the various circuit parameters picked are optimal. This was done by making several runs around the nominal design point. In addition to this activity, two- and three-mesh circuits, and circuits containing saturable reactors and other methods of pulse shape control, have been tried. Empirically it has been determined that these techniques have very little (if any) positive effect on the gain. In all cases the model indicated the same results. For instance a two-mesh circuit gave a 2 to 3% increase in gain coefficient, which is certainly not worth the additional complexity of a two-mesh circuit.

Rod Amplifier Circuit Design. The 40-mm rod amplifier has been modified to fire six lamps in series and use the same basic circuit as the disk amplifiers. This effort was undertaken to eliminate on Shiva the two different generic circuits used on the existing amplifier systems and to eliminate the excessive number of prefires being experienced using the 5-kV circuit with trigger injection. The modeling of this circuit was quite successful and accurately predicted the end waveforms.

The modified circuit uses the standard 20-kV switching ignitron, five 14.5- μ F, 20-kV capacitors, and a 435- μ H inductor. Six 13-mm-o.d., 20.3-cm-long

lamps are used in series in this circuit. The circuit has performed quite well; there have been no failures to trigger the lamps and no prefires.

Reliability Improvement. Several of the year's activities have centered around improving the system reliability. The changes to the installation systems of the rod amplifiers as discussed above eliminated prefires from that system. The use of a common 20-kV system for all devices which require energy storage has allowed the incorporation of a redundant supply to back up all capacitor charging supplies in the Shiva system. Additionally a redundant supply has been incorporated in the PILC system to insure its reliable operation. These redundant supplies have been incorporated at a cost of under \$20,000, which is less than 5% of the total power-supply costs. The improved PFN (pulse-forming network) design discussed below should improve system reliability by the elimination of several connections in the resistor strings which are presently used.

Energy-Storage Capacitors. The energy-storage capacitor used in the laser fusion program at present is essentially the same capacitor that was developed some 15 years ago for use in the Sherwood program. This unit has a castor oil/Kraft paper dielectric system and thin-aluminum-foil electrodes. A cutaway view is shown in Fig. 4-57.

The capacitor was designed for high-voltage reversal (ringing or under-damped conditions) and large peak currents. Two hundred units from four vendors

Fig. 4-57. Energy storage capacitor for pulsed laser systems. Dielectric system is Kraft paper and castor oil; electrodes are thin aluminum foil.

have been tested under these conditions. The mean life of the units was found to be 70×10^3 pulses. However, the test conditions are more severe than the actual operating conditions, in which the capacitor sees voltage reversal only during an occasional fault and the peak currents are considerably smaller than those of the test condition.

The cost of a Sherwood-type capacitor is 12 cents per joule. An alternative design costing less (5 to 6 cents per joule) and offering higher energy density is being tested.¹⁹ Table 4-5 compares the two designs.

The 29- μ F unit cuts costs by driving the design toward the specific requirements of laser fusion. Higher energy density and lower materials and labor costs are achieved by using the basic construction of the 14.5- μ F unit but allowing the dielectric stress to rise from 2,100 to 2,600 V/mil. This development produces system cost savings because fewer capacitors are needed for a given amount of energy storage. However, the life of

the capacitor is a function of dielectric stress, percentage voltage reversal, and ringing frequency. By scaling from the reference point of the 14.5- μ F unit with a mean life of 70×10^3 pulses in high-voltage-reversal use, the life in laser fusion use is 10^6 pulses for the 14.5- μ F capacitor and 0.3×10^6 pulses for the 29- μ F capacitor.

An operating laser-fusion facility such as Shiva might be expected to total 50,000 pulses over a 10-year period. Clearly, the projected wearout life of the 29- μ F unit better fits the immediate requirements. Initial testing of prototype units has verified the projected life of the 29- μ F capacitor.

The results of these tests are shown in Table 4-6. Here, two capacitors from each of five manufacturers were tested under damped and 80% voltage reversal conditions. Given a 10-year, 50,000-pulse life requirement, it is apparent from the test results that the new design will meet the needs of a large laser-fusion

Table 4-5. Options for energy-storage capacitors^a

Parameter	14.5- μ F capacitor	29- μ F capacitor
Stored energy (kJ)	3	5.8
Dielectric stress (V/mil)	2080	2600
Estimated life ^b (pulses)	$0.5-1.0 \times 10^6$	$0.2-0.5 \times 10^6$
Cost per joule	\$0.12	\$0.06

^aData for castor-oil/Kraft-paper capacitors rated to withstand 20 kV.

^bNonringing service.

Table 4-6. Performance comparison of high-density capacitors

Manufacturer	Damped shots	Ringing shots
A	178,750	10,461
	178,750	13,602
B	178,750	1,623
	178,750	19,293
C	178,750	11,002
	178,750	29,569
D	178,750	900
	178,750	2,992
E	178,750	3,250 and still running
	178,750	3,250 and still running

Fig. 4-58. Circuit boards presently used in the pulse-forming network (PFN) for Shiva.

facility such as Shiva.

Industry Critique of the Shiva Banks. Two study contracts were let to critique the Shiva bank design for reliability, cost, and system optimization. Several constructive suggestions resulted from this review and are discussed below.

Racks. A detailed discussion on rack recommendations is given in the power conditioning section of the Shiva design. Procurement is under way following these recommendations, and a net saving to the program of \$65,000 has been realized.

Pulse Forming Network (PFN). Several manufacturing improvements have been recommended for the PFN. Figure 4-58 shows the two circuit boards required for the PFN as presently designed. Figure 4-59 shows the same circuit if all of the suggested changes are incorporated. This circuit was fired into a dummy load by Maxwell to insure its integrity. As may be seen from the figures, a space saving of approximately 7-1/2 in. is realized from this new configuration. The primary changes incorporated in this design are an improved inductor encapsulation which reduces the total amount of epoxy required, the use of carborundum resistors in place of wire-wound resistors, the use of clips rather than hard connections for mounting the fuses and the resistors, and an improved overall layout which resulted from making these changes. Figure 4-60 shows the gradient rings which had been used in our existing design where the shields are separated from the center conductors. These gradient rings are required to prevent a sharp field buildup and subsequent insulation breakdown. Figure 4-61 shows two proposals to reduce the cost of the gradient rings. In the design shown with the nut, a screw machine has been used to produce the part. The second design is made from a stamping. The cone is carried farther out; however, installation dif-

Fig. 4-59. Proposed revision to PFN circuit-board design of Fig. 4-58.

Fig. 4-60. Gradient rings used in present PFN design.

difficulties are increased by the requirement of three fasteners for each connection.

Figure 4-62 shows both the capacitor racks and the proposed PFN board under test at Maxwell. In all cases breakdown occurred in excess of 55 kV. Table 4-7 shows the resulting cost improvements from these changes.

Each of these items will be evaluated independently through construction of several prototype boards and an extensive test program to insure that they have the same high degree of reliability that our existing PFN networks possess. Only after this activity is completed with these improved PFN ideas be incorporated into the baseline Shiva.

G. R. Allen
W. L. Gagnon
P. R. Rupert

Fig. 4-61. Two proposed revisions to PFN design to reduce cost.

Fig. 4-62. Capacitor racks and proposed PFN board under test at Maxwell.

Table 4-7. Estimated PFN cost improvement

Item	LLL cost	Improved design cost	Cost savings
Inductor	\$55	\$50	\$ 5
Panels	\$12	\$ 9	\$ 3
Coaxial connectors	\$16	\$ 4	\$12
Spark gap	\$12	\$ 6	\$ 6
Resistors (1)	\$50	\$60	- \$10
Capacitor rack space (1)			\$10
Saving			
		Total	\$26

Note: The Shiva system has 1114 such PFN's for a total cost reduction of \$29,000 if all items are incorporated. The reliability of the system should also be improved due to fewer connections.

4.2.8 OPTICAL COMPONENTS AND THEIR PROCUREMENT

The procurement history of high-precision optical components required for the high-energy glass lasers being developed for the fusion program has been characterized by continuous interaction with industry to obtain higher quality optics at reasonable prices and deliveries. In general the response has been excellent, and our ever-increasing expectations have largely been satisfied.

Flat Optics

The majority of optical components in the laser systems are flat transmissive optics, although there are also many reflectors and beam splitters for beam turning and for both laser and target-interaction diagnostics. The most prevalent components are the laser disks, which are used at Brewster's angle and hence have an aspect ratio of about two to one. The two-arm Argus laser contains 48 8.5-cm-aperture disks and 24 20-cm-aperture disks. The Shiva laser will contain 360

10-cm disks, 80 15-cm disks, and 60 20-cm disks. Other flat components include polarizers (Brewster's angle), Faraday rotators (normal incidence), laser rods, windows, mirrors, and beam splitters (various angles).

Since a typical large-aperture laser chain has about 120 surfaces in it, our wavefront requirement on each component is very high, as illustrated by Table 4-8.

The properties of the material itself are, of course, very importantly related to what can be achieved in the finishing stage, and we require very high quality for inclusions, striations (essentially none), and homogeneity (explicit or implicit). The manufacturers of the currently used types of silicate-laser-glass disks have achieved a high level of reliability in producing excellent material, and the finishers have been able to take full advantage of the material quality.

An interferogram of a 20-cm-aperture $\times$ 3-cm-thick disk, taken at Brewster's angle in double pass at $\lambda = 632.8$ nm, is shown in Fig. 4-63. The actual disk is an

Table 4-8. Wavefront transmission specifications for Shiva optics. Single-pass transmission at 632.8 nm (He-Ne)

Component	Aperture diameter (cm)	Peak to valley (λ)	Gradient (λ/cm)
β Disk	10	1/12	1/30
γ Disk	15	1/10	1/30
δ Disk	20	1/8	1/40
β Rotators	10	1/10	1/25
δ Rotators	20	1/8	1/40

Fig. 4-63. Interferograms of an 18-cm-aperture, 3-cm-thick disk taken at Brewster's angle in double pass at 632.8-nm wavelength.

Fig. 4-64. Interferograms of a 9-cm-aperture disk in a 30-cm-aperture Fizeau cavity.

ellipse 21 by 40 cm. Figure 4-64 shows a 10-cm disk in a 30-cm-aperture Fizeau cavity. It is clear from these that, with the right equipment and material, it is possible to achieve outstanding results on flatwork. Both of these items were done on continuous polishing machines (at different vendors). The LLL optical fabrication group, especially Norman J. Brown, should

receive a great deal of credit for the extensive work in the systematizing of the continuous polishing process and the dissemination of this information to industry.

Rather good cumulative optical distortion results can be achieved through a large number of laser components. This is illustrated in the interferogram showing Cyclops wavefront distortion (Fig. 3-12). In this

interferogram, the gullwing shape is due to spherical aberration in a non-aspherized 10-cm-aperture f/10 spatial filter assembly. In addition, Cyclops contains an astigmatism corrector, designed to remove systematic errors produced by slight beam divergence through Brewster's-angle components, but which can also be used to correct random astigmatism. The residual aberration shown in the interferogram of the beam, which contains over 100 surfaces, demonstrates a quality of about $\lambda/5$ peak-to-valley at 1064 nm.

Aspheric Optics

We have chosen to use aspherics for spatial filter lenses, for diagnostic applications, and for target irradiation. The spatial filter lenses, which are in general f/10, require very little departure from spherical, and the required deformation can be polished in by a skilled optician with little more difficulty than the manufacture of a high-precision spherical surface, except it must be individually worked. The departure from the best-fit sphere for even a 20-cm-aperture f/10 lens is only about $2\text{ }\mu\text{m}$.

For steep aspherics, such as those used for target irradiation, the amount of asphericity is substantial. A 20-cm-aperture f/1 BK-7 lens shaped for minimum coma requires about 2 mm of departure from the best-fit sphere for the correction of spherical aberration. Until recently, the fabrication of such a lens was a very lengthy and uncertain process; however, within the last several months considerable effort in industry has been devoted to applying modern computer-controlled machining techniques to the problem, with very encouraging results. It has been possible by an iterative process of generating, measuring, and adjusting to achieve an aspheric within about $1\text{ }\mu\text{m}$ of the required curve before final hand-figuring in the optical testing stage, and work is currently in progress to reduce the whole process to a controlled machine process. This is a rapidly progressing area, and it is reasonable to say that it will become fairly routine to obtain aspherics of 30-cm aperture with several mm of departure and $\lambda/4$ or better specifications, in two-to-three-month manufacturing cycles.

Surface Characteristics

Our specifications on surface characteristics are fairly primitive as they do not specifically deal with the finishing process except to specify the avoidance of ferrous polishing compounds, and the application of a modified MIL-O-13830 scratch and dig standard. The modified test consists of using the scratch number to

represent the scratch width in μm , which is generally conceded to be a more liberal interpretation than the use of the unquantified scratch standards, but we also require much more critical illumination, using a 300-W projector (from behind, for transmitting surfaces), with the observation to be made against a black background in a clean booth, as opposed to the 100-W flashed-bulb test. Observed scratches and digs are then measured. This procedure for laser disks will be described in the appropriate revision of Lawrence Livermore specification MEL-74-001250.

These specifications do not deal specifically with damage, durability, and transmission-related factors such as rms surface roughness, residual subsurface grinding flaws, or surface scatter. However, through frequent and detailed interaction between our own shop personnel and industry, the technology related to these factors is dealt with to a considerable extent in an informal manner. As laser technology and understanding of the damage phenomena of surfaces (uncoated and coated) advance, it seems probable that in the near future these areas of surface processing and characterizing will receive more explicit attention in specifications.

Coatings

As the laser fusion effort tends to push the technology and logistics of finishing flatwork and aspheric surfaces, so also does it tend, perhaps even more so, to tax the resources of the thin-film coating technologists. The most difficult problem in this area is still the thin-film multilayer-dielectric polarizer, the processing of which, for large apertures, is still an uncertain and low-yield process. However, the past year has seen a great deal of increase in analysis, experimentation, planning, and experience in the manufacture of such components, with greatly improved results in the B or β size (10-cm aperture, $\sim 10 \times 20$ -cm ellipse on the part) and substantial experience in γ (~ 15 -cm) and δ (~ 20 -cm). The process, as far as LLL is concerned, has been substantially assisted by the demand for similar components by KMS Fusion, who have had several 14-cm-aperture polarizers manufactured to specifications very similar to ours. This has smoothed out the production effort and added to the development and experimental base.

On the larger sizes at the present level of specifications, the most difficult problem seems to be uniformity of transmission, for both wavefront and throughput. With coatings of about 30 layers adding up to thicknesses on the order of $8\text{ }\mu\text{m}$, small percentage variations in

thickness affect those parameters, which are typically 0.03 λ /cm (at $\lambda = 1064$ nm) for wavefront gradient and 0.1%/cm for transmission gradient. The 10-cm-aperture polarizers received this year have, however, shown improved total levels of transmission and extinction ratios with average transmission (T_p for transmitting polarizers) in excess of 98% over the full aperture and T_e less than or equal to 0.3%. One 20-cm-aperture polarizer has very nearly met specifications at the 95% transmission level, and several are in the works now on which we hope to achieve 97.5% or more in transmission.

Coating Damage

Damage testing and techniques are dealt with in more detail in Sec. 4.3.2; however, it is worth noting that, while it appears possible to specify and obtain damage levels from experienced vendors which are acceptable for present laser staging (on the order of 40 GW/cm² beam normal delivered in 0.1 ns pulses), we expect that these damage levels will eventually limit laser usefulness. There will be ongoing development

work to increase these levels to what we expect are the basic material limitations, in the range of 2.5 to 5.0 times present thresholds.

Coating of Laser Rods

A special problem exists in the antireflection coating of large laser rods. For the Shiva system, we are procuring large (up to 50-mm-diam), long (400-mm) rods to display stress birefringence not exceeding 1.0 nm/cm and wavefront occurrences of 0.1 λ PV at 1064 nm. In addition, high efficiency (1-4%), damage-resistant antireflection coatings are required for the ends, which are perpendicular to the optical axis. There is a potential problem in the reaction of such a massive optical component to the heat required to apply reasonably resistant coatings. Two of our vendors, a laser glass supplier and a coater, are currently carrying on a joint program to determine a process which will produce adequately hard coatings while at the same time maintaining the stress and wavefront flatness specification.

E. P. Wallerstein

4.3 Experimental Physics

Two important properties of lasing materials for high-power lasers are the gain coefficient and the nonlinear refractive index coefficient n_2 . The latter is especially significant for fusion lasers since intensity-dependent changes in the refractive index cause self-focusing, beam breakup, and a resultant loss of focusable energy. For long complex amplifier chains, such as used in Nd:glass fusion lasers, beam degradation originates in all the transmissive elements. These include the lasing medium, lenses, windows, polarizer substrates, Faraday rotators, and nonlinear crystals. Both the gain and n_2 vary with glass composition. Their values, in turn, affect the staging of components in long laser amplifier chains. To optimize these parameters, the optical and spectroscopic properties of many different laser glasses and crystals have been investigated.

Because of the importance of the nonlinear refractive index of materials, this property has received

considerable attention. Empirical expressions have been found which relate the linear and nonlinear optical susceptibilities.^{20,21} In general, low n_2 values are expected for materials having low refractive indices and dispersion. A good correlation has been obtained between predicted and measured electronic contributions to n_2 for several isotropic materials including silicate glasses and crystals.²¹

Most laser glasses have been oxide glasses, principally silicates and more recently phosphates. It has been found, however, that the nonlinear refractive indices of materials containing fluorine are significantly lower than those containing oxygen. Various classes of fluoride glasses and crystals have been investigated and are discussed in Sec. 4.3.1 on laser materials. Figures of merit have been developed which relate expected improvements in new glass performance to the performance of currently used glasses. This is

discussed also in Sec. 4.3.1.

Several approaches have been employed to determine experimentally the nonlinear refractive index of optical materials. Of these, time-resolved interferometry provides a direct measurement which does not involve assumptions about models used for self-focusing. Materials with small nonlinear coefficients are of special interest because of their importance for high-power lasers. To facilitate these measurements, a modified Michelson interferometer was developed which provides a convenient arrangement for passing the beam through the sample twice, thus increasing the propagation pathlength and the fringe shift. This made possible the measurement of the smallest nonlinearities in solids reported to date.

The absorption and stimulated-emission cross sections of neodymium laser materials are host-dependent. It has been demonstrated that changes in the emission cross sections by a factor of 2-3 can be obtained in silicate glasses by varying the glass network modifier ions.²² Similar variations have now been observed in neodymium-doped phosphate glasses. A wide range of potential laser glass compositions have been examined, including borates, germanates, tellurites, calcium aluminates, titanates, fluorosilicates, phosphates, fluorophosphates, and fluoroberyllates. A summary of these results is presented in Sec. 4.3.1.

The laser gain coefficient is given by a product of the stimulated-emission cross section and the population inversion. Fluorescence sensitization has been utilized to increase the latter and improve the optical pumping efficiency of solid-state crystalline laser materials.²³ Codopant ions are desired which have complementary absorption bands, which transfer their excitation efficiently to the upper laser level of Nd^{3+} , and which do not quench the Nd^{3+} fluorescence. Two ions which satisfy these criteria in Nd:glass are Ce^{3+} and Cr^{3+} . Spectroscopic properties of these ions, energy transfer efficiencies, and calculations of potential improvements in optical pumping and gain coefficient are discussed in Sec. 4.3.1.

Nonradiative decay rates from excited states of rare-earth ions determine three important properties of rare-earth lasers: pump conversion efficiency, radiative quantum efficiency, and lifetime of the terminal laser level. When the energy gap between an excited level and the next-lower level is greater than the energy of the most energetic lattice vibration, the nonradiative decay must involve the emission of several phonons. This multiphonon relaxation among the $4f^n$ levels of rare earths has been investigated in crystals, and has

now been extended to a series of oxide glasses. As shown in Sec. 4.3.1, there is a systematic dependence of the rate of multiphonon relaxation on the size of the energy gap to the next-lower level. The temperature dependence of the process established that the highest energy vibrations in the glass are most important for multiphonon relaxation. Since these are associated with vibrations of the glass network former, large changes in the nonradiative decay rates are observed in different glass types. The systematic behavior observed can therefore be used to estimate nonradiative decay rates and quantum efficiencies of various rare-earth excited states in different glasses.

As noted elsewhere, changes in glass composition affect line strengths, linewidths, and radiative and nonradiative lifetimes; these, in turn, affect cross sections, optical pumping efficiency, and gain coefficient. Systematic variations in these parameters with glass network modifier ions are observed and can be used to tailor glass for specific laser applications. To facilitate the above measurements and calculations, the apparatus for absorption and fluorescence spectra and fluorescence decay is interfaced directly with a minicomputer. With this computerized digital data acquisition and processing system, rapid characterization of materials and evaluation of many different glass compositions is possible. A description of this experimental facility is given in Sec. 4.3.1.

The final part of Sec. 4.3.1 describes fluorescence line narrowing studies of rare earths in glass. Due to the nature of amorphous materials, paramagnetic ions such as Nd^{3+} reside in glasses at many sites having different local field strengths and symmetries. This gives rise to the large inhomogeneous broadening characteristic of the optical spectra of ions in glass. This broadening masks details of the energy level structure and ion-ion interactions. By using tunable narrowband lasers, it is possible to excite selected groups of ions within the inhomogeneous absorption profile and study their properties. These experiments provide new insights into the structure of glasses and their effects of laser parameters.

In Sec. 4.3.2 laser-induced damage thresholds are reported for several optical components of interest for high-power lasers: dielectric films, turned metal surfaces, and evaporated metal films. These measurements were made at $1.06\text{ }\mu\text{m}$ using 100-ps pulse durations. Plans are under way to extend this capability to shorter wavelengths and longer pulse durations. As materials become available which have smaller n_2 values and therefore permit the propagation of more

intense beams, higher damage thresholds for thin-film coatings and surfaces become increasingly important.

The generation of laser pulses having preselected intensity-vs-time properties is of interest since the yields of laser fusion experiments are expected to depend strongly on the laser pulse shape. Passive pulse stackers are among the simplest devices for obtaining pulse shapes of interest. In Sec. 4.3.3 experiments are described in which single and multiple etalons are used to produce a variety of pulse shapes of 100-600 ps duration. Streak-camera and two-photon-fluorescence techniques indicate that interpulse interference effects are negligible for the 60-ps-FWHM bandwidth-limited input pulses used. Improved pulse-stacker designs have been considered based on requirements for large laser systems used for fusion experiments. Active pulse shaping using fast (~ 100 -ps) Pockels cell switching and amplifying etalon are also discussed briefly.

Both the heating of plasmas and the thresholds for plasma instabilities are predicted to increase at shorter wavelengths. Harmonic generation techniques are being pursued for frequency conversion of large-aperture, high-power Nd:glass lasers. These include the use of nonlinear crystals, such as KDP, and alkali-metal vapors. In the latter case, phase matching by the use of buffer gases and by noncollinear phase-matching techniques has been explored. These results are presented in Sec. 4.3.4.

The propagation of intense laser beams through long amplifier chains is the subject of the final section, 4.3.5. Experimental observations of the effects of gas turbulence and static and thermally induced distortions are described. Experience on the Cyclops and Janus lasers indicates the desirability of adjustable wavefront compensation of aberrations caused by the above effects.

Studies of whole-beam self-focusing have been extended to include time-resolved records of the dynamic profile changes which can occur in solid-state lasers used to irradiate fusion targets. Analytical expressions have been developed to model the observed effects. Based upon these findings, diagnostics for time-resolved monitoring of the beam profile in a plane equivalent to the target plane are included in the Cyclops laser system.

The propagation properties of small-scale structure have also been investigated, including the dominant spatial frequencies and the effect of beam breakup on the near- and far-field spatial profiles and the temporal profiles. Modeling of small-scale self-focusing has also been carried out. Control of small-scale self-focusing can be achieved with spatial filters. The consequences of the use of spatial filters on the design of long laser chains are considered at the conclusion of Sec. 4.3.5.

M. J. Weber

4.3.1 LASER MATERIALS

In the pursuit of optical components having a small nonlinear refractive coefficient n_2 , one generally seeks materials having a low refractive index n_0 and weak dispersion or large Abbé number ν . The electronic polarizability of fluorine is smaller than that of oxygen; therefore the use of fluoride glasses and crystals should be considered for high-power laser systems.

In addition to low refractive indices, fluoride materials generally have excellent uv and ir transmission properties, thus extending their potential usefulness.

A commonly used and convenient way of grouping glasses is to plot them using the d-line refractive index n_d and Abbe value ν_d as coordinates. The latter is defined by $\nu_d = (n_d - 1)/(n_F - n_C)$. Readily available optical glasses have values of 1.45-2.0 for n_d and 20-70 for ν_d . The lowest n - and highest ν -values are generally found for phosphate, fluorosilicate, and borosilicate crown glasses.

The comparative index values for various fluoride glasses versus ordinary optical glasses are illustrated by

the n_d -vs- ν_d plot in Fig. 4-65. Also shown are lines of constant electronic n_2 . The latter quantity was calculated from an approximation relating n_2 to the index and Abbe number.²¹ As is readily apparent, fluoride glasses are very attractive for low- n_2 optical components.

The fluorosilicates and fluorophosphates in Fig. 4-65 are at the extreme of present optical glasses. These are oxide glasses containing significant amounts of fluorine. Measurements of n_2 for fluorosilicate and fluorophosphate glasses are in reasonable agreement with predicted values.

Fluoride glass network formers include BeF_2 , AlF_3 , and ZrF_4 . Of the fluorides, beryllium fluoride is particularly attractive since the ion refractivities of Be^{2+} and F are among the smallest known for cations and anions. BeF_2 forms a glass analogous to SiO_2 , the bonding being weaker (lower melting point) and more ionic for the former. Pure BeF_2 and SiO_2 glasses are included in Fig. 4-65 and represent the extreme of each

Fig. 4-65. Refractive indices for various fluoride glasses and ordinary optical glasses.

glass type. The addition of various network-modifiers produces changes in the optical properties and the n_d - v_d regions shown. Oxyfluorides are also BeF_2 -based glasses but contain some phosphate in addition to various fluorides.

Several binary and ternary glasses based upon BeF_2 and containing various alkali and alkaline-earth fluorides are known.²³ With respect to predicted n_2 , the fluoroberyllate glasses have the lowest values. Thus the improvements with respect to reduced beam breakup may be very large. The toxicity and expense of beryllium and the chemical/physical durability of these glasses are important considerations.

Crystalline fluoride materials can also be considered for optical elements since in many cases they can be grown in sizes sufficient for large-aperture laser applications (≥ 15 cm). In addition, some single crystals which are cubic can be hot-forged to increase the aspect ratio by a factor of 2 or more. They can also be prepared by hot pressing and sintering; however, theoretical densities are difficult to achieve using this

technique. Scattering and reducing overall optical quality are characteristic of such materials.

Several candidate fluoride crystal materials are shown in an n - v diagram in Fig. 4-66, again together with optical glasses. In addition to the attractive low index values, the low- n_2 materials have good ultraviolet and infrared transmission properties.

The effects of whole-beam and small-scale self-focusing grow exponentially with propagation distance as $\exp(B)$, where B is a beam breakup integral defined by

$$B = \frac{2\pi}{\lambda} \int \frac{n_2}{n_0} I d\ell \quad (1)$$

In Eq. (1), I is the beam intensity (W/cm^2) and ℓ is the optical path length. For parallel beams having a uniform intensity distribution I , the breakup integral for various optical elements is minimized by reducing the following quantities:

$\frac{n_2}{n_0}$ for laser rod, Faraday rotator, window, etc., perpendicular to beam,

$\frac{n_2}{n_0}$ for amplifier disk, at Brewster's angle. (2)

$\frac{n_2}{n_0(n_0 - 1)}$ for lens.

For a complex laser system containing many optical elements of different index values, the total beam breakup is dependent upon the relative placement of amplifiers, isolators, spatial filters, etc. This staging, in turn, is a compromise to achieve a best figure of overall performance. The staging methodology may be flux-limited, wherein each component has a flux value

above which its damage rate becomes unacceptable, or beam-breakup-limited.

The laser system is limited to intensities of about 10^{10} W/cm² by beam breakup. Since for short pulses (~ 100 ps) the amplifiers are operated far from saturated gain, a large quantity of stored energy in the lasing medium is not utilized. Thus a reduction in n_2 can result in a direct increase in deliverable laser power, assuming that the coating damage thresholds are not surpassed.

To illustrate the potential improvements possible with fluoride glasses, lines of constant figure of merit for lenses, rods or substrates, and amplifier disks are shown in Figs. 4-67 and 4-68. The figure of merit is based upon beam breakup and is given by the reciprocal of the terms in Eq. (2). The lines in Figs. 4-67 and 4-68 are normalized to unity for BK-7 and FLD-2, the glasses presently used in lenses and Nd lasers. In both cases,

Fig. 4-66. Refractive indices for various fluoride crystals and ordinary optical glasses.

Fig. 4-67. Figure-of-merit plots for lenses.

improvements of greater than two are possible if suitable glasses or crystals can be developed.

There are a number of properties common to most optical materials used in high-power laser systems. These include high homogeneity, high damage threshold, low birefringence, low absorptivity at the lasing wavelength, and freedom from striae and impurities such as metallic platinum inclusions. Thermal properties, stress-optic coefficients, strength, ease of fabrication and finishing, and chemical durability in the operating environment are also important considerations. These combine to dictate cost and an overall figure of merit for a given material.

Measurements of Refractive Index Nonlinearity

The nonlinear refractive index coefficients of 15 optical materials were measured using a variation of the time-resolved interferometric technique described in

Bliss *et al.*²⁶ The most significant departure from the previous study was development of a modified Michelson interferometer to allow double-pass measurements of samples with very small nonlinear indices. The details of this interferometer are shown in Fig. 4-69. Linear fringes are formed at the output of the interferometer by superimposing a fraction of the intense beam propagated through the sample on the beam propagated in the other arm. The fringe pattern is imaged onto a streak camera so that fringe shifts can be recorded with 10-ps resolution. Fringe shifts induced by propagating an intense beam through the sample are a measure of the nonlinear refractive index of the sample.

Absolute integrated energy density of the beam propagated through the sample is determined from multiple-image beam photographs by means of the PHOTOCAL code.²⁷ This information, combined with the streak camera record of relative intensity, yields the absolute laser-pulse intensity to within 10%. Since

Fig. 4-68. Figure-of-merit plots for laser rods and disks.

there is a comparable uncertainty in the measurement of the recorded fringe shifts, errors $\geq 20\%$ are possible for any single absolute nonlinear-index measurement. Several measurements are made for each material and averaged to obtain a result accurate to $\pm 10\%$. Larger errors are associated with materials for which few measurements were made. Results for the 15 materials are given in Table 4-9. The data in Table 4-9 are in good agreement with values calculated from the linear refractive indices and Abbe numbers of the associated materials.²⁴

Stimulated-Emission Cross Sections In Glasses

Significant improvements in the gain coefficient of laser glass are possible by the development of improved glass compositions. A large number of new glasses for amplifier applications have been studied and predictions of gain coefficient, based upon measurements of

absorption and fluorescence spectra and decay properties, have been made. The results for several silicate and phosphate glasses are in good agreement with the actual performance in a laser cavity.²⁵ Since the information required for this evaluation can be obtained from small samples of the laser material, this considerably simplifies the comparison and selection of Nd:glass for use in large laser amplifiers.

The overall scheme for evaluating new laser materials has been described previously. The absorption spectra of candidate glasses is recorded from 1000 to 250 nm. Using the measured line strengths, a set of optical intensity parameters Ω is derived from a least-squares fit of calculated and measured values. These parameters are used to calculate the fluorescence line strengths and branching ratios for the ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ transitions of Nd^{3+} . The stimulated-emission cross section is determined from the calculated line strength and the linewidth measured from the fluorescence spectrum. The radiative lifetime is also calculated and

compared with the observed fluorescence decay rate to determine the radiative quantum efficiency. The latter is dependent upon the Nd concentration and the host glass.

Using the per-ion absorption spectrum, a computer program, VODAC, calculates the fractional absorption of xenon flashlamp power by the material as a function of optical depth (thickness times doping) and current density in the flashlamp.²² VODAC contains a model of the flashlamp output spectrum that is modified by rerunning some of the light back through a layer of plasma to approximate the multiple passes that actually occur inside the laser pumping cavity. The output curves of fractional absorption as a function of optical depth are used in conjunction with decay rate information and cross sections to predict the relative behavior of different materials in disk laser amplifiers.

Dependence on Glass Composition. The number of inorganic glass-forming systems is large. It includes elements, simple and conditional oxides, halides, chalcogenides, and hydrogen-bonded compounds. For practical laser glasses, the oxides have received the major consideration. The spectroscopic properties and laser parameters of an ion such as neodymium are

dependent on the glass host. This is illustrated in Table 4-10 where spectroscopic properties associated with the ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ fluorescence transition of Nd^{3+} are given for several oxide glass compositions. Included are the wavelength λ_p of the emission peak, the effective fluorescence linewidth $\Delta\lambda_{eff}$ (effective, since the fluorescence bands in glass are usually asymmetric), the peak stimulated-emission cross section σ_p , the fluorescence branching ratio β , and the radiative lifetime τ_0 of the ${}^4F_{3/2}$ state. The total uncertainty in the σ_p values is about $\pm 10\%$.

As can be seen from Table 4-10, the stimulated emission cross section can vary by more than a factor of 2.5 by changing the glass network modifier ions. Earlier studies in silicate glasses²³ demonstrated that variations of σ_p by a factor of about 3 were possible by changing the modifier ions. With combined changes of both network former and network modifier ions, cross sections σ_p for Nd^{3+} varying by as much as a factor of 5 have been produced in oxide glasses.²²

The effects of changing modifier ions within a given glass former can be studied by systematically varying the type and quantity of monovalent alkali ions, alkaline earth or other divalent cations (Cd^{2+} , Zn^{2+}),

Fig. 4-69. Interferometer used for n_2 measurements. This configuration allows double-pass measurements, which are needed for samples with small nonlinear indices.

Table 4-9. Nonlinear refractive index coefficients of optical materials measured interferometrically using linearly polarized 125-ps, 1064-nm laser pulses

Material	Type	n_D	ν_D	n_2 (10^{-13} esu)
Optical glass:				
Borosilicate	BK-7	1.517	64	1.24 ± 0.12
Fused silica	4000	1.458	68	0.95 ± 0.10
Fluorosilicate	FK-5	1.487	70	1.07 ± 0.11
Fluorophosphate	FK-51	1.487	84	0.69 ± 0.07
Nd laser glass:				
Silicate	ED-2	1.567	54	1.41 ± 0.14
Phosphate	LHG-5	1.541	63	1.16 ± 0.12
Phosphate	LHG-6	1.532	66	1.01 ± 0.10
Phosphate	EV-1	1.507	69	0.91 ± 0.09
Fluorophosphate		1.492	81	0.71 ± 0.14
Faraday rotator glass:				
Tb-silicate	FR-5	1.686	52	2.1 ± 0.4
Crystals				
CaF ₂	Cubic	1.434	95	0.57 ± 0.15
LiF	Cubic	1.392	99	0.35 ± 0.10
MgF ₂	Tetragonal	1.378 (o) ^a	108	0.30 ± 0.10
		1.389 (e) ^b	98	
KH ₂ PO ₄	Tetragonal	1.468 (e)	70	1.0 ± 0.3
		1.509 (o)	57	

^aThe abbreviation "o" is for ordinary waves.

^bThe abbreviation "e" is for extraordinary waves.

Table 4-10. Dependence of Nd³⁺ fluorescence properties on glass network former

	Borate	Silicate	Phosphate	German- ate	Tellurite	Aluminate	Silicate- titanate	Fluoro- phosphate
Composition (mole%)	67 B ₂ O ₃ 18 BaO 15 K ₂ O	67 SiO ₂ 18 BaO 15 K ₂ O	67 P ₂ O ₅ 18 BaO 15 K ₂ O	67 GeO ₂ 18 BaO 15 K ₂ O	80 TeO ₂ 20 BaO	32 Al ₂ O ₃ 52 CaO 11 SiO ₂ 5 BaO	50 SiO ₂ 25 TiO ₂ 25 Na ₂ ⁺	80 LiF 20 Al(PO ₃) ₃
$^4F_{3/2} \rightarrow ^4I_{11/2}$								
Fluorescence:								
λ_p (nm)	1061	1060	1055	1062	1063	1069	1064	1054
λ_{eff} (nm)	36.8	34.9	25.3	34.7	28.9	43.1	38.6	27.2
σ_p (10^{-20} cm ²)	2.2	1.5	4.1	1.9	2.9	1.8	2.5	3.5
$\beta(^4F_{3/2} \rightarrow ^4I_{11/2})$	0.49	0.46	0.48	0.45	0.46	0.46	0.47	0.48

Table 4-11. Characteristics of alkali phosphate glasses. Composition (mole%): 55 P₂O₅, 30 M₂O, 10 CaO, 5 Al₂O₃

M =	Li ⁺	Na ⁺	K ⁺	Rb ⁺
Nd ³⁺ intensity parameters (10 ⁻²⁰ cm ²):				
Ω ₂	3.1	3.6	4.2	4.3
Ω ₄	5.9	6.2	6.5	6.2
Ω ₆	5.6	6.1	6.5	5.9
⁴ F _{3/2} → ⁴ I _{11/2} fluorescence:				
σ (10 ⁻²⁰ cm ²)	3.9	4.5	4.7	4.4
Δλ _{eff} (nm)	26.1	24.5	23.7	24.1

trivalent ions (e.g., Al³⁺, La³⁺), or ions having other sizes and valence states. Cross sections are affected by changes in the oscillator strength of the transition and/or the linewidth. The variation in σ_r, observed for silicate glasses, however, is not identical to that observed for phosphate glasses. Therefore the behavior with modifier ions should be established by observation within each glass former.

The intensity parameters Ω govern the rates and cross sections for radiative transitions. Their dependence on the modifier ion for some simple binary and ternary silicate glasses has been shown previously.²⁹ These studies have been extended to phosphate glasses; some results are shown in Tables 4-11 and 4-12. Aluminophosphates have also been investigated. When the concentration of Al³⁺ is larger, the linewidths are broad and the cross sections correspondingly small. As noted by Deutschbein and Pautrat,³⁰ the fluorescence linewidth of Nd³⁺ increases with the valence state of the modifier ion. For a given valence state, the linewidth decreases with ion size for alkali and

alkaline-earth ions. This is observed in Tables 4-11 and 4-12. Note, however, that the intensity parameters Ω₄ and Ω₆ which determine the ⁴F_{3/2} → ⁴I_{11/2} transition probability exhibit only small variations. The combination of large oscillator strengths (Ω's) and narrower linewidths accounts for the large cross sections for alkali ion systems. Also, the cross section is increased when the amount of alkali M₂O is increased with respect to P₂O₅, as is seen by comparing the phosphate glass in Table 4-10 with that shown later in Table 4-13. While the behavior of the spectroscopic properties in multicomponent glasses is complicated, the general trends of Ω, Δλ, λ_{fl}, σ, and τ_{fl} with glass properties such as network and modifier ions can be identified by these studies. In addition, the overall procedure is useful for evaluating and comparing more complex glass compositions.

Comparison of Oxide and Fluoride Glasses. As discussed earlier in this chapter, glasses containing fluorine have low linear and nonlinear refractive indices. In Table 4-13, the refractive indices and the

Table 4-12. Characteristics of alkaline-earth phosphate glasses. Composition (mole %): 55 P₂O₅, 40 MO, 5 La₂O₃

	Be ²⁺	Mg ²⁺	Ca ²⁺	Sr ²⁺	Ba ²⁺
Nd ³⁺ intensity parameters (10 ⁻²⁰ cm ²):					
Ω ₂	7.0	5.7	4.4	4.0	3.6
Ω ₄	4.0	5.0	5.1	5.1	5.0
Ω ₆	3.9	5.0	4.9	4.9	5.3
⁴ F _{3/2} → ⁴ I _{11/2} fluorescence:					
σ (10 ⁻²⁰ cm ²)	2.1	2.8	3.0	3.2	3.6
Δλ _{eff} (nm)	34.2	32.7	31.6	30.1	28.3

spectroscopic properties of Nd^{3+} in some oxide and fluoride glasses are compared. These include oxide glasses (a silicate and a phosphate), one fluorosilicate and one fluorophosphate (oxide glasses with some oxygen replaced by fluorine), and a pure fluoride glass having BeF_2 as the network former. There are several things to note in Table 4-13. First, there is a dramatic and very important reduction in n_2 for fluoride glasses. This is illustrated in Fig. 4-70 where known glass-forming regions of various oxide and fluoride glasses are indicated in an n -vs- ν diagram. The locations of several commercial optical and laser glasses in this parameter space are also indicated. The dashed curves are lines of constant n_2 estimated from a simplified formula.²⁴ It can be seen that since fluoride glasses have low index and dispersion, the predicted nonlinear indices are significantly lower than for oxide glasses.

The cross sections for the silicate and phosphate glasses in Table 4-13 are among the largest measured for these two glass types. Compositional studies of the remaining glasses are not complete and therefore it is not known how representative the values cited are with respect to the extremes possible.

Studies of the effects of changing modifier ions in

fluorophosphate glasses are under way. As an example, the dependence of refractive indices, density, and spectroscopic properties on alkaline earth is shown in Table 4-14. The observed systematic behavior in these properties provides guidance in selecting compositions to tailor glass for specific laser applications. Thus far fluorophosphate glasses with indices of about 1.47, $\nu \approx 87$, $n_2 \approx 0.65 \times 10^{-13} \text{ esu}$ (calculated), and cross sections ranging up to $3.7 \times 10^{-20} \text{ cm}^2$ have been identified.

The effect of fluoride glass composition on non-radiative relaxation of Nd^{3+} by multiphonon emission and ion-ion interactions is also being studied. No deleterious properties are expected. The longer radiative lifetime for the fluoroberyllate glass is due in large part to the smaller refractive index which enters as $n(n^2 + 2)^2$ in the spontaneous emission probability. Thus for equal emission cross sections, pumping rates to achieve equal gains may be less in the fluoroberyllate glasses.

In summary, the stimulated emission cross sections for fluoride glasses should be comparable to those from silicate glasses but lower than the high-gain phosphate glass in Table 4-13. However, the advantage of high-gain glasses is reduced if the amplifier is parasitic-

Table 4-13. Comparison of the refractive indices and spectroscopic properties of the $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{11/2}$ transition of Nd^{3+} in oxide and fluoride glasses

	Silicate	Phosphate	Fluoro-silicate	Fluoro-phosphate	Fluoro-beryllate
Refractive index n_d	1.567	1.507	1.488	1.492	1.347
Nonlinear index n_2 (10^{-13} esu)	1.41	0.91	1.0	0.71	~ 0.4 (est)
Cross section σ (10^{-20} cm^2)	2.9	4.7	1.9	2.5	2.9
Linewidth, FWHM (nm)	29	19	27	26	20
Branching ratio	0.47	0.47	0.48	0.49	0.50
Fluorescence peak (nm)	1062	1054	1057	1054	1047
Radiative lifetime (μs)	340	330	410	460	600
Relative optical absorption efficiency	1.0	0.78	0.85	0.73	0.81

Glass compositions (mole %):

Silicate — 60 SiO_2 , 27.5 Li_2O , 10 CaO , 2.5 Al_2O_3 .

Phosphate — 50 P_2O_5 , 33 K_2O , 17 BaO .

Fluorosilicate — SiO_2 , K_2O , B_2O_3 , F_2 .

Fluorophosphate — P_2O_5 , Al_2O_3 , MgF_2 , CaF_2 , SrF_2 , BaF_2 .

Fluoroberyllate — 48 BeF_2 , 27 KF , 15 CaF_2 , 10 AlF_3 .

Fig. 4-70. Linear and nonlinear refractive indices of various optical materials.

limited. In high-power Nd fusion lasers, low n_2 is always advantageous. Therefore, because of their smaller n_2 values, low-index fluorophosphate and fluoroberyllate glasses should be superior laser materials.

M. J. Weber
C. B. Layne
R. A. Saroyan

Optical Pumping Efficiency: Fluorescence Sensitization

Ce $\rightarrow$ Nd Energy Transfer. The Nd ion does not absorb at some wavelengths where xenon flashlamps emit. In order to make use of the energy that is radiated in these spectral regions, several techniques have been proposed to either shift the light into Nd absorption bands or to sensitize the Nd by coupling with another

ion that absorbs in these regions and transfers its excitation to Nd. Xenon flashlamps operated at the current densities typical of disk laser amplifiers emit a significant fraction of their energy in the near ultraviolet. Ce^{3+} ions are doped into many Nd laser glasses in order to absorb the ultraviolet light below 300 nm and protect the glass from solarization damage. We have investigated the possibility of using Ce as a sensitizing ion for Nd in ED-2 laser glass.³¹

Both radiative and nonradiative transfer of excitation from Ce to Nd is made possible by the overlap of the Ce emission spectrum with an absorption band of Nd (see Fig. 4-71). Radiative transfer effectively shifts flashlamp output from short wavelengths to the region of the Nd absorption at 350 nm, through absorption and subsequent reemission by Ce. Nonradiative transfer can take place by the coupling of the electric dipole fields of the excited Ce ion and a nearby Nd ion. This dipole-dipole coupling results in the transfer of excita-

Table 4-14. Characteristics of fluorophosphate glasses.^a Composition (mole %): 20 Al(PO₃)₃, 47 LiF, 14 Li₂O, 18 MF₂, 1Nd₂O₃

	Values when M is:			
	Mg	Ca	Sr	Ba
n_d	1.5132	1.5190	1.5269	1.5335
ν_d	78	76	73	72
n_2 (10^{-13} esu) (calc.)	0.85	0.09	0.98	1.01
d (g/cm ³)	2.74	2.78	3.02	3.22
Ω_2 (10^{-20} cm ²)	1.94	1.78	2.08	1.86
Ω_4 (10^{-20} cm ²)	2.90	3.38	3.28	3.60
Ω_6 (10^{-20} cm ²)	3.20	3.55	3.82	3.84
τ_R (μ s)	611	533	511	483
λ_p (nm)	1053.8	1054	1055	1055.4
$\Delta\lambda_{FWHM}$ (nm)	26.8	26.4	26.5	25
σ (10^{-20} cm ²)	1.90	2.13	2.22	2.37

^aGlasses melted by D. Blackburn, National Bureau of Standards.

tion from the Ce to the Nd ion without the emission of a photon by the Ce.

The existence of nonradiative transfer from Ce to Nd is indicated by the results shown in Fig. 4-72. The decay rate of Ce excitation is unaffected by radiative transfer, but nonradiative transfer to Nd increases the

Ce decay rate. Figure 4-72 shows that the decay rate of Ce increases linearly with the concentration of Nd ions. The efficiency of energy transfer from excited Ce to Nd ions was determined as a function of Nd concentration from Fig. 4-72; transfer efficiency is just the ratio of the nonradiative rate to the total rate. Experiments at low

Fig. 4-71. Absorption and emission spectra of Ce³⁺ and overlapping Nd³⁺ absorption. The Ce³⁺ emission scale is arbitrary.

Fig. 4-72. Decay rate ($W_{\text{tot}} = 1/\tau$) of excited Ce^{3+} as a function of Nd^{3+} concentration. Solid dots represent samples containing 0.006 mole % CeO_2 ; open dots are for 0.16 mole % CeO_2 . The corresponding concentrations in Ce^{3+} ions/cm³ are shown.

Fig. 4-73. Conversion efficiency of Nd^{3+} and Ce^{3+} as a function of xenon-flashlamp current density. The solid curves are calculated by including a layer of absorbing plasma to simulate the effects of reflection within a laser pump cavity. The dashed curves do not include any cavity effects.

temperatures indicate that there are only two decay mechanisms for Ce in ED-2: excited ions either radiate, or they nonradiatively transfer to Nd with a rate proportional to the Nd concentration.

The VODAC-ABSGEN computer programs²⁸ were used to determine the energy absorbed by Nd and by Ce

Fig. 4-74. Nd^{3+} and Cr^{3+} absorption spectra. The Nd sample was 2.93 mm thick with 2.7 wt% Nd_2O_3 in phosphate glass. The Cr sample was 5.8 mm thick with 0.1 wt% Cr_2O_3 in the same base glass.

in ED-2 glass. The concentrations of Ce and Nd were chosen to give uniform excitation throughout the bulk of a glass disk. In this case, there is no competitive absorption: Ce does not absorb at the same wavelengths as Nd. Figure 4-73 shows the efficiencies of absorption of Ce and Nd as a function of flashlamp current density. As the current density increases, the light output is shifted more to the ultraviolet, resulting in lower absorption efficiency for Nd but higher efficiency for Ce. The total energy absorbed by Ce is shown in Fig. 4-74, but only about 25% of this excitation is transferred to Nd at the concentrations typical of disk amplifiers.

The amount of Ce normally included in ED-2 as an antisolarizing agent is about 10 times the amount chosen for Fig. 4-73. This causes all the light below 300

nm to be absorbed in about the first 1 mm of glass. In order to decrease the doping for uniform sensitizing, the problems of solarization by the ultraviolet radiation must be solved in another way. With the high concentration of Ce, the energy that is absorbed near the surface is reradiated, accomplishing the desired spectral shift to match the Nd pump band.

Given the low nonradiative transfer efficiency from Ce to Nd at the Nd concentrations used in disk lasers, it is unlikely that decreasing the Ce content will provide more than a few percent improvement through nonradiative transfer to Nd. The additional problem of inhibiting solarization in a glass with reduced Ce content makes the proposed Ce sensitization scheme impractical.

Cr³⁺ → Nd³⁺ Energy Transfer. Many other ions are potential sensitizers for Nd, but in general the sensitizer will absorb at some of the same pump-band wavelengths as Nd. With anything less than 100% transfer efficiency, this competitive absorption may lead to a decrease in performance. In order to evaluate sensitizing ions in general, the VODAC-ABSGEN programs were modified to accept both the Nd absorption spectrum and the sensitizer's absorption spectrum. The calculation keeps account of energy stored in both ions, including the effects of competitive absorption, and transfers energy from the sensitizer to Nd with the specified transfer efficiency. This evaluation technique has been applied to the Cr-Nd system, where the broad absorption bands of Cr overlap Nd bands (see Fig. 4-74). The experiments to determine the transfer efficiency from Cr to Nd are not completed, but the VODAC-ABSGEN calculation indicates that a high efficiency will be necessary (50% at normal Nd concentrations) if Cr is to provide improved pumping of Nd.

The possibility of a two-photon absorption in Cr-sensitized glass, like that considered earlier for Nd,³² was investigated experimentally. A two-photon absorption at 1.06 μm would lead to an intensity-dependent absorption of the form

$$I = I_0 \exp(-\gamma I x),$$

where the intensity I at position x is reduced by the absorption coefficient γI which is proportional to intensity. A series of experiments using the IL-5 laser system determined the transmission through a Cr-doped glass sample as a function of incident laser power up to about 10^{10} W/cm^2 . These measurements established that the coefficient γ for Cr-doped glass was less than $5 \times 10^{-13} \text{ cm/W}$ at the doping levels appropriate for sensitized laser glasses. This value of γ will result in two-photon absorption of less than 0.01 cm^{-1} even at the highest power levels ($2 \times 10^{10} \text{ W/cm}^2$) of Nd glass

lasers, compared to typical gain coefficients of 0.05 to 0.1 cm^{-1} .

C. B. Layne
M. J. Weber

Quantum Efficiency: Nonradiative Decay by Multiphonon Emission

Nonradiative relaxation of excited levels of Nd takes place through the emission of phonons, sufficient in energy to make up the difference between electronic states. When the gaps between electronic levels are large compared to the maximum phonon energy, several of the highest energy phonons will be required to conserve energy. The rates of these multiphonon decays have previously been measured for several energy gaps in F:D-2 laser glass where they were found to obey the predicted exponential dependence of the rate on the width of the energy gap

$$W_{\text{NR}} = W_0 \exp \{ -\alpha \Delta E \},$$

where W_{NR} is the multiphonon decay rate across the energy gap ΔE ; W_0 and α are constant for a particular glass. The dependence of multiphonon decay rates on glass composition was investigated in the series of oxide glasses—borate, phosphate, silicate, germanate, tellurite.³³

The compositions chosen were simple three-component glasses doped with Nd, Er, and Tm (see Table 6-7, p. 266 of last year's Annual Report). Figure 4-75 shows the excitation and fluorescence schemes with the nonradiative decays that were measured indicated by wiggly lines. A short laser pulse excites the ions into the desired level from which they decay rapidly across small energy gaps until a large gap requiring the emission of several phonons is encountered. Here the decay rate slows to a measurable rate (10^3 to 10^4 s^{-1}). Observation of the time dependence of the fluorescence from the various electronic levels allows the determination of the decay rates. Figure 4-76 shows the multiphonon rates for the five glasses, as a function of the energy gap to the next lowest level. The particular ions and electronic levels are indicated at the top of the figure. All five glasses obey the exponential dependence of rate on energy gap, but the magnitude of the rates for the same energy gap vary by a factor of almost 1000 from the slowest (tellurite) to the fastest (borate). The nonradiative rates in borate glass are so fast that the large energy gap below the Nd ${}^4\text{F}_{3/2}$ laser level is relaxed by multiphonon decay faster than the radiative rate for this level, making borate glasses poor candidates for Nd laser materials.

The large differences in multiphonon rates for dif-

Fig. 4-75. Excitation and fluorescence schemes to study multiphonon relaxation. Wavy lines indicate the decays measured.

ferent glass composition are due to the variations in the vibrational spectra of these glasses. Figure 4-77 shows the Raman spectra of the five glasses, with the high-energy phonon peaks varying from 800 cm^{-1} for tellurite glass to 1400 cm^{-1} for borate glass. In multiphonon decay, the highest energy phonons which conserve energy in the lowest order are dominant in the relaxation. This is further verified by the temperature dependence of the multiphonon decays in Tm shown in Fig. 4-78. Multiphonon theory predicts a temperature dependence that results from the Bose-Einstein distribution for the active phonons. The solid curves in Fig. 4-78 are calculated from the theory, using the phonon energies of the highest energy peaks in each glass. Other phonon energies, such as that of the prominent peaks at lower energy, do not fit the data.

C. B. Layne
W. H. Lowdermilk
M. J. Weber

Computerized Spectroscopy Facility

To expedite the measurement of glass parameters, computer-instrument interfaces have been installed in the solid-state spectroscopy laboratory. The computer and its peripherals are used for instrument control and data processing. Presently, the following properties are measured: ultraviolet to near-infrared absorption spectra, fluorescence spectra, and fluorescence lifetimes. After data has been gathered, calculations leading to desired parameters may be performed. Example calculations include the Judd-Ofelt Ω parameters, reduced absorption spectra, refractive indices, and sample densities.

Absorption data are taken by a Cary 17I spectrophotometer, fluorescence spectra by a McPherson monochromator, and fluorescence lifetime by a Tektronix Digital Processing Oscilloscope or Transient Digitizer, all of which are computer-controlled to varying degrees. Table 4-15 lists some of these control

Fig. 4-76. Multiphonon decay rates of rare-earth ions in five oxide glasses as a function of energy gap to next lower level. The ions and energy levels whose decays were measured are indicated at the top of the figure.

functions. In most cases, only sample placement and initial setting of electronic controls need be done to begin data acquisition. Should the computer be unavailable, any of these devices may be operated manually.

A block diagram of the computer system is shown in Fig. 4-79. The computer is a Digital Equipment Corporation PDP 11/40 with a 32K memory. Attached to it are a Laboratory Peripheral System, a disk cassette drive, a dual-cassette tape drive, a magnetic tape drive, a Tektronix display terminal and hard copy unit, and a Zeta plotter. The tape systems are used for data storage or program and data transfer to other disks or other computers. The graphics display terminal provides

Fig. 4-77. Polarized Raman spectra of five oxide glasses.

Fig. 4-78. Temperature dependence of the Tm³F₄ to ³H₆ decay for four oxide glasses. Number and energy of phonons are indicated; radiative rates were included for tellurite and germanate glasses.

input via a keyboard and printed or graphical output on a CRT. Permanent copies of CRT output may be made with the hard copy unit. The terminal also allows data input from the CRT by means of a cursor which may be positioned by thumb wheels or a joy stick. Graphical output may also be sent directly to the Zeta plotter. Experimental control is via the Laboratory Peripheral System in the case of fluorescence measurements, an LLL interface for the Cary 171 spectrophotometer, or

special interfaces for the Tektronix digital oscilloscopes.

The primary software system is the DEC disk operating system RT-11. Under this system we operate several versions of the language Basic. These versions differ in the special functions they control. The languages and their functions are listed in Table 4-16. We have the capability to use Fortran, but Basic is preferred because of ease of quickly programming special

Fig. 4-79. Block diagram of computer system in solid-state spectroscopy laboratory.

Table 4-15. Computer-controlled functions of instruments in spectroscopy laboratory

Cary 171	McPherson	Digital Processing Oscilloscope or Transient Digitizer
Scan rate	Data point averaging	All display functions
Scan limits	Sampling rate	All postprocessing
Source	Scan limits	
Detector		
Scan averaging		

data-processing programs immediately after data acquisition. Some of the Basic programs developed are listed in Table 4-17. The relationship of these programs to the measurement of glass parameters and production of data for design analysis is shown in Fig. 4-80.

Examples of the output of these programs are shown in the next figures for a phosphate glass, EV-2.2. The absorption and fluorescence spectra are shown in Fig. 4-81. These plots were created by SPLOT7 from data gathered by CARY17 and FLUOR. The result of using ABSGEN on the absorption spectrum is shown in Fig. 4-82. JUDDOF output is shown in Fig. 4-83. This program uses or displays data collected or calculated by the remaining programs in Fig. 4-80.

Future computerization efforts include improved data processing, transfer of data to the Laboratory's CDC 7600 computers for calculations too lengthy for the minicomputer, and addition of new experiments.

R. A. Saroyan
M. J. Weber

Studies of Laser-Induced Fluorescence Line Narrowing (FLN) in Glass

The optical spectra of paramagnetic ions in glasses are characterized by large inhomogeneous linewidths due to variations in the local fields. This broadening masks many of the spectroscopic details of interest, such as the crystal-field splitting and homogeneous linewidth. Such information can be obtained, however, if one uses tunable lasers rather than broadband radiation for excitation since only those ions resonant with the narrowband laser radiation are probed. We have employed laser-induced fluorescence line narrowing (FLN) techniques to investigate site-to-site variations in: (1) energy level structure where, from an analysis of

Table 4-16. Computer languages for glass analysis programs

Language	Function
BASLPS	Controls Laboratory Peripheral System
BASLPP	Adds graphics to BASLPS
CARY	Controls Cary 171 spectrophotometer
WDI	Controls Tektronix digital oscilloscopes

Table 4-17. Computer programs for glass analysis

Program	Purpose
CARY17	Controller for Cary 171 spectrophotometer
FLUOR	Controller for McPherson Fluorescence monochromator
ABSGEN	Creates data for VODAC
SPLOT7	Displays spectra and integrates absorption bands
JUDDOF	Calculates Judd-Ofelt parameters
REFRAC	Calculates refractive indices and Abbe' number
FINDN2	Calculates nonlinear index from REFRAC data
CHAMPE	Calculates sample density

the Stark splitting, crystal-field parameters are derived and related to changes in the coordination structure; (2) fluorescence decay times where factor-of-three varia-

tions in radiative transition probabilities are observed; (3) homogeneous and inhomogeneous linewidths using resonant and nonresonant absorption-emission cycles which, together with fluorescence decay results, demonstrate the occurrence of accidental coincidence of energy levels; and (4) ion-ion energy transfer and spectral energy migration to nearby but spectrally different sites. Thus far Nd^{3+} , Eu^{3+} , and Yb^{3+} in several silicate and phosphate glasses have been studied.

Several examples of resonant and nonresonant absorption-emission cycles for FLN experiments⁴⁴ are

illustrated at the top of Fig. 4-84. Levels 1 and 3 represent the lowest Stark levels of two J states; levels 2 and 4 are higher-lying Stark levels of the same or other J states. At low temperatures homogeneous broadening of levels 1 and 3 can be very small (<1 MHz), and scheme I yields "laser-narrow" emission. At higher temperatures, the FLN linewidth measures the homogeneous lifetime broadening of levels 1 and 3. The homogeneous linewidths of levels 2 and 4 are studied using schemes II and III, the latter involving excitation from a thermally populated level. Analysis

Fig. 4-80. How the computer programs are interrelated to measure glass parameters and produce data for design analysis.

Fig. 4-81. Computer output of (a) absorption and (b) fluorescence spectra for a phosphate glass, EV-2.2.

Fig. 4-82. Result of using ABSGEN code on the absorption spectrum of EV-2.2 in Fig. 4-81.

of the FLN linewidths in cases of nonresonant excitation-fluorescence cycles, shown at the top right of Fig. 4-84, is more complicated since possible homogeneous broadening of all three levels involved and the relative sensitivity of the levels to inhomogeneous broadening must be considered.

FLN can be frustrated by accidental coincidence of levels as illustrated at the bottom of Fig. 4-84. Ions at sites A, B, C, D, and E are all excited by the same wavelength but fluoresce at different wavelengths, thus "laser-narrow" nonresonant emission is not observed. C is an example where excitation from a thermally populated level generates upconverted anti-Stokes fluorescence. D and E are phonon-assisted transitions leading to fluorescence at nonresonant wavelengths.

Energy Levels. Because of the relative simplicity of the Eu^{3+} energy levels, we have examined the FLN spectra of Eu^{3+} in silicate, phosphate, and $\text{Eu}(\text{PO}_3)_3$ glasses using ${}^7\text{F}_0 \rightarrow {}^5\text{D}_0$ excitation and low temperatures. The results below are from detailed studies performed by C. Brecher and L. Riseberg of GTE

Laboratories under contract from LLL. The overall distribution of Stark splittings in the various glasses are very similar, but the centers of gravity of the J manifolds differ. The Stark levels of the ${}^7\text{F}_1$ and ${}^7\text{F}_2$ manifolds, observed by varying the laser excitation wavelength λ_1 and plotted as a function of effective crystal field, are shown in Fig. 4-85. Note the large range of ${}^7\text{F}_1$ splittings, from about 150 to 550 cm^{-1} . Thus, in a single silicate glass, sites exist which have Stark splittings ranging from among the smallest and the largest reported in crystals.

Possible coordination structures have been analyzed³⁵ to account for the changing energy levels in Fig. 4-85. Using C_{2v} site symmetry, which is the highest symmetry in which the full splitting of ${}^7\text{F}_1$ is allowed and the lowest symmetry amenable to simple crystal-field calculations, a set of crystal-field parameters B_{nm} were derived. The energy levels calculated using the parameters are indicated by the dashed lines in Fig. 4-85. A model involving the gradual intrusion of a ninth ligand into an originally octocoordinate site is

homogeneous linewidths for a given temperature changed with λ_1 . This arises from changes in the energy structure and/or ion-phonon coupling at different sites.

Energy Transfer. Energy transfer between rare earths occurs via electric multipole processes and may be resonant or phonon-assisted. It is apparent from Fig. 4-84 that a multiplicity of energy-conserving pairs of transitions are possible in inhomogeneous systems. For example, the ${}^3D_0 \rightarrow {}^7F_1$ (A_2) transition of Eu^{3+} at one site can be resonant with a ${}^7F_0 \rightarrow {}^5D_0$ transition at another site, thus giving rise to resonant transfer between dissimilar sites even without phonon assistance. Using time-resolved spectroscopy and rare-earth concentrations >0.1 mole% energy transfer between unlike sites can be studied. The FLN spectrum usually grows in time to resemble the inhomogeneous spec-

Fig. 4-84. (Top) Several possible resonant and nonresonant excitation-fluorescence schemes for rare earths. Wavy lines denote nonradiative transitions. (Bottom) Examples of sites (A, B, C, D, E) excited by the same frequency but which fluoresce nonresonantly at different frequencies.

Fig. 4-85. Observed (solid line) and calculated (dashed line) energy levels for Eu^{3+} in silicate glass. Level assignments are for C_2 symmetry.

Fig. 4-86. Linewidths of Eu^{3+} in silicate glass measured for nonresonant ${}^7F_0 \rightarrow {}^5D_0$ excitation.

Fig. 4-87. Time evolution of the resonant line-narrowed spectra for 0.5% Yb^{3+} in silicate glass at ~ 100 K.

trum. This is shown for Yb^{3+} in Fig. 4-87, where the initial line-narrowed fluorescence at 987.5 nm decreases and a broad emission similar to the inhomogeneously broadened fluorescence grows. Since the transfer is only to spatially nearby sites, these sites must be spectrally dissimilar to account for the growth

at the full inhomogeneous width. The time dependences of the decays for both Eu^{3+} and Yb^{3+} establish that the dominant transfer is dipole-dipole in origin.

M. J. Weber
J. A. Paisner

4.3.2 STUDIES OF LASER-INDUCED DAMAGE TO MATERIALS

Damage tests have been performed, using the ILS facility,³⁶ to support the tasks of selecting both vendors and component design, and to evaluate proposed new materials. Linearly polarized 1064-nm laser pulses with durations in the range 125 ± 25 ps were used in all tests. Focal diameters at the sample (FWHM at e^{-2} in intensity) ranged from 1-4 mm. The smaller beams were used with damage-resistant samples.

The experimental arrangement used is shown in Fig. 4-88. The peak on-axis integrated energy density of each pulse was determined by using a calorimetric

measure of pulse energy to normalize the energy density profile. The relative beam profiles were reconstructed from I-Z photographs via the PHOTOCAL code.²⁷

A triple-beam apparatus, shown in Fig. 4-89, was used for the final set of measurements performed this year. Three beams with intensities approximately in the ratios 3:4:5 were formed in each firing. The three beams impinged on different sites, staggered in time, so that the least intense beams arrived first at the sample. The peak on-axis energy density for the least

intense beam was determined using the usual PHOTOCAL process.²⁷ Energy densities for the remaining two beams were obtained from the measured splitting ratio of the sectored mirror.

The samples were observed visually during irradiation. Near-threshold damage in dielectric films or polished surfaces results in emission of a faint glow. Emission of actual sparks or an audible snap indicates damage at levels well above threshold. In dielectric samples, confirmation of damage was made by the "breath" test, or by optical microscopy. Some metal films and turned metal surfaces were found to suffer

damage at levels well below that at which light was emitted from the sample. For metal surfaces both dark-field and Nomarski microscopy, and the "breath" test, were used to determine which sites had been damaged.

Peak energy densities in the laser pulse can be determined within $\pm 5\text{--}7\%$ for most firings. Beyond this uncertainty, there is the problem of defining the power level at which threshold damage occurred, and additionally, possible site-to-site threshold variations on the sample. These effects in combination usually produce uncertainties of 10–15% in measured damage

Fig. 4-88. Laser and apparatus used for damage experiments. Laser pulses are 125 ps in duration with energy up to 0.5 J. The beam profile is formed by passive optics. In-place diagnostics include diodes to record waveforms of the mode-locked train (A) and selected pulse (B) and pulse energy before (C) and after (D) amplification. The fundamental energy monitor is the calorimeter shown in the damage apparatus.

Fig. 4-89. Triple-beam damage experiment. The profile for the first beam is recorded on a self-calibrating photographic plate. Profiles of all three beams are recorded on Polaroid film.

thresholds. The uncertainty can be reduced by taking additional data, provided the sample is sufficiently uniform. Time required to do such additional evaluation was usually unavailable.

The results of the studies described below indicate that dielectric films are routinely available which withstand 3.5 J/cm^2 , and a few are being fabricated which withstand $6-10 \text{ J/cm}^2$. Metal surfaces have withstood up to about 4 J/cm^2 . These data demonstrate the magnitude of the improvements that can be expected for several types of optical components.

Dielectric Films

Many samples were dielectric films which were of four different types:

- 99% reflective at 0° incidence.
- 99% reflective at 45° incidence.
- Antireflective.
- Thin film polarizers.

Histograms of damage thresholds measured for members of the first three classes are shown in Fig. 4-90. Data from all samples evaluated is included, to show both the average performance and the range of thresholds for each type of coating. Since thin-film polarizers were frequently tested using both S- and P-state polarization, these thresholds are given in Table 4-18, so that both thresholds retain identification with a given sample. All devices evaluated are included irrespective of size, material, or fabricator. No particular correlation between component size and damage

threshold was observed, though sizes ranged from $5 \text{ cm} \times 5 \text{ cm}$ to $24 \text{ cm} \times 50 \text{ cm}$. The average thresholds observed for the two polarizations were approximately the same, but the spread was larger for the S-polarization. Thresholds stated in Table 4-18 are those measured in a plane normal to the beam, which was incident on the sample at Brewster's angle in each test.

Fig. 4-90. Histograms showing damage thresholds for three classes of films: antireflection films, films that are 99% reflecting at 0° incidence, and films that are 99% reflective at 45° incidence.

Turned Metal Surfaces

Since turned metal surfaces are potentially useful for handling of intense pulses, we have continued to test such samples to aid their development. The usual fabrication process is as follows: the metal substrate is electroplated (EP) with about 30 μm of the desired metal, possibly heat-treated (HT) to relieve stress, diamond turned (DT), and then rinsed (R) free of cutting fluids. The sample may additionally be coated (C) or polished (P). Some samples turned directly from nonelectroplated OFHC copper were also tested, to determine the value of electroplating.

Additional cleaning, beyond dusting with a gas jet, may be done prior to the damage tests. This final cleaning usually consists of swabbing the sample with cotton balls soaked in solvents such as acetone or alcohol, followed by flushing with solvent which is blown off the sample using CO_2 or Freon jets. Symbols denoted above are used in Table 4-19 to characterize the samples. Tests were performed at nearly normal incidence except as noted in the table. Samples 11.1, Cu 44, and 1.1.1, Ag 6 were polished using sus-

pended carbon particles; Baker 10 was polished using diamond and silicon oil.

Polished metal surfaces were damaged at about 0.5 J/cm^2 or less and are therefore of limited value for handling intense short pulses. Turned surfaces have thresholds from 2-4 J/cm^2 , and exhibit the expected increase in threshold for S-state polarization incident at 45° . Surfaces prepared directly from OFHC copper were only slightly better than polished samples. A complete report of this work is available.¹²

Evaporated Metal Films

Inconel films are of interest for fabrication of apodizers. Evaporated Inconel films of several thicknesses have been damage tested. Film thicknesses were estimated from measured optical densities. Damage thresholds, given in Fig. 4-91, correspond to the lowest incident power level which left any detectable permanent change in the film.

D. Milam

Table 4-18. Damage thresholds for polarizing dielectric films

Sample	Threshold ($\text{J}/\text{cm}^2 @ 125 \pm 25 \text{ ps}$) ^a	
	P-polarization	S-polarization
1	5.5 ± 1.0	3.3 ± 0.7
2	3.0 ± 0.5	5.0 ± 1.0
3	2.7 ± 0.5	1.0 ± 0.2
4	5.3 ± 0.5	5.0 ± 1.0
5		9.0 ± 1.5
6		1.2 ± 0.3
7		1.3 ± 0.3
8		5.4 ± 1.0
9	2.5 ± 0.5	3.3 ± 0.5
10	3.2 ± 0.5	3.4 ± 0.5
11	5.9 ± 1.5	7.0 ± 1.0
12	2.9 ± 0.5	1.1 ± 0.3
13	3.8 ± 0.5	2.2 ± 0.5
14	5.3 ± 1.0	1.7 ± 0.4
15	3.6 ± 0.5	3.9 ± 0.5
16	3.3 ± 0.5	4.1 ± 0.7
Average values	3.92	3.62

^aEnergy densities are these in a plane perpendicular to the beam. Polarizers were at Brewster's angle relative to the input beam for both S and P tests.

Table 4-19. Summary of laser damage thresholds. Beam incident at 0° unless otherwise noted

Sample	A	E_{dam} (J/cm ²)	$E_{\text{no dam}}$ (J/cm ²)	E_{theory} (J/cm ²)	Comments
Silver					
LLL-Ag-7	0.010	4.0 ^b	4.0 ^b	4.8	EP/HT/DT/R
		3.9 ^c	1.6 ^c		45° P-polarization
		5.4 ^d	4.8 ^c		45° S-polarization
LLL-Ag-5	0.009	2.2 ^c	2.2 ^c	5.3	EP/HT/DT/R/C
LLL-Ag-6	0.020	0.43 ^c	0.24 ^c	2.4	EP/HT/DT/R/P/C
Copper					
LLL-Cu-78	0.01	2.0 ^b	2.6 ^b	6.5	EP/HT/DT/R
		2.0 ^c	1.6 ^c		45° P-polarization
		5.9 ^c	4.9 ^c		45° S-polarization
75y-037		2.8 ^c	2.1 ^c		EP/HT/DT/R
75y-038		2.6 ^c			EP/HT/DT/R
75y-001		0.6 ^c	0.8 ^c		DT on OFHC/R
75y-019		0.8 ^c	0.6 ^c		DT on OFHC/R
LLL-Cu-44	0.042	0.16 ^c	None	1.5	EP/DT/R/C/P/C
Baker 10	0.026	0.7 ^c	0.4 ^c	2.5	P
Spawr Cu	0.018	0.39 ^c	0.41 ^c	3.6	P

^aEP = electroplated, HT = heat-treated, DT = diamond-turned, R = rinsed, C = cleaned, P = polished.

^bData accuracy $\pm$ 20%

^cData accuracy $\pm$ 10%

^dData accuracy $\pm$ 5%

4.3.3 PULSE SHAPING

In 1975 a laboratory was established for pulse-shaping investigations.³⁶ Pulse generation and diagnostic equipment in use in the latter half of the year consisted of a passively dye-mode-locked oscillator (PMO) for short (30-250 ps) pulses, a Q-switched laser producing 1-2 ns pulses, an LLL fast streak camera ($\sim$ 10-ps resolution), electronic and optical fast-pulse diagnostics, and two-photon fluorescence (TPF) techniques. In the latter half of 1975, testing was begun on first-generation passive pulse stackers and fast Pockels cells.

Passive Pulse Stackers

Passive stacking of laser pulses that are delayed in time and of variable amplitude offers in principle the desired degree of freedom to produce arbitrary pulse shapes. In practice, temporal stacking of pulses is an interferometric process and there can be anomalous intensity fluctuations in the overlap region of stacked pulses. For this reason, initial pulse-stacking experiments were performed with a commercial Fabry-Perot (FP) etalon having two 95% reflective mirrors. The

Fig. 4-91. Damage thresholds for Inconel films as a function of film opacity.

time delay between successive pulses is given by $\Delta\tau = 2d/c$, where d is the mirror spacing. The ratio of successive pulse intensities is given by $R^2 = \alpha = 0.90$. The expected pulse shape from a simple etalon stacker is, then,

$$I(n\Delta\tau) \approx A(\Delta\tau) \exp\{-n\Delta\tau / \Delta\alpha\},$$

where $A(\Delta\tau)$ will depend on the input pulse shape. If the etalon is adjusted for constructive interference (maximum throughput) with a cw laser, then the output for the stacked pulse will be an exponentially decaying pulse. Figure 4-92 shows a streak-camera trace of the FP etalon output with a 60-ps-FWHM input pulse from the PMO and constructive interference. No anomalous intensity fluctuations are observable down to the 10-12 ps resolution of the streak camera. Figure 4-93 shows the TPF trace obtained with a different FP etalon with $\alpha = 0.23$, $\Delta\tau = 16$ ps, and a 60-ps-FWHM input pulse. In this arrangement wavelength chirp of 0.1-10 nm can be detected as a variation in the intensity autocorrelation (TPF density). No anomalous intensity fluctuations can be seen down to 1-2 ps resolution. A bandwidth-limited pulse of 60-ps-FWHM should have a width of less than 0.05 nm, which is in agreement with the above measurements. The statement can then be made that there should be no anomalous intensity fluctuations when stacking bandwidth-limited pulses of 30 ps or longer. For destructive interference (minimum cw throughput) the FP etalon output pulse is shorter than the input pulse, as would be expected.

Double-etalon pulse stackers³⁸ can produce exponentially rising and square output pulses. This configuration consists of two etalons tilted with respect to each other and to the input beam. The timing between pulses is obtained by adjusting the etalon spacings and

then tilt with respect to the input beam and to each other. Pulse intensity ratios are determined by the etalon reflectivities as outlined in the previous Annual Report.³⁸ Two different configurations of the double-etalon stacker were implemented based on two solid etalon plates and a four-mirror version. As expected the four-mirror version offered the most parameter flexibility but at the expense of increased mounting difficulties. The double-solid-etalon version was the most stable mechanically but in this first-generation test still required readjustment several times an hour for optimum performance. A more serious limitation was the optical quality of the components acquired for both versions. Solid etalons must have wedges of less than 0.5 arc-sec for this application, and surfaces of better than $\lambda/10$ total wavefront aberration are necessary to avoid spurious interference effects. The solid etalons were specified with less than 1 arc-sec wedge but had between 1.8 and 6.6 arc-sec wedge when finally delivered. The surfaces for the four-mirror configuration were specified as $\lambda/20$; the best surface was $\lambda/10$, the worst $\lambda/2$ at 0.633 nm. The surface and wedge tolerances meant that constructive interference could not be obtained for all pulses in the stack. Table 4-20 summarizes the various configurations. Figure 4-94 shows the streak-camera trace of solid-etalon pair II (square pulse $\alpha = 1$) for two different adjustments. The intensity minimum in trace (a) can be moved around in the envelope as seen in (b) but cannot be eliminated. Figure

Fig. 4-92. FP etalon output with 60-ps-FWHM input pulse, $R_1 = R_2 = 0.95$, $\Delta\tau = 33$ ps.

Fig. 4-93. FP etalon output TPF with 60-ps-FWHM input pulse, $R_1 = 0.56$, $R_2 = 0.41$, $\Delta\tau = 16$ ps, contrast ratio = 2.05 uncorrected for reciprocity.

Fig. 4-94. Double solid etalon stacker I with 60-ps-FWHM input pulse, $\alpha = 1.08$, two different alignment conditions.

Fig. 4-95. Four-mirror stacker II with 60-ps-input, $\alpha = 1.53$, exponentially rising output.

4-95 shows the output from four-mirror configuration II (exponentially rising pulse $\alpha = 1.53$). It was determined from cw monitoring that constructive interference could be arranged for only about 10 of the 14 pulses in this stacker, which accounts for the rather ragged pulse envelope. Similar results were obtained for the other configurations listed in Table 4-20.

Based on these results, pulse stacking appears very favorable for exponentially rising or square pulses of duration approximately 10 times the input pulse, provided optical tolerances and mechanical mounting stability are good. Second-generation designs for square output pulses of 300-1500 ps duration have been established based on double solid etalons with improved optical performance and stable mounts. Also considered is a configuration intermediate between solid

Table 4-20. Passive pulse-stacker test configurations

	α	I/I_0	No. of beams/ pulses	$\Delta\tau$ (ps)
FP etalons I	0.903	0.0025	—	30-150
II	0.230	.260	—	16
Solid etalons I	1.08	.0043	5	87
II	1.04	.0030	6	31
Four-mirror I	1.34	0.0030 ^a	14	19
II	1.53	0.0035 ^a	14	48

^a I_{14}/I_0

etalons and four-mirror stackers that employs two mirrors and a wedge. In this configuration each of the two etalons is formed by a mirror and one surface of the wedge. There is a reduction in the amount of glass in the beam over double solid etalons, with the ability to change pulse delays as in the four-mirror designs but without the latter's alignment complexity. Passive stackers are particularly well suited to the production of medium length (200-1500 ps) square or rising pulses.

Active Pulse Shaping

Fast Pockels Cell Switching. Previous reports have covered relatively conventional Pockels cells for use as switchouts,³⁹ isolators,⁴⁰ combinations of Pockels cells with saturable absorbers for shaped pulses,⁴¹ and refractive Pockels cell shapers.⁴² In the second half of 1975 the testing of fast Pockels cell switches was extended to cover their operation as ultrafast (<150-ps-risetime) switches for use in pulse shaping. The electronically controllable chopping out of a pulse from a longer optical pulse is a particularly attractive approach to controllable, easily varied pulse shaping.

To determine the net optical response of a particular cell and its associated electronic properties, several experiments were performed using the test configuration in Fig. 4-96. Tests of optical risetimes using the LLL fast streak camera were performed on several KD*P Pockels cells obtained from Lasermetrics as well as in-house designs. Initial data indicates that optical pulse risetimes on the order of 200-300 ps are obtainable with relatively conventional cells and electronics (laser-triggered spark gap). Further reduction in risetime may be possible because time-delay reflectometry (TDR) measurements indicate some impedance mismatch is still present in cells designed to be a 50- Ω match to the transmission lines. Several new designs for cell/transmission line structures and fast electronic pulsing schemes are currently in progress.

Amplifying Etalons. A potential candidate for applications in which the insertion loss of a pulse stacker (typically 20 dB) is prohibitive is an etalon containing a medium with gain. In an etalon having a length ℓ , index n , and mirror reflectivities R_1 and R_2 , the intensity of the n th pulse and the delay time are given by

Fig. 4-96. Ultrahigh-speed Pockels cell testing configuration.

$$I_n = (1 - R_1)(1 - R_2)(R_1 R_2)^{n-1} G^{2n-1} I_0$$

$$\Delta\tau = \frac{2n\ell}{c},$$

where G is the gain per pass in the medium. The pulse intensity ratio is given by

$$\frac{I_{n+1}}{I_n} = R_1 R_2 G = \alpha.$$

For a square output $R_1 R_2 \approx 1/G$. The device is a regenerative amplifier and must be kept from self-oscillating by a nonlinear element such as a saturable dye in the etalon cavity. We then have what is basically

a Q-switched regenerative amplifier. Such a device can be used for the production of exponentially rising pulses and for pulse stretching. A design has been implemented using a 5-cm Nd:YAG rod ($\Delta\tau = 600$ ps), a helical flashlamp, and external mirrors and is undergoing initial testing.

Other techniques for pulse shaping such as saturable and optically gated dye cells,¹³ multiple oscillator synchronization, polarization devices, and combinations of all techniques will be studied in 1976 with the goal of reliably producing shaped pulses for present and planned laser systems.

W. E. Martin
B. C. Johnson

4.3.4 FREQUENCY CONVERSION

The application of nonlinear optical processes to frequency conversion of high power lasers is being investigated. Harmonic generation can be used to increase the laser frequency, and lower frequencies can be created by stimulated Raman scattering.

Second Harmonic Generation

Angle phase-matched second harmonic generation in uniaxial crystals may be accomplished in two ways. In Type I phase matching, the second harmonic extraordinary (e) wave is generated from ordinary (o) waves at the fundamental frequency. The phase matching angle θ_1 is given by solution of the equation $n_o(\omega) = n_e(\theta_1, 2\omega)$, when $n_{o,e}$ are the refractive indices for the ordinary and extraordinary waves. The second harmonic e-wave in Type II phase matching is created by addition of o and e fundamental waves with the phase match angle θ_{II} defined by $n_o(\omega) + n_e(\theta_{II}, \omega) = 2n_e(\theta_{II}, 2\omega)$. The relative merits of Types I and II phase matching in KDP have been studied. The results are summarized in Table 4-21. On the basis of these results, the following comparison is found for the

second harmonic intensity and acceptance angle for the two types of phase matching assuming the same crystal length and fundamental beam intensity in both cases.

$$\frac{I_{II}}{I_I} = 1.7,$$

$$\frac{\Delta\theta_{II}}{\Delta\theta_I} = 1.86.$$

Type II phase matching has the additional advantage that a finished crystal of given aperture may be cut from a smaller boule than a crystal for Type I phase matching.

Third Harmonic Generation

Frequency tripling may be accomplished by a two-step process using nonlinear crystals. A portion of the fundamental is converted to the second harmonic and this beam is then mixed in a separate crystal with the remainder of the fundamental beam. The third har-

Table 4-21. Comparison of Types I and II phase matching for KDP

	Type I	Type II
Polarization rotation from fundamental	90°	45°
Phase-match angle	41.5°	59.8°
Second order susceptibility, d_{eff}	0.6589 d_{36}	0.8988 d_{36}
Acceptance angle (FWHM), $L\Delta\theta$ (rad-cm)	1.182	2.200

monic may also be generated in isotropic media, which has the advantage of less limited aperture size and absence of permanent damage to the medium should breakdown occur. Investigation of frequency tripling in alkali metal vapors directed toward achievement of high conversion efficiency is proceeding. Work by Prof. S. Harris at Stanford University on phase matching by addition of normally dispersive inert gas to the anomalously dispersive metal vapor is being supported by LLL under contract. Three systems have been studied: Na-Xe, Na-Mg, and Rb-Xe.

The best conversion efficiency to date, achieved in the Rb-Xe system, is 10% in a 50-cm length of Rb at 3 Torr, at a power density of 10^{10} W/cm².⁴³ This power density, limited by multiphoton absorption, is compatible with present high-energy glass laser systems. In studying this system, it became apparent that the efficiency was limited by breaking of phase matching caused by an intensity-dependent change in the index of refraction. This change is due to the third-order Kerr effect which at higher power levels leads to self-focusing and beam breakup in solid state lasers. Because of the sensitivity of the phase matching process, this limiting of efficiency is observed at lower levels than the more usual beam distortions.

Both third harmonic generation and the Kerr effect are third-order processes having identical functional dependencies on the experimental parameters (power density, length, and atomic density), and it would seem that little can be done to favor one over the other. There are, however, two possible approaches to higher efficiencies. The first is the relatively obvious technique of "biased phase matching," in which the Xe pressure is adjusted so that the system is phase-matched only after the Kerr effect has modified the index during the applied pulse.

The second compensation scheme makes use of the fact that Cs has a Kerr effect opposite in sign to that of Rb (and the rest of the alkali metals). Thus, the proper mixture of Cs and Rb would not exhibit the Kerr effect. An initial estimate of the required ratio of Rb to Cs is 1:3, although a complete cancellation would not be

required in most systems. The mixture also results in a reduction in the third harmonic generation nonlinear coefficient, but to a much lesser extent.

In an anomalously dispersive medium, it is also possible to obtain phase matching by the use of noncollinear beams. This method eliminates the need for addition of a second "phase-matching" vapor. In the case of noncollinear phase matching, the length over which the interaction occurs is determined by the beam diameter. Consequently, this technique is most applicable to large aperture lasers. An investigation of noncollinear phase matching is in progress at LLL.

The experiments have been performed using a passively mode-locked Nd:YAG oscillator. With appropriate mirrors and optical delays, the oscillator pulse is separated into two parallel collimated beams. These beams pass through a lens which focuses them, increasing their intensity to approximately 10^{11} W/cm², which is the limit set by multiphoton ionization in Na. The lens also recombines the beam at a fixed angle in the vapor. The Na vapor is contained in a simple open-end heat pipe whose temperature can be varied. The energy of the fundamental and third harmonic pulses is monitored by separated photomultipliers. The photomultiplier pulses are sent to a Tektronix R7912 Fast Transient Digitizer. The results are processed by a PDP 11 computer which also receives a measurement of the Na vapor temperature. This technique allows the phase-match tuning function to be plotted directly as a function of cell temperature.

Stimulated Raman Scattering

Further theoretical analysis has been made of the previously reported observations of self-induced gain and loss modulation of the Raman-Stokes and laser pulses in hydrogen gas.⁴⁵ The effect is the result of coherent transient response of the material polarization and plays an important role in the propagation of high-intensity, short-duration laser pulses through Raman-active media.⁴⁶

4.3.5 PROPAGATION

Aberrations Affecting the Beam as a Whole

Experimental Observations

Turbulence. During initial operation of the Cyclops laser as a target irradiation facility, large temporal intensity fluctuations with a frequency on the order of 10 Hz were observed in the target illumination plane when using a cw alignment laser. These fluctuations

are considerably reduced by installation of closed plastic beam pipes with plastic junction boxes from the output of the last amplifier to the target chamber. To prevent lower frequency drift due to stratification of the gas in the tubes, it is necessary to stop the flow of N₂ cooling gas from the final amplifier into the laser end of the beam tube 15 min or more before starting alignment so that the gas composition and temperature in the tubes

can equilibrate. These results emphasize the need for optimizing not only the optical quality of the glass in a large laser system but also the optical properties of the atmosphere through which the beam propagates.

E. S. Bliss
F. Rainer
J. A. Glaze
K. R. Manes

Static and Thermally Induced Distortions. The passive optical quality of the Cyclops laser chain has been measured using a radial-shear, local-reference interferometer.¹⁷ The interferogram in Fig. 4-97a, taken with the cw alignment beam, shows the wave-front distortion to be approximately 1/2 wave at 1.06 μm over the central 80% of the beam, with a large part of that coming from spherical aberration generated by the spherical spatial filter lenses. The interferogram in Fig. 4-97b, taken with all the amplifiers pumped and a weak 100-ps pulse propagating through the system, demonstrates that the optical quality of the passive system is preserved for low-power, but full-gain, pulsed operation.

These very encouraging results are modified when the system is not in thermal equilibrium, as is the case for a period of at least several hours after a shot, for example. The aberrations which result from thermal distortion are illustrated by the photographs in Fig.

4-98, which were obtained by using a mirror pair and a system of lenses to obtain images of successive planes in the focal region of the vacuum spatial filter. The images in the figures are of planes in the spatial filter separated by 0.43 mm along the beam direction, starting on the oscillator side of the aperture at the left in the figure. The ratio of energies in successive images is 86%. The circles show the position and relative size of the 305- μm pinhole. Figure 4-98a shows the residual astigmatism of the "cold" system, and 4-98b a case where the thermally induced astigmatism has fortuitously cancelled this residual. However, some thermally induced coma is apparent. In Fig. 4-98c strong thermally induced astigmatism dominates all other distortions, making it obvious that a capability for shot-to-shot, real-time compensation for thermal changes is desirable.

J. E. Murray
G. E. Sommargren
F. Rainer
E. S. Bliss

Shot-to-Shot Compensation. Since the largest component of the residual and thermal aberrations in large disk amplifiers is astigmatism, adjustable cylinder-lens pairs were obtained. Their position in Cyclops, for example, is shown in Fig. 3-10. They have a range of approximately ± 9 waves of astigmatism and are ad-

(a) Passive system

(b) Amplifiers pumped

Fig. 4-97. Interferograms of the complete Cyclops amplifier chain taken (a) with a cw laser beam through the passive Cyclops system, and (b) with a weak laser pulse through the fully pumped system.

(a) First shot of the day

(b) 165 min after three shots at 45-min intervals

(c) Second shot after (b), with 30-min firing interval

Fig. 4-98. Thermally induced aberrations as detected near the focal point in the Cyclops vacuum spatial filter.

justed on a shot-to-shot basis when necessary. The high quality of the lenses, fabricated in the LLL Optics Shop, is shown in the interferograms of Fig. 4-99. Figure 4-99a shows the cylindrical power of one of the lenses, and 4-99b the nearly neutral effect when the two lenses are positioned with their cylindrical axes crossed. In 4-99b the spherical contribution of the crossed pair has been removed by a compensating adjustment of the Twyman-Green interferometer. The sum of the errors in cylindrical figure for the two lenses at a diameter of 9 cm is less than $\lambda/8$ at $1.064 \mu\text{m}$.

Experience on Cyclops and Janus has led us to the conclusion that adjustable wavefront compensators, similar in their ease of operation to the cylinder lenses

but capable of compensating for a much greater variety of aberrations, must be developed. A multielement refractive corrector looks promising.¹⁸

J. E. Murray
G. E. Sommargren

Whole-Beam Self-Focusing, Focal Zoom. Self-focusing effects have been discussed for many years and documented in varying detail. Final data reduction from an experiment described earlier^{49,50} has provided unambiguous time-resolved records of dynamic whole-beam self-focusing. In this experiment a high-

(a) One cylinder lens

(b) Two lenses with axes crossed

Fig. 4-99. Cylinder lenses used for compensation of astigmatism have high optical quality as seen in these $0.633\text{-}\mu\text{m}$ Twyman-Green interferograms.

intensity $1.06\text{-}\mu\text{m}$ laser pulse is propagated through a glass rod and focused by a plano-convex lens. An image of the beam profile in a plane just ahead of the low intensity focus is relayed simultaneously to a 10-ps -resolution streaking camera³¹ and to a conventional $I\text{-}Z$ film plate.

The time-integrated far-field photographs typically show a central bright spot surrounded by concentric rings of gradually decreasing intensity and rather low contrast as seen in Fig. 4-100. The central maximum and the rings are also detected on the streak camera, which is aligned to record the temporal development of a radial slice through the far-field intensity distribution in the same image plane. The streak camera photograph in Fig. 4-100 shows that the rings have an intensity-dependent radius with the smallest radius occurring at the temporal peak of the pulse. The useful dynamic range of the camera has been increased by use of a filter with optical density 1.35 in the central, most intense part of the image.

The formation of these rings, and the details of their motion, can be accurately predicted by calculations of the self-focusing properties of the beam as a whole. Using a nonlinear optical-ray-tracing code for propagating the initially Gaussian spatial intensity profile through the glass sample³² and a linear diffraction code for propagating the resulting distorted beam through the lens to the focus,³³ we have generated constant-intensity contour plots of the focal region for a range of input intensities. Figure 4-101 shows the focal region for an accumulated phase delay on the beam axis of 1.5λ , which corresponds to the peak input intensity reached by the pulse in Fig. 4-100. The beam comes from the left, and in the region ahead of the focus the intensity contours confirm the presence of several diffraction rings, which are identified by solid dark lines.

In the inset of Fig. 4-101 the radial position of each ring in the plane indicated by the dashed line is plotted (o) both for the 1.5λ calculation and for 1.0λ . On the same plot are the corresponding ring positions measured on the streak picture in Fig. 4-100 (x) at peak intensity and $2/3$ peak intensity. The shift in the radial position of a given ring as the intensity is changed results from the combined effects of intensity-dependent aberrations and intensity-dependent focal position, the point of best focus being drawn closer to the lens as the intensity increases. If an image plane more than 12 cm farther from the focusing lens had been chosen for the experiment, the contour plot shows that an on-axis minimum would have been observed at the peak of the pulse, and such on-axis reductions have been previously reported.³⁴ It is important to recognize, however, that the effects of whole-beam self-focusing on beam focusing properties depend strongly on the plane being observed and, of course, on the radial

Fig. 4-100. Time-integrated and time-resolved far-field photographs in a plane slightly ahead of best focus. The time-resolved photo (made with a streak camera) records the temporal development of a radial slice through the intensity distribution in the same plane as the time-integrated photo (made with a conventional I-Z film plate). The streak camera photo shows clearly the intensity dependence of the diffraction ring diameters.

intensity and phase profiles of the initial beam.⁵⁵

The effect of these dynamic profile changes must be considered when large solid-state lasers are used to irradiate fusion targets. Accordingly diagnostics on the Cyclops laser, for example, include a capability for time-resolved monitoring of the beam profile in a plane equivalent to the target plane.

E. S. Bliss
J. T. Hunt
P. A. Renard
G. E. Sommargren

Modeling of Whole-Beam Aberrations

Useful Analytic Expressions for Semi-Quantitative Modeling. The simplest model possible for predicting the effect of low-order thermal and static phase distortions on the focusing properties of a beam is obtained by assuming that the amplifier disks act as weak,

imperfect lenses. Although this is an obvious oversimplification, calculations using ray optics and low order phase distortions produce intensity patterns in the vicinity of the fusion target that have the same general features as the patterns that have been measured in our laser systems.

The phase distortions we consider with their respective radial and azimuthal dependences are: Defocus $\propto \beta_1 \rho^2$, spherical $\propto \beta_2 \rho^2(1 - \rho^2)$, astigmatism $\propto \beta_3 \rho^2 \cos 2\theta$, and coma $\propto \beta_4 \rho^3 \cos \theta$. Here $\rho = r/a$, and the quantities β_i are the maximum distortion of the wave front in waves.

The effect of defocus is to shift the "best" focus of the beam by an amount Δz , given by

$$k\Delta z/(f\text{-number})^2 = 16\pi\beta_1. \quad (11)$$

If the beam is observed in a fixed plane forward of the diffraction focus the radius of the beam (determined by

Fig. 4-101. Calculated constant-intensity contours in the focal region for an accumulated on-axis phase delay of 1.5 wavelengths. The solid dark lines identify the positions of diffraction rings. Inset plot shows close agreement of the calculated (o) and measured (x) diffraction ring radii in the plane imaged in Fig. 4-100 for accumulated phase delays of 1.0 and 1.5 wavelengths.

the marginal ray) in this plane will change. The radius change in waves is

$$\Delta r = -4(f\text{-number})\beta_1. \quad (2)$$

This feature of a changing beam size is observed in fusion laser systems when the amplifiers have not been allowed sufficient time to cool between shots.

Another common feature observed in the laser system is a "doughnut"-shaped beam in target planes between the lens and its focal plane. This characteristic shape is the result of off-axis ray crossings caused by spherical aberration, and the distance z from the focal plane to the plane in which a ray crosses its neighbor is given by

$$kz/(f\text{-number})^2 = -64\pi\beta_2(1 - 6\rho^2). \quad (3)$$

The complete set of ray crossings described by Eq. (3) produces an off-axis caustic surface of revolution. A similar expression,

$$kz/(f\text{-number})^2 = -64\pi\beta_2(1 - 2\rho^2), \quad (4)$$

gives the positions at which on-axis ray crossings occur. These correspond to on-axis maxima and have also been observed experimentally.

In the vicinity of the fusion target, astigmatism tends to reshape the circular beam into an elliptical beam. If the phase distortion is pure astigmatism, the beam will exhibit two line foci in the neighborhood of

the focal plane of the lens. These line foci occur at a distance

$$k\Delta z/(f\text{-number})^2 = 16\pi\beta_1 \quad (5)$$

on either side of the focus.

The effect of coma is to make the beam "lopsided." This lopsidedness is caused by the rays on one side of the beam crossing before the rays on the opposite side of the beam. A geometrical calculation shows that the marginal ray on one side of the beam crosses in front of the focus whereas the corresponding ray on the other side of the beam crosses behind the focus. The planes in which these ray crossings occur are

$$k\Delta z/(f\text{-number})^2 = \pm 48\pi\beta_1 \quad (6)$$

Finally, we consider the effect of nonlinear phase distortion accumulated by the beam in traversing the laser. If the constant shape approximation is assumed, the number of waves of nonlinear phase retardation accumulated by the beam at the final focusing lens is

$$\Delta\delta = \int [\Delta n_0/\lambda] dz F(\rho) = (B/2\pi)F(\rho), \quad (7)$$

where Δn_0 is the nonlinear index change on-axis, λ is the laser wavelength in vacuum, and $F(\rho)$ is the normalized transverse intensity profile. If the profile is quadratic or close to it, then the only effect of the nonlinear phase distortion is to cause a time-dependent shift of the focus of the beam. For a modified quadratic intensity profile,⁵⁶ the only modification of Eqs. (1)-(2) that is needed to obtain the dynamic focal shift and the change in the beam radius is to scale $\beta_1 = B/2\pi$ by the splice point b . (This profile for the specific case $b = 0.79$ is described in Ref. 56.) Hence,

$$k\Delta z/(f\text{-number})^2 = 8B/b, \quad (8)$$

$$\Delta r = 2B(f\text{-number})/\pi b. \quad (9)$$

For an intensity profile other than quadratic, distortion of the beam also occurs. For example, if the intensity profile is super-Gaussian,⁵⁶ one finds that the defining feature of the associated phase distortion is to cause a doughnutlike structure similar to that exhibited by a beam possessing spherical aberration.⁵⁵

J. T. Hunt

Detailed Modeling in the Presence of Several Simultaneous Low-Order Aberrations and Whole-Beam Self-Focusing. Beams possessing a combination of static low-order phase distortions focus to rather complicated profiles in the neighborhood of the fusion target.

These profiles can be determined in detail only by computer calculations.⁵³ For example, a combination of astigmatism and spherical phase distortion causes the annular regions of an otherwise axisymmetric beam to break up, concentrating the energy of the annulus at two points along the line $y = 0$. The extent of this breakup depends on the viewing plane and the relative amounts of the two distortions. Figure 4-102 shows the focused profile of an $n = 5$ super-Gaussian beam in the plane $kz/(f\text{-number})^2 = 290$ with 1.25 waves of spherical aberration and two waves of astigmatic phase distortion. The two insets in this figure are one-dimensional scans of the intensity distribution along the x and y axes with the diffraction-limited profile shown by dashed lines for comparison. Similarly, the focused pattern resulting from one wave of spherical distortion and one wave of coma is shown in Fig. 4-103. These calculations show that an intensity differential of 50% across the beam is possible.

When nonlinear phase distortion and static aberrations are both present, the beam size changes at the target as a function of time as it does for an unaberrated beam, but in addition, the details of the intensity distribution also change. For example, Fig. 4-104 is the intensity profile exhibited at the peak of the pulse by a beam possessing two waves of astigmatism, one wave of spherical aberration, and one wave of nonlinear phase delay on-axis. Comparison with Fig. 4-102, which is the profile of the same beam with $\Delta n = 0$, shows that the beam has decreased in size and changed its intensity distribution.

From the foregoing discussion we conclude that static and dynamic phase distortions have pronounced effects on the beam quality at or near the fusion target. The static phase distortions can in principle be removed by phase correction devices, and the effects of nonlinear distortion on the focused profile are minimized by use of a quadratic intensity profile in the laser. The effects of all of the whole-beam phase distortions are reduced by increasing the f -number of the final focusing lens.

J. T. Hunt
P. A. Renard

Propagation Properties of Small-Scale Structure

Experimental Observations

Dominant Spatial Frequencies. During operation of the Cyclops system over the last year, a large number of near-field beam photographs have been taken at various places in the amplifier chain. Some representa-

Fig. 4-102. Focused intensity distribution in the plane $kz/(f\text{-number})^2 = 190$ for an $n = 5$ super-Gaussian beam having 1.25 wavelengths of spherical aberration and 2.5 wavelengths of astigmatism. The cross-section plots compare the intensity profile of the aberrated beam with the diffraction-limited intensity profile along the two transverse axes $kx/f\text{-number}$ and $ky/f\text{-number}$.

Fig. 4-103. Focused intensity distribution in the plane $kz/(f\text{-number})^2 = 290$ for an $n = 5$ super-Gaussian having 1.25 wavelengths of spherical aberration and 1.0 wavelength of coma. The cross-section plots compare the intensity profile of the aberrated beam with the diffraction-limited beam along the two transverse axes $kx/f\text{-number}$ and $ky/f\text{-number}$.

Fig. 4-104. Focused intensity distribution in the plane $kz/(f\text{-number})^2 = 290$ for an $n = 5$ super-Gaussian having 1.25 wavelengths of spherical aberration, 2.5 wavelengths of astigmatism, and 1.0 wavelength of nonlinear phase distortion. The cross-section plots compare the intensity profiles of the aberrated beam and the diffraction-limited beam along the two transverse axes $kx/f\text{-number}$ and $ky/f\text{-number}$.

Fig. 4-105. Near-field distortion of beam profile results from beam breakup when a beam with high spatial-frequency modulation in the region near its center is passed through a spatial filter.

tive examples are shown in Fig. 3-11. From such photographs one can make some general observations about the spatial frequency content of the beam at various points in the system. For example, at the output of the B amplifiers, the most obvious structure has characteristic dimensions of about 2 mm. In the spatial filter, these high frequencies are removed, and the full size beam in the C amplifiers starts out with weak structure having characteristic dimensions of approximately 20 mm. By the time the beam reaches the end of the chain, however, a fairly strong component with dimensions of 5 mm is observed.

The apparent dominance of different spatial frequencies in different sections of the system is related to such things as the size and number of noise sources, the intensity levels, and the distribution of components (e.g., disk thickness and spacing). No detailed inferences have yet been drawn from the data described above, but the lower frequency content of the output from the more widely spaced C amplifier disks compared to that from the more closely packed B amplifier disks suggests that diffraction has caused the self-forming gain peak to shift to lower spatial frequencies³⁷ (discussed later in this section).

E. S. Bliss
F. Rainer

Effects of Beam Breakup on Near-Field and Far-Field Spatial Profiles. In an amplifier chain containing spatial filters, the near-field intensity profile immediately following a filter is not only smoother, it is also distorted by preferential depletion of those regions which contained the most small-scale structure at the

filter input. Figure 4-105 illustrates this effect. The midchain spatial filter in Cyclops has preferentially removed energy from the central part of the beam where beam breakup was most pronounced. The extent of this profile distortion varies with time as the pulse intensity rises and falls on each shot, and this scan of a near-field photograph is the time-averaged result.

In the far field the overall profile is not dramatically changed by beam breakup,^{49,50} because the scattered light is spread over a large area at relatively low intensity. The time-integrated far-field picture in Fig. 4-106 has been intentionally overexposed on the beam axis in order to record light with several orders of magnitude lower intensity at large radii. As a result, the central ring pattern is not visible and is drawn in schematically. Now at radii corresponding to scattering angles as large as 4 mrad, blotches of light are seen which, when integrated over the extremely large area involved, can account for a significant portion of the total beam energy if the system is driven too hard.

E. S. Bliss
F. Rainer
L. D. Thorson
G. E. Sommargren

Effects of Beam Breakup on Temporal Profiles. The streak camera picture in Fig. 4-106 is taken on the same shot and demonstrates that the high-divergence components of the far-field energy distribution are coming from the temporal peak of the pulse as well as from the spatial peak. The on-axis intensity, as determined by a densitometer scan with appropriate allowance for camera and film response characteristics,⁵⁸ behaves in an apparently normal fashion as a function of time except near the time corresponding to the peak of the input pulse when losses from the center of the far-field pattern suddenly increase and light appears at an angle of about 1.5 mrad. From the time-integrated photo, it seems quite plausible that a blotch of light could fall on the streak camera slit at 1.5 mrad, and we believe that all of the energy in the rather random pattern of large-angle light is generated in the same way; namely, by being scattered during beam breakup in the high intensity parts of the pulse. Two-photon absorption has been considered as an additional loss mechanism; however, earlier measurements in ED-2 have shown the intensity-dependent absorption to be less than 10% at the maximum intensity used here,³⁹ and some portion of that 10% may actually have been due to beam breakup.

Loss from beam breakup is observed in varying degrees over a range of peak B values, and the depletion of the temporal peak of the pulse can be quite

Fig. 4-106. Time-integrated and time-resolved far-field photos at a plane slightly ahead of best focus. The exposure levels are chosen to show the energy scattered out of the central part of the beam at angles on the order of milliradians. The time-resolved photo confirms that the scattered light appears predominantly at the peak of the pulse and that depletion of the on-axis intensity occurs at the same time.

severe. For the pulse in Fig. 4-107, for example, the power in the central $12\text{ }\mu\text{m}$ of the focused beam is reduced to less than 20% of its expected value at the peak of the pulse, with smaller but significant losses being measured as the streak photograph is integrated over larger apertures. It has been stated, based on calculations using a formalism appropriate for small perturbations on the beam, that losses resulting from beam breakup cannot exceed 45%,⁴⁰ but these calculations cannot be expected to apply to the advanced stages of self-focusing. In fact, the large loss and the steepness of the time-resolved focusable-fraction-vs-B curve in Fig. 4-107 suggest that there is no real limit on the extent to which focusing can be degraded by small-scale beam breakup in a rod. In extreme cases essentially all of the power can be scattered out of the primary beam and become unfocusable for fusion-size targets.

The time-resolved power focused inside the $12\text{-}\mu\text{m}$ aperture is actually influenced by both whole-beam and small-scale self-focusing. Initially, as the intensity of the input pulse increases, whole-beam self-focusing draws the point of best focus toward the lens, thus enhancing the measured on-axis intensity in a plane

ahead of the low intensity focus. As the input intensity continues to rise, however, high angle losses from beam breakup increase abruptly and dominate the focusing properties for large B values. A feature of Fig. 4-107 not yet understood is the leading and trailing edge asymmetry of the power-vs-time curves. This asymmetry may not be real, and may simply be an indication of the amount of uncertainty inherent in the experiment. On the other hand, it has been seen on several shots and the sense of the asymmetry has never been reversed. In plotting the focused-fraction curves for Fig. 4-107 the leading and trailing edges of the pulse have been averaged.

As noted previously^{49,50} these properties of high-power solid-state lasers must be monitored and accounted for when performing target experiments. Target laser diagnostics must, for example, include streak camera examination of the pulse being directed to the target as described in Sec. 3.2.1.

E. S. Bliss
G. E. Sommargren
H. J. Weaver

Fig. 4-107. Temporal distortion and loss of focusability due to small-scale self-focusing. (a) An example of severe temporal distortion of the light transmitted through two aperture sizes. Since the focal length of the lens is 1 m, the apertures could also be labeled as $12\text{ }\mu\text{rad}$ and $750\text{ }\mu\text{rad}$. (b) Corresponding plots of the fraction of the pulse power focused through the apertures as a function of the breakup integral $B = \int_0^L (2\pi\gamma l/\lambda_{vac}) dz$ where $\gamma \equiv \Delta n/L$.

Modeling of Small-Scale Self-Focusing

Focusability as a Function of Structure Size. After passing through a laser amplifier and a focusing lens, a high-power laser pulse has a scalar electric field of the form

$$\psi = e^{-ik(z - r^2/2f)} A(r) e^{ik\phi} \left[1 + \sum_n \alpha_n \exp(i\vec{K}_n \cdot \vec{r}) \right]. \quad (1)$$

In this expression $(z - r^2/2f)$ is the phase that a diffraction-limited beam would possess, where f is the focal length of the lens; r and z are the radial and longitudinal coordinates; $A(r)$ is the primary or whole-beam amplitude profile; $\phi(r, \theta)$ is the whole-beam phase distortion resulting from static, thermal, and nonlinear aberrations; and the set of functions $\alpha_n \times \exp(i\vec{K}_n \cdot \vec{r})$ represents the small-scale structure on the beam. In Eq. (1) it is assumed that the f -number of the lens is large enough that paraxial optics is applicable.

For sufficiently small α_n , Eq. (1) describes a primary beam and a set of secondary beams. The propagation directions of the secondary beams are different than that of the primary beam. This difference in propagation direction results in interference between the primary and secondary beams which in turn produces an intensity modulation of the primary beam. The peak-to-peak magnitude of the modulation caused by a single component of the secondary beam is $4\alpha_n$. As the beam moves toward the focal plane of the lens, the secondary beam separates from the primary beam. The angle between the propagation direction of the primary beam and the n th component of the secondary beam is K_n/k . In the focal plane of the lens the diffraction pattern for any single component of the secondary beam is identical to that of the primary beam but is reduced in intensity by $|\alpha_n|^2$ and centered a distance $d = (K_n/k)f$ from the primary beam.

To assess the effect of small-scale structure on the whole beam, we must relate the "structure size" at the lens to a representative spatial frequency K . Nodal lines of the intensity modulation in the lens plane are defined by the equations

$$\cos \vec{K} \cdot \vec{r} = 0, \quad K_x = \pm \frac{2\pi\alpha}{a}, \quad K_y = \pm \frac{2\pi\beta}{a}. \quad (2)$$

where a is the radius of the primary beam. In other words, $\vec{K} \cdot \vec{r} = (N + 1/2)\pi$. These lines form a regular grid at the lens with maxima and minima as shown in Fig. 4-108. If we define the "structure size" to be the radius of a circle whose area equals the area of the cells outlined in the figure; i.e.,

$$r_0 = \sqrt{1/(8\pi\alpha\beta)} a, \quad (3)$$

we are in a position to construct a simple model for estimating how much of a certain size small scale structure will strike a given size target.

From the expression for d above and Eq. (3), the minimum distance between the center of the primary beam and a secondary beam with an associated structure size r_0 occurs when $\alpha = \beta$ and is given by

$$\left| \frac{kd}{f\text{-number}} \right|_{\min} = \sqrt{4\pi} a/r_0, \quad (4)$$

where $f\text{-number} = f/2a$. Hence, if the primary beam is focused to a diameter D in the target plane, the secondary beam will completely miss that part of the target when

$$\frac{r_0}{a} \leq \frac{\sqrt{4\pi} (f\text{-number})}{kD}. \quad (5)$$

Fig. 4-108. Intensity modulation grid for small-scale structure with spatial frequency $K_x = 2\pi\alpha/a$, $K_y = 2\pi\beta/a$, where a is the radius of the primary beam.

Fig. 4-109. Percentage of the secondary beam which focuses within the primary focusing diameter is proportional to the overlap between the two beams.

For many of the recent target experiments on Cyclops, this means that energy associated with r_0 values less than 2 mm misses the target completely. This is consistent with the experimental estimates of the focusing properties of the Cyclops beam presented above.

For structure with larger characteristic dimensions, we can estimate what percentage of the secondary beam focuses within the primary focusing diameter D . Figure 4-109 is a diagram showing the overlap between the primary and secondary beam. If we assume the focused profile has uniform intensity out to its edge, then the fraction F of the secondary beam that strikes the target is proportional to the area of overlap of the two beams. Therefore, for θ in radians,

$$F = \frac{2}{\pi} \left(\theta - \frac{1}{2} \sin 2\theta \right), \quad (6)$$

$$\text{where } \cos \theta = (f\text{-number})(\lambda/\sqrt{\pi} D)(a/r_0).$$

J. T. Hunt

Theory of Irregularity Growth on Laser Beams.

Because of the importance of understanding the growth of small intensity irregularities on high-power laser beams, the small-signal analysis of perturbations on a plane wave (reported in last year's annual) has been simplified and extended, and two computer programs have been written to numerically model structures similar to actual laser amplifiers. As a result, we now have a greater understanding of the growth of the large-scale irregularities which cannot be spatially filtered and thus set the limit on the power obtainable from a short-pulse laser system.

Small-Ripple Theory. We write the electric field of a laser beam as

$$\bar{E} = \hat{p} \sqrt{2} \operatorname{Re} (E e^{-i\omega t}),$$

where $\hat{p}$ is a polarization vector and E is a complex scalar field which gives the rms value of the field. If we use an expansion about a plane wave propagating along the z axis, then

$$\Psi = E e^{ikz}$$

and Ψ obeys the paraxial equation

$$\frac{\partial \Psi}{\partial z} = \frac{i}{2k} \nabla^2 \Psi + ik\mu \Psi,$$

where k is the average wave number

$$k = \frac{2\pi}{\lambda}$$

and μ is the fractional change in k due to intensity-induced refractive index changes.

We have

$$\mu = \frac{\delta n}{n} = \frac{n_2 I}{n} = \frac{n_2 \Psi^* \Psi}{n}$$

so that the paraxial equation is

$$\frac{\partial \Psi}{\partial z} = \frac{i}{2k} \nabla^2 \Psi + \frac{ikn_2}{n} \Psi^* \Psi.$$

The field is written as one strong wave plus a number of small ripple modes.

$$\Psi = C \left[1 + \sum_i a_i(z) e_i(x, y) \right],$$

where the mode eigenfunctions are real and obey

$$\nabla^2 e_i + \alpha_i^2 e_i = 0.$$

As long as the ripples are small, so that

$$\sum_i a_i e_i \ll 1,$$

the coefficients a_i are all independent and obey the differential equations

$$\frac{\partial a}{\partial z} = \frac{i\sigma^2}{2k} a - 2ik\mu \operatorname{Re}(a)$$

in which the μ is that due to the strong wave alone.

If we separate the coefficient a into real and imaginary parts,

$$a = u + iv,$$

then the complex differential equation for a becomes two coupled real equations:

$$\frac{du}{dz} = -\frac{\sigma^2 v}{2k}$$

and

$$\frac{dv}{dz} = \left(\frac{\sigma^2}{2k} - 2k\mu \right) u.$$

Taking the derivative of the first equation and substituting from the second, we get

$$\frac{d^2 u}{dz^2} = \left(\sigma^2 \mu - \frac{\sigma^4}{4k^2} \right) u,$$

which in a slab where the intensity is constant has solutions

$$u = C_1 e^{\beta z} + C_2 e^{-\beta z},$$

where

$$\beta = \sigma \sqrt{\mu - \frac{\sigma^2}{4k^2}}$$

The coefficients are not free, but are determined by the initial values of u and v as

$$C_1 = \frac{1}{2} \left(u_0 - \frac{v_0}{S} \right),$$

$$C_2 = \frac{1}{2} \left(u_0 + \frac{v_0}{S} \right),$$

where

$$S = \sqrt{\frac{4k^2 \mu}{\sigma^2} - 1}.$$

In a slab of length L we thus find that

$$u = u_0 \cosh \beta L - v_0 \frac{\sinh \beta L}{S},$$

$$v = -u_0 S \sinh \beta L + v_0 \cosh \beta L.$$

These relations become clearer if we write them in terms of the mode vacuum diffraction angle

$$\Theta = \frac{\sigma^2 L}{2k}$$

and the B-integral through the slab,

$$B = k\mu L,$$

in which case we find

$$S = \sqrt{\frac{2B}{\Theta} - 1}$$

and have

$$u = u_0 \cosh \Theta S - v_0 \frac{\sinh \Theta S}{S},$$

$$v = -u_0 S \sinh \Theta S + v_0 \cosh \Theta S.$$

In vacuum B is zero and so $S = i$, in which case

$$u = u_0 \cos \Theta - v_0 \sin \Theta,$$

$$v = u_0 \sin \Theta + v_0 \cos \Theta,$$

which is just a rotation of the original complex mode coefficient a through an angle Θ in the complex plane. As B increases, the rotation rate becomes smaller and the coefficient traces out ellipses rather than circles. Finally, when B becomes large enough the trajectory becomes a hyperbola and large growth can take place.

The ripple amplitude due to any one mode is $a + a^* = 2 \operatorname{Re}(a)$, and the power is $a a^*$. To see how the mode power changes going through a slab, we can write the real and imaginary parts of a as a vector,

$$\vec{w} = \begin{pmatrix} u \\ v \end{pmatrix},$$

so that the slab transformation is

$$\vec{w} = \vec{M} \vec{w}_0$$

with the transformation matrix

$$\vec{M} = \begin{bmatrix} \cosh \Theta S & -\frac{\sinh \Theta S}{S} \\ -S \sinh \Theta S & \cosh \Theta S \end{bmatrix}.$$

The power gain of a mode through the slab is then

$$G = \frac{\vec{w} \cdot \vec{w}}{\vec{w}_0 \cdot \vec{w}_0} = \frac{\vec{M} \vec{w}_0 \cdot \vec{M} \vec{w}_0}{\vec{w}_0 \cdot \vec{w}_0} = \frac{\vec{w}_0 \cdot \vec{M}^T \vec{M} \vec{w}_0}{\vec{w}_0 \cdot \vec{w}_0}$$

Since $\vec{M}^T \vec{M}$ is a symmetric matrix (note that $\vec{M}$ is not!) the maximum and minimum gains are equal to the eigenvalues of $\vec{M}^T \vec{M}$. In any matrix, the product of the eigenvalues is equal to the determinant and the sum of the eigenvalues is equal to the trace. The determinant of $\vec{M}$ is unity, and so the determinant of $\vec{M}^T \vec{M}$ is also. Thus the product of the two eigenvalues is unity, so that the minimum mode gain is the inverse of the maximum. The trace of $\vec{M}^T \vec{M}$ is the sum of the squares of the elements of $\vec{M}$, so the trace is

$$T = 2 + \left(\frac{2B \sinh \Theta S}{\Theta S} \right)^2$$

and the power gains (eigenvalues) are

$$G_{\pm} = \frac{T}{2} \pm \sqrt{\left(\frac{T}{2} \right)^2 - 1}$$

The eigenvectors corresponding to these gains are 90° apart because $\vec{M}^T \vec{M}$ is symmetric. Thus modes striking the slab with coefficient phases separated by 90° suffer maximum gain or loss. If the elements of $\vec{M}$ are

$$\vec{M} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$$

then the angles of maximum and minimum gain are

$$\phi_{\pm} = \frac{G_{\pm} - (M_{11}^2 + M_{12}^2)}{M_{11}M_{12} + M_{21}M_{22}},$$

as we may find by solving for the eigenvectors. If a mode comes into the slab with its coefficient at an angle δ from the angle of maximum gain, then we find (by decomposing along the eigenvectors) that the gain is

$$G = \frac{(G_+^2 - 1) \cos^2 \delta + 1}{G_+},$$

and so if modes strike with random phase the average gain is

$$\begin{aligned} G_{av} &= \frac{2}{\pi G_+} \int_0^{\pi/2} [(G_+^2 - 1) \cos^2 \delta + 1] d\delta \\ &= \frac{G_+^2 + 1}{2G_+}. \end{aligned}$$

Note that for large gain, the average power gain is half the maximum.

In a series of slabs, some of which may be vacuum, each slab has its own transformation matrix and the result of all the slabs is just the product of the matrices. Since each matrix has a determinant of unity, the whole system also has unit determinant. The expressions given above thus all apply, except that the trace is complicated and must be found as the sum of the squares of the elements of the product matrix.

Numerical Calculation of Mode Power Gains. A computer program has been written to find the maximum power gain G_+ and the corresponding mode coefficient angle ϕ_+ for complicated systems of slabs and vacuum gaps, in an attempt to model the behavior of actual disk amplifiers. The model should be thought of as representing a uniform-intensity patch of the beam, since changes in background intensity cannot be allowed for. In addition, the tilted disks in an amplifier are represented by slabs perpendicular to the beam, and the intensity of the beam is constant through a slab instead of exponentially increasing. Even with these limitations, the program supplies very useful guidance in understanding the patterns observed in laser propagation experiments.

The gain of a ripple in a slab is specified completely by the breakup integral B in the slab, and by the ratio of the mode eigenvalue to the slab's cutoff eigenvalue. The cutoff eigenvalue is the point at which the growth equations switch from oscillatory to exponentiating solutions, and has the value

$$\sigma_c = 2k \sqrt{\mu}.$$

The mode vacuum diffraction angle in the slab is

$$\theta = \frac{\sigma^2 L}{2k} = \left(\frac{\sigma}{\sigma_c} \right)^2 \frac{L \sigma_c^2}{2k} = 2BR^2,$$

where we have used the fact that

$$B = k\mu L$$

and defined the eigenvalue ratio

$$R = \frac{\sigma}{\sigma_c}.$$

Thus from B and R we can find θ and therefore S , so that the transformation matrix for the slab is completely defined.

A subsequent vacuum region has a diffraction angle

$$\phi = \frac{\sigma^2 V}{2k},$$

where V is the length of vacuum, which we can write as

$$\phi = Q\theta,$$

where we define

$$Q = \frac{V}{L}.$$

Thus only the ratio of vacuum to slab length is important.

The computer program calculates the transformation matrices for a sequence of slabs and vacuum spaces from the above formulas. A total amount of B is distributed uniformly among the slabs. A length of vacuum specified as a given ratio times the length of solid is distributed between the slabs. The vacuum

spacing between slabs can alternate between two values to partially simulate the effect of alternately tilting disks in a laser amplifier.

Figure 4-110 shows some typical results. Here we see ripple gains as a function of initial mode coefficient phase angle, the angle for which the gain is largest, and the corresponding maximum gains. In Fig. 4-111, the effect of holding B constant at 3 while the number of slabs is varied is shown. More and more complicated oscillations appear on the maximum gain as the effects of successive slabs go in and out of phase. The result is that the gain for large eigenvalues (small ripples) tends to decrease on the average while small eigenvalues (large ripples) diffract slowly between slabs and are relatively unchanged. In particular, the gain limit for very large ripples,

$$G_+(0) = 1 + 2B^2 (1 + \sqrt{1 + B^2}),$$

Fig. 4-110. Ripple gain as a function of initial mode coefficient phase angle, the angle for which the gain is largest, and the corresponding maximum gains. Breakup, 3.0; vac/sol ratio, 6.0; first vacuum fraction, 0.20; six slabs. (a) Ripple power gain through six slabs of alternating spacing, as a function of the initial phase angle of the mode coefficient. Curves are shown for various mode eigenvalues. Note that gain is much more likely than loss, so that ripples arriving with random phase will probably be increased in power. (b) Variation of the mode coefficient angle of highest gain as the eigenvalue is increased. The plot is in terms of the ratio of the eigenvalue to the Bessel-Talanov cutoff eigenvalue. (c) The ripple power gain at the maximum-gain angle. Also shown is the Bessel-Talanov gain coefficient. Note that the mode power can increase both for small ripples above the Bessel-Talanov cutoff, and for large ripples. The growth of large unfilterable ripples is especially harmful in large lasers.

Fig. 4-111. Worst ripple power growth as a function of eigenvalue ratio (inverse size) for various numbers of slabs with the same total B integral in each case. Note that increasing the slab count reduces gain over much of the curve, but does not help for large unfilterable ripples. Breakup, 3.0; vac/sol ratio, 3.0.

is unchanged by the insertion of vacuum spaces in the structure. The conclusion is that disk and amplifier spacing will have a small effect on the large, hard-to-filter ripples we are worried about. In fact, examination of Fig. 4-111 shows that there is an intermediate region where spacing actually makes things worse.

In an actual amplifier, the beam intensity changes both across the beam and during the duration of the pulse, so that a time-integrated picture will smear out the sharp oscillations in gain. Changes in power correspond directly to changes in B , which not only modifies the shape of the curves but also changes the horizontal scale, since we can easily show that the cutoff eigenvalue is given by

$$\sigma_c = 2 \sqrt{\frac{kB}{L}}$$

Many graphs in addition to those illustrated have now been produced, and an attempt is under way to correlate them with experimental results from large-aperture terawatt lasers such as Cyclops.

Numerical Calculation of Spatial Profiles. The program outlined in the previous section calculates the growth of power in modes as a function of their size. However, it is difficult to measure mode powers directly, and most experiments are done by analyzing the spatial profile of the beam in the near field of the laser. This may give a considerably different impression than that gotten from mode power analysis, since if a mode has coefficient a at some point then the mode power is a^2 while the contribution to the intensity is $2 \operatorname{Re}(a)$. Thus only the amplitude (real) part of a contributes to spatial profiles, while considerable power may be hidden in the phase (imaginary) part. In particular, the large power gains seen by big ripples (small σ) are largely due to increases in $\operatorname{Im}(a)$ which is physically just the phase delay due to increased index due to increased intensity in the ripple.

An additional problem is that calculations of mode power gain tell us nothing unless we know the input to the modes due to noise. A noise spectrum preferentially located in the small- or large-ripple-size region will accentuate that region in the laser output and give a ripple spectrum which may bear only small resemblance to the gain spectrum.

A computer program was thus written in which an initial set of mode coefficients is specified, and they are then followed through a system of slabs and vacuum spaces. In this program, the slabs and spaces are individually specified, so that greater variation is possible. The output shows the amplitude and phase of the resulting pattern at any plane in the system (Fig. 4-112), as well as a phasor diagram of the mode coefficients.

J. B. Trenholme

A Laser Design Assuming Perfect Spatial Filtering.

This section represents the design of a laser system under the assumption that spatial filtering removes all irregularities on the laser beam, so that B is "reset to zero." This assumption is illustrated in Fig. 4-113, where the beam degradation is plotted as a function of distance along the laser. The degradation is probably best defined as the equivalent solid angle of the beam, found by dividing the raw power out of the laser by the maximum power per steradian (intensity) in the far field:

$$\Omega_{eq} = \frac{\text{power}}{\text{peak intensity}}$$

In fact, this assumption is not correct, because spatially large irregularities cannot be removed by spatial filtering and continue to grow all along the chain. Such large ripple growth has been observed on the Cyclops laser chain. Its effect is illustrated in Fig. 4-114. Even with a very large number of filters, the growth of large ripples sets an upper limit on the amount of B integral that can be accumulated along a laser chain. Of course, frequent spatial filtering is still necessary to remove the faster growing small ripples before they rob too much power from the beam or cause damage.

The design presented here is not as far from optimal as might be suggested by the above discussion, since the driver sections were deliberately offloaded to be closer to a B -limited design. The output, however, runs with enough B accumulation to be a severe test of the power of spatial filters to remove beam degradation.

Ground Rules and Basic Concepts. The system was required to be designed with existing B and C amplifiers, which greatly simplified the design task by removing the variables involving amplifier size and gain. We describe components by the performance factor X , which is the ratio of power to breakup for a square-profile beam. In a disk amplifier, this is given by

$$X = \frac{\alpha n^2 d^2}{316 n_2 (1 - 1/G)}$$

where (for X in watts per neper) α is the gain coefficient (in cm^{-1}), n is the refractive index, d is the beam diameter (in cm), n_2 is the nonlinear index (in esu, typically $\sim 10^{-13}$), and G is the gain. The numbers used for B and C amplifiers are given in Table 4-22.

For a plate such as a Faraday rotator normal to the beam (and approximately for a lens) we find

$$X = \frac{n d^2}{316 n_2 L}$$

C-module approx 001
 Distance 131.80
 Breakup 2.00

In zone number 8
 Zone breakup 0.0
 Zone thick 31.00
 Index (ppm) 0.0
 Cutoff (mrad) 0.0
 Mode count 100
 Wavelength 1.060

Fig. 4-112. Calculation of near-field intensity and phase perturbations on a laser beam passing through four slabs separated by vacuum. An initial scratch-like perturbation is expanded into 100 modes, each of which is analytically propagated using the small-perturbation approximation. The field is here reconstructed well beyond the last slab. A phasor plot of the mode coefficients is also shown.

Fig. 4-113. Beam degradation along the laser assuming that each spatial filter fully restores the quality of the beam.

Fig. 4-114. Beam degradation when spatially large ripples pass through the filters and grow along the chain.

Table 4-22. Characteristics of B and C amplifiers used to optimize chain design

	B amplifier	C amplifier, solid-clad	C amplifier, liquid-clad
α (cm ⁻¹)	0.085	0.065	0.08
n	1.56	1.56	1.56
d (cm)	9	19	19
n ₂ (esu)	1.5×10^{-13}	1.5×10^{-13}	1.5×10^{-13}
G	3.8	3.3	4.0
X (GW/Np)	500	1700	2000

In a chain, X factors combine according to the rule

$$X = \frac{1}{\frac{1}{X_1} + \frac{1}{G_1 X_2} + \frac{1}{G_1 G_2 X_3} + \dots}$$

Initial Configuration. The initial setup analyzed was essentially the same as the Cyclops chain. Since Cyclops was originally designed on a flux-limited basis, this was not a high performance system. Its only advantage was the use of all proven components. In Fig. 4-115, we see why the performance is low. The X-factor of the output section is found from its individual components to be 740, and the gain 9.2, as shown in Table 4 23. A similar calculation gives $X = 265$, $G = 36.3$ for the B driver section. Seen through the output stage gain of 9.2, this is equivalent to an X of 2400 at the output, so the driver is lightly loaded when compared to the output section.

The problems with this design are obvious. The output section X is reduced by the large amount of solid material in the beam, thus reducing the available output power. The components are too thick (except for the focus lens, whose thickness is fixed by its diameter).

Let us first keep the requirement for a 10-cm spatial filter, and see what we can do. Under the "less is more" principle, we remove one of the C amplifiers from the output system. To increase drive capability in the B section, we isolate a B between 10-cm spatial

filters. This allows higher intensities and thus more output from this critical section. We thin up the rotators, polarizers, and spatial filter lenses as much as possible. Because the beam is diverging, we move the focus lens away from the laser and make it larger. The resulting system is shown in Fig. 4-116. The output section X is increased by 12% to 830, and the cost is reduced by the removal of one of the two C amplifiers. Because the X is raised and the gain is lowered, we need more drive capability from the B amplifiers. This higher drive is supplied by the isolated B, which has an X of 420. Seen through the output gain of 2.8, this is equivalent to an X of 1200, so the power limit is in the output and not the driver. The isolated B is in turn driven by a section of 2 B's with X of 200. Thus, each smaller section has lighter loading, which reduces whole-chain B integral effects with a slight cost increase. Note that this design not only has higher output and lower cost, but also better isolation. However, it does not do as well if whole-chain B is the performance limit, since its whole-chain X is less.

The way to get more output yet is to use 20-cm spatial filtering, since we must filter between C amplifiers in order to get high power from them. In fact, because C amplifiers are constructed as two separate three-disk heads, we can isolate three disks between spatial filters and get even more output. A system was therefore designed using 20-cm spatial filters. To get a bit more output from the last section, the focus lens,

Fig. 4-115. Initial configuration. A section with two solid-clad C amplifiers (C_s) is driven by another section with three B amplifiers. Only 10-cm spatial filters are used; the beam is allowed to expand after the second filter to fill the C amplifiers. S = spatial filter, A = amplifier, P = polarizer, R = Faraday rotator, F = focus lens. For overall chain, $X = 560$ GW/Np.

Table 4-23. Calculation of X-factor for Cyclops output section from X-factors of individual components

Component	X	G	Comments
Focus lens	3000	0.98	BK-7, 4 cm, $\sim f/1.2$
C amplifier	1700	3.3	Solid edge-cladding
Rotator	3000	0.98	EY-1, 4 cm
Polarizer	10,000	0.9	BK-7, 1.6 cm
C amplifier	1700	3.3	Solid edge-cladding
S.F. lens	1500	0.98	BK-7, 2 cm
Overall	740	9.2	

Faraday rotator, and polarizer were isolated from the last C amplifier by a spatial filter at the output. The resulting chain is shown in Fig. 4-117. The overall chain's X-factor is only 440, but the X of the limiting last C head (referred to the output) is 1700 GW/Np. This design is essentially what was constructed as the Argus laser; the only significant difference is that only one isolated C head is used in Argus, instead of two.

J. B. Trenholme

Cylindrically Symmetric Vacuum Focusing. As a check on the modal expansion methods already in use, the Campbell-DeShazer-method integrating propagation code was modified to include features relevant to fusion-laser vacuum focusing. The first feature was the allowance for power-filletted-quadratic intensity profiles. The second was the addition of a phase delay to the beam with the same radial profile as the beam intensity, to model whole-chain B-integral defocus effects. In addition, automatic parameter incrementing was added to simplify usage. Typical results from the program are illustrated in Fig. 4-118.

As a check on this and other numerical methods, an analytical calculation of the axial intensity due to a pure

quadratic profile was done. Such a profile is very undesirable for laser use, but serves as a useful test case.

We have an initial intensity

$$I = 1 - (r/a)^2$$

where a is the focusing lens radius. The amplitude after the lens is then

$$U_0 = \sqrt{1 - (r/a)^2} \exp\left(-\frac{ikr^2}{2f}\right),$$

where $k = 2\pi/\lambda$ and f is the lens focal length. In scalar diffraction theory, amplitudes obey

$$U = \frac{-i}{2\lambda} \int U_0 \frac{e^{ikR}}{R} (1 + \cos \beta) dS_n,$$

and if we approximate

$$R = \sqrt{z^2 + r^2} \approx z + \frac{r^2}{2z}$$

Fig. 4-116. Improved system with constraint of 10-cm maximum size for spatial filters. Output is increased by 12%, one less C amplifier is required, and isolation is better. Overall chain $X = 380$ GW/Np.

Fig. 4-117. Final system designed with 20-cm spatial filters, isolated three-disk C heads, and isolated final polarizer, rotator, and focus lens. Limiting X-factor is now 1700 GW/Np. This design is essentially the one used in constructing the Argus laser.

and use $R = z$ in the denominator, $R = z + r^2/2z$ in the exponential, and take the inclination factor to be constant we get the paraxial approximation

$$U \approx \frac{-ie^{ikz}}{\lambda z} \int U_0 \exp\left(\frac{ikr^2}{2z}\right) dS_n.$$

Using cylindrical symmetry, $dS_n = 2\pi r dr$ and

$$U \approx \frac{-ike^{ikz}}{z} \int_0^a \sqrt{1 - (r/a)^2} \exp\left[\frac{ikr^2}{2} \left(\frac{1}{z} - \frac{1}{f}\right)\right] r dr.$$

This becomes, by the change of variable $ax = r$,

$$U \approx \frac{-ika^2 e^{ikz}}{z} \int_0^1 \sqrt{1 - x^2} e^{iPx^2} x dx,$$

where

$$P = \frac{ka^2}{2} \left(\frac{1}{z} - \frac{1}{f} \right).$$

Thus the axial intensity is

$$I = U^*U = \left(\frac{ka^2}{z} \right)^2 f^2(F),$$

where the nasty integral which we need to solve the problem is

$$f(P) = \int_0^1 \sqrt{1 - x^2} e^{iPx^2} x dx.$$

Letting $u^2 = 1 - x^2$, we get $x dx = -u du$ and

$$f(P) = e^{iP} \int_0^1 e^{-iPu^2} u^2 du.$$

Note that

$$d(u e^{-iPu^2}) = e^{-iPu^2} du - 2iPu^2 e^{-iPu^2} du,$$

so that we can integrate by parts using

$$u^2 e^{-iPu^2} du = \frac{i}{2P} d(u e^{-iPu^2}) - \frac{i}{2P} e^{-iPu^2} du,$$

and get

$$f(P) = \frac{ie^{iP}}{2P} e^{-iP} - \frac{ie^{iP}}{2P} \int_0^1 e^{-iPu^2} du$$

or

$$f(P) = \frac{i}{2P} - \frac{ie^{iP}}{2P} \int_0^{\sqrt{P}} e^{-iw^2} dw,$$

where $w = U\sqrt{P}$

The integral here is just the Fresnel integrals and so

$$f(P) = \frac{i}{2P} - \frac{ie^{iP}}{2P} \sqrt{\frac{\pi}{2|P|}} \left[C\left(\sqrt{\frac{2|P|}{\pi}}\right) - i \operatorname{sign}(P) S\left(\sqrt{\frac{2|P|}{\pi}}\right) \right].$$

Since we only need the magnitude of $f(P)$, we ignore the phase i and have

$$I(z) = \left(\frac{ka^2}{z} \right)^2 \frac{1}{4P^2} \left| \frac{C\left(\sqrt{\frac{2|P|}{\pi}}\right) - i \operatorname{sign}(P) S\left(\sqrt{\frac{2|P|}{\pi}}\right)}{\sqrt{\frac{2|P|}{\pi}}} \right|^2 e^{-e^{iP}}.$$

(a)

INTENSITY AND PHASE BEFORE LENS

PROP 1B U 12H47M03S THU, NOV 20, 1975

JOHN B. TRENNOLME

PLOT 57

WAVELENGTH 1.0600E-03
LENS RADIUS 1.5000E+02
FOCAL LENGTH 4.8000E+02
B INTEGRAL 8.0000E+02
FILLET RADIUS 1.3500E+02
FILLET INTEN 1.0000E+01

PARABOLA CUTOFF 1.4E30E+02
POWER OF FILLET 2.0000E+02
PEAK TO AVERAGE 0.0100E+01

Fig. 4-118. Results from the integrating cylindrically symmetric propagation program. The program allows input of variable beam shapes and corresponding whole-beam phase delays. A series of beam profiles can be produced for various positions near focus. (a) Initial state of the laser beam. (b) Profile near focus.

(b) -1.0000E-02 FROM FOCAL POINT OF LENS

PROP 1B U 12H47M03S THU, NOV 20, 1975

JOHN B. TRENNOLME

PLOT 62

WAVELENGTH 1.0600E-03
LENS RADIUS 1.5000E+02
FOCAL LENGTH 4.8000E+02
B INTEGRAL 8.0000E+00
FILLET RADIUS 1.3500E+02
FILLET INTEN 1.0000E-01

RAYLEIGH RANGE 3.4550E-01
FRESNEL NUMBER 9.2130E-01
MAX INTEG ZONES 1
SUCCESSFUL 200
TOO MANY CALLS 0
STACK FULL 0
TOTAL CALLS 14480
MAX PER ZONE 434

where we recall

$$P = \frac{ka^2}{2} \left(\frac{1}{z} - \frac{1}{f} \right).$$

The behavior near focus can be examined by writing the distance from focus,

$$\beta = z - f,$$

so that

$$P = \frac{-\beta}{\left(1 + \frac{\beta}{f}\right)} \frac{ka^2}{2f^2}.$$

For $\beta \ll f$, we have

$$P \approx -\beta \frac{ka^2}{2f^2},$$

and noting that the f-number of the lens is

$$F = \frac{f}{2a},$$

we have

$$P = \frac{-k\beta}{8F^2}.$$

Thus near focus

$$I(U) = 16 \left(\frac{ka^2}{f} \right)^2 \frac{1}{U^2} \left| 1 - e^{-iU/8} \right| \times \left[\frac{C\left(\frac{1}{2} \sqrt{\frac{|U|}{\pi}}\right) + i \operatorname{sign}(U) S\left(\frac{1}{2} \sqrt{\frac{|U|}{\pi}}\right)}{\frac{1}{2} \sqrt{\frac{|U|}{\pi}}} \right]^2,$$

where

$$U = \frac{k(z - f)}{F^2} \approx \frac{k\beta}{f^2}.$$

As $U \rightarrow 0$, we find that

$$I \rightarrow \frac{1}{9} \left(\frac{ka^2}{f} \right)^2,$$

so that the intensity relative to that in the focal plane is

$$\frac{I(U)}{I_0} = \left(\frac{12}{U} \right)^2 \left| 1 - e^{-iU/8} \right| \times \left[\frac{C\left(\frac{1}{2} \sqrt{\frac{|U|}{\pi}}\right) + i \operatorname{sign}(U) S\left(\frac{1}{2} \sqrt{\frac{|U|}{\pi}}\right)}{\frac{1}{2} \sqrt{\frac{|U|}{\pi}}} \right]^2.$$

A simple program has been written which plots I/I_0 as a function of U . A typical example of its output is shown in Fig. 4-119. Note that for $U \gg 1$, the source of oscillation is the $\exp(-iU/8)$ term, which causes one cycle of oscillation every $16\pi \approx 50.27$ change in U . For a uniformly illuminated aperture, Born and Wolf¹¹ show that there is one cycle of change every 32π . In the uniform case, the oscillations have 100% modulation. Here the $C + iS$ term rapidly becomes $1/2(1 + i)$, so that an amplitude of length $2\pi/U$ gets added to unit amplitude with oscillatory phase. The intensity then goes from

$$I_{\max} \approx \left(1 + \sqrt{\frac{2\pi}{U}} \right)^2$$

Fig. 4-119. Computer plot of calculated axial intensity of parabolically apodized beam near focus.

to

$$l_{\min} \approx \left(1 - \sqrt{\frac{2\pi}{U}}\right)^2$$

so that the modulation is approximately

$$\pm \sqrt{\frac{2\pi}{U}} \left(2 + \sqrt{\frac{2\pi}{U}}\right).$$

These results do not apply directly to fusion-laser beams, since such beams have smooth tails on the edge of the beam in order to reduce just the oscillations we have calculated for a parabolic beam. However, the parabolic beam does provide a good test case for diffraction computer programs that get unhappy with the abrupt drop at the edge of a uniformly illuminated aperture. Besides, it's been fun.

J. B. Trenholme

Amplified Spontaneous Emission (ASE)

The instantaneous ASE power through a circular aperture at the focus of a lens (e.g., the lens in the target chamber) may be expressed analytically. The major assumption is that the chain's small-signal gain is sufficiently high that the fluorescence spectrum may be approximated by a Gaussian distribution. The derivation is too lengthy for inclusion in a report of this nature, but the complete set of equations is:

$$P = \sum_i (D_i^2 \Omega_i / 32 \tau_i \beta) \left[\prod_{j=1}^i T_j \right] \left[\Phi \left\{ \ln \left(\prod_{j=1}^i G_j \right) \right\} - \Phi \left\{ \ln \left(\prod_{j=1}^{i-1} G_j \right) \right\} \right] \quad (1)$$

where the amplifiers are numbered sequentially from the output end of the chain to the input and where

P = instantaneous ASE power through the aperture at focal plane of target lens,

D_i = clear-aperture diameter of the i th amplifier,

Ω_i = limiting solid angle for ASE from the i th amplifier

$$= (\pi/4\pi^2) [\min(d/f, D_q/S_i, \theta_{sfi})]^2,$$

η = refractive index of laser glass (1.554 for ED-2),

d = focal-plane aperture diameter,

f = focal length of target-focusing lens,

D_q = clear diameter of target-focusing lens,

S_i = distance from center of i th amplifier to target-focusing lens,

θ_{sfi} = smallest acceptance full-angle of all spatial filters between i th amplifier and target-focusing lens,

τ_i = radiative lifetime of transition of interest ($\approx 625 \mu s$ for 1062-nm line of ED-2; neglecting the other lines will cause an underestimate of roughly 4%),

β = specific gain (at line center) for the laser material ($\beta = 0.15 \text{ cm}^2/\text{J}$ for ED-2),

T_j = instantaneous transmission (unpumped) of j th amplifier plus all components between j th amplifier and $(j-1)$ th amplifier (if $j=1$, between first amplifier and target),

$$\Phi(z) \approx e^z - 1, \quad 0 \leq z \leq 1,$$

$$\approx (e^z - 1)/\sqrt{z}, \quad z \geq 1,$$

$$\Phi(z) \approx 0.9z + (e^z - 1 - z)/\sqrt{z}, \quad 0 \leq z;$$

G_j = instantaneous gross small-signal gain, at line center, of the j th amplifier (if G_{yj} is the ratio of the "pumped" and "unpumped" throughputs of an ED-2 glass amplifier as measured with a YAG probe beam, $G_j \approx G_{yj}^{29/27}$),

$$\prod_{j=1}^{i-1} G_j \approx 1 \text{ for } i = 1.$$

If the G_j satisfy $\ln \left(\prod_{j=1}^i G_j \right) \geq 1$ for all i , as is usually the case, then

$$P = \sum_i \left(\frac{D_i^2 \Omega_i}{32 \tau_i \beta} \right) \left(\prod_{j=1}^i T_j \right)$$

$$\times \left[\frac{\prod_{j=1}^i G_j - 1}{\sqrt{\ln \left(\prod_{j=1}^i G_j \right)}} - \frac{\prod_{j=1}^{i-1} G_j - 1}{\sqrt{\ln \left(\prod_{j=1}^{i-1} G_j \right)}} \right] \quad (2)$$

If $G_i/(G_i - 1) \sim 1$ for all i , a reasonable approximation to Eq. (2) is:

$$P = \sum_i \frac{D_i^2 \Omega_i}{32 \tau_i \beta} \frac{T_i (G_i - 1) \prod_{j=1}^i (T_j G_j)}{\sqrt{\ln \left[(G_i - 1) \prod_{j=1}^{i-1} G_j \right]}} \quad (3)$$

We have applied Eq. (3) to obtain an approximation

Table 4-24. Calculated ASE power contributions in Cyclops system

	Area (cm ²)	Small-signal gain	Transmission	Half-angle (μrad)	Peak ASE power (W)
Rod 1	4.5	10.5	0.9	—	7.85
Rod 2	4.5	10.5	0.9	—	0.90
Rod 3	4.5	10.5	0.9	—	0.11
A-disks	10.2	11	0.8	—	0.028
B-disks	56.8	13	0.8	—	0.022
Spatial filter	—	—	0.8	150	—
C-disks	314	11.5	0.8	—	0.038
Focusing lens	—	—	0.8	200	Total ASE power peak = 8.95 W

(see Table 4-24), accurate within about 10%, to ASE as measured on Cyclops by J. E. Murray and co-workers. This procedure serves as "code normalization," and gives us confidence in estimating Argus and Shiva ASE.

Preliminary results of experiments give an ASE energy of 2.7 mJ/pulse. Also, peak chain gain (and peak ASE power) occur after approximately three-tenths of the total ASE has arrived at the detector. Estimating the area under the experimental power curve at 0.09 ms-W, we obtain $P_{tot} \approx 9$ W, in good agreement with the calculation in Table 4-24. These numbers are summarized in Fig. 4-120. It therefore seems that this ASE model is reasonably accurate and can be extended with some measure of confidence to Argus and to Shiva. Predicted peak ASE powers for Argus and Shiva are shown in Tables 4-25 and 4-26.

Fig. 4-120. ASE measurements on Cyclops laser system.

Table 4-25. Calculated ASE power contributions in Argus system

	Area (cm ²)	Small-signal gain	Transmission	Half-angle (μrad)	Peak ASE power (W)
Rod 1	4.5	5	1.0	—	3.8
Rod 2	4.5	10	0.9	—	0.92
Rod 3	4.5	10	0.9	—	0.13
Rod 4	12.6	6	0.9	—	0.037
B-disks	56.8	41	0.7	—	0.052
Spatial filter	—	—	0.8	150	—
C-disks	314	13	0.7	—	0.034
Spatial filter	—	—	0.8	200	—

Total ASE power peak = 4.95 W/arm, or approx 20 W for the four arms of Argus

Table 4-26. Calculated ASE power contributions in Shiva system

	Area (cm ²)	Small-signal gain	Transmission	Half-angle (μrad)	Peak ASE power (W)
β ₁ rod	19.4	12.35	0.15	—	0.575
Apodizing aperture	—	—	0.1	—	—
α rod	4.9	107.4	0.8	—	2.97
β ₂ rod	19.6	12.35	0.8	—	0.16
β-disks	56.8	67.9	0.8	—	0.060
Spatial filter	—	—	—	150	—
γ-disks	189	2.84	0.8	—	0.009
Spatial filter	—	—	—	200	—
δ-disks	314	2.1	0.8	—	0.006
Focusing lens	—	—	—	200	—
Total ASE power peak = 3.78 W/arm, or approx 75.6 W for the 20 arms of Shiva					

Techniques considered for suppression of ASE are summarized in Table 4-27. In general, 25-mm-clear-aperture Pockels cells are readily available, have been tested on Cyclops, and will definitely be used for Argus. 50-mm Pockels cells are not yet available in sufficient quality (although they will presumably be ready for Shiva). Fast Faraday rotators are considered here because they are competitive in some respects to an electromechanical shutter deployed at the final spatial filter focus. It is felt that dye cells, though effective as ASE suppressors, have too much insertion loss and beam quality degradation, and are therefore to be avoided if at all possible.

The obvious extension of the above analysis is to map, as a function of time, the ASE distribution in the volume in which a target might be located. It is also obvious that this is most appropriately done by a

computer, and such a code is currently being written. For this application, it is less useful to consider the ASE in the focal plane than to compute the images, in the target chamber, of the amplifiers. These images are thin disks, and it is (conceptually) easy to trace the light backward (or forward) from these disks to find the volume distribution of ASE. An interim code which performs this time-independent function yields Fig. 4-121 for the instantaneous volume distribution of ASE from a comparatively simple, commercially available all-rod system.

W. D. Fountain
W. W. Simmons
J. B. Trenholme
J. S. Chin

Table 4-27. ASE control techniques

	Clear aperture (mm)	Pulse insertion transmission	Effective shutter time (μ s)	Advantages	Disadvantages
1. Pockels cells	25 50	0.8 (0.9) 0.7 (0.8)	0.01 0.01	Working (in Cyclops) Probably will work	Small aperture Small aperture
2. Fast Faraday rotator "A"	50	0.95	2-6 ^a	Simple to implement; must be prototyped	High RFI; slow; requires much energy for large aperture
Fast Faraday rotator "B"	100	0.95	4-8 ^a		
Fast Faraday rotator "C"	200	0.95	7-15 ^a		
3. Dye cells	Any size	0.6-0.7	0.	Simplest to implement	High insertion loss; beam quality degradation
4. Chopper wheel	Any S.F.	1.00	8-12 (typ.)	Zero insertion loss	Must be phased and synchronized; slow
5. "Pinched" foil	Any S.F.	1.00	10 (typ.)	Zero insertion loss; easy synchronization	Foil must be replaced between shots; slow; high RFI

^aCable loading included.

Fig. 4-121. Calculated instantaneous volume distribution of ASE in a comparatively simple, commercially available all-rod laser system. (a) Overall view of ASE in target volume. Images of final rod amplifiers are seen. (b) Magnified view of central region. Images of driver rods and preamps are visible. (c) The most intense ASE region. The principal contribution is from the second preamplifier rod (the first rod is isolated by a Pockels cell).

References

1. J. F. Holzrichter and D. R. Speck, "Laser Focusing Limitations from Nonlinear Beam Instabilities," to be published in *J. Appl. Phys.* (1976).
2. 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).
3. J. A. Glaze, *SPIE Proceedings* **69**, 45 (1975).
4. B. C. Johnson, *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), pp. 135-138.
5. J. A. Glaze, W. W. Simmons, and W. F. Hagen, *J. Opt. Soc. Amer.* **65**, 1208 (1975).
6. A. J. Campillo, B. Carpenter, B. E. Newnam, and S. L. Shapiro, *Opt. Commun.* **10**, 313 (1974).
7. L. L. Steinmetz, T. W. Pouliot, and B. C. Johnson, *Appl. Opt.* **12**, 1468 (1973).
8. S. Sackett and R. Healey, *A Digital Computer Program for the Numerical Solution of the Linear Poisson Equation*, Lawrence Berkeley Laboratory, Rept. UCRL-18721 (1969).
9. *Laser-Fusion Program Semiannual Report—July-December 1972*, Lawrence Livermore Laboratory, Rept. UCRL-50021-72-2 (1973), pp. 7-21.
10. *Laser-Fusion Program Semiannual Report—January-June 1973*, Lawrence Livermore Laboratory, Rept. UCRL-50021-73-1 (1973), pp. 4-19.
11. *Laser-Fusion Program Semiannual Report—July-December 1973*, Lawrence Livermore Laboratory, Rept. UCRL-50021-73-2 (1974), pp. 13-18.
12. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), pp. 143-160.
13. Ref. 12, pp. 178-199.
14. R. F. King, "An Improved Pegasus Method for Root Finding," *BIT* **13**, 423 (1973).
15. Ref. 12, pp. 237-238.
16. G. R. Allen, W. L. Gagnon, P. R. Rupert, and J. B. Trenholme, *Energy Storage and Power Conditioning System for the Shiva Laser*, Lawrence Livermore Laboratory, Rept. UCRL-77499 Preprint (1975).
17. Maxwell Laboratories, bank optimization study conducted under Contract No. 6721505; Physics International Co., Shiva system study conducted under Contract No. 6721515.
18. J. P. Markiewicz and J. L. Emmett, *IEEE J. Quant. Electron.* **QE-2**(11), 707 (Nov. 1966).
19. W. L. Gagnon and J. R. Hutzler, *Development of a Reliable, Low Cost Energy Storage Capacitor for Laser Pumping*, Lawrence Livermore Laboratory, Rept. UCRL-76495 Preprint (1975).
20. C. C. Wang, *Phys. Rev. B* **2**, 2045 (1970).
21. N. L. Boling, A. J. Glass, and A. Owyung, *An Empirical Relationship for Predicting Nonlinear Refractive Index Changes in Optical Solids*, Lawrence Livermore Laboratory, Rept. UCRL-75628 Preprint (1974).
22. R. R. Jacobs and M. J. Weber, *IEEE J. Quant. Electron.* **QE-12**, 102 (1976).
23. M. J. Weber, "Insulating Crystal Lasers," in *CRC Handbook of Lasers*, R. J. Pressley, Ed., p. 392 and references cited therein.
24. Ref. 12, pp. 256ff.
25. See, for example, W. Jahn, *Glastechn. Ber.* **34**, 107 (1961) and references cited therein.
26. E. S. Bliss, D. R. Speck, and W. W. Simmons, *Appl. Phys. Lett.* **25**, 728 (1974).
27. H. J. Weaver, G. E. Sommargren, and E. S. Bliss, *Proc. SPIE* **48**, 63 (1974).
28. Ref. 12, pp. 269-271.
29. Ref. 12, pp. 262ff.
30. O. K. Deutschlein and C. C. Pautrat, *IEEE J. Quant. Electron.* **QE-4**, 48 (1968).
31. R. R. Jacobs, C. B. Layne, M. J. Weber, and C. Rapp, "Ce³⁺ — Nd³⁺ Energy Transfer in Silicate Glass," to be published in *J. Appl. Phys.*, May 1976.
32. Ref. 12, p. 272.
33. C. B. Layne, *Multiphoton Relaxation and Excitation Transfer in Rare-Earth Doped Glasses*, Ph.D. thesis, University of California, Davis (August 1975); also available as Lawrence Livermore Laboratory Rept. UCRL-51862 (1975).
34. M. J. Weber, J. A. Paisner, S. S. Sussman, W. M. Yen, L. A. Riseberg, and C. Brecher, *J. Luminescence*, March 1976 (in press).
35. C. Brecher and L. A. Riseberg, *Phys. Rev. B* **13**, 81 (1976).

36. *Laser-Fusion Program Semiannual Report—January-June 1973*, Lawrence Livermore Laboratory, Rept. UCRL-50021-73-1 (1973); *Laser-Fusion Program Semiannual Report—July-September 1973*, Lawrence Livermore Laboratory, Rept. UCRL-50021-73-2 (1974).
37. J. T. Sato, D. Milam, P. Baker, and G. Murphy, *Laser-Induced Damage in Optical Materials*, National Bureau of Standards Special Publication No. 435 (U.S. Govt. Printing Office, Washington, D.C.), to be published.
38. D. Milam, in Ref. 12, p. 284.
39. B. C. Johnson, in Ref. 12, p. 128.
40. B. C. Johnson, in Ref. 12, p. 167.
41. W. Fountant, in Ref. 12, p. 132.
42. W. Simmons, in Ref. 12, p. 138.
43. G. A. Massey and R. A. Elliott, *IEEE J. Quant. Electron.* **QE-11**, 358 (1975).
44. D. M. Bloom, G. W. Bekkers, J. F. Young, and S. E. Harris, "Third Harmonic Generation in Phase Matched Alkali Vapors," *Appl. Phys. Lett.* **26**, 687 (1975).
45. W. H. Lowdermilk and G. I. Kachen, in Ref. 12, p. 279.
46. W. H. Lowdermilk and G. I. Kachen, *Appl. Phys. Lett.* **27**, 133 (1975).
47. G. Sommargren and E. Bliss, in Ref. 12, p. 242.
48. R. A. Buchroeder and R. B. Hooker, "Aberration Generator," *Appl. Optics* **14**, 2476 (1975).
49. E. Bliss, G. Sommargren, and H. J. Weaver, in Ref. 12, p. 191.
50. 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.* (to be published, July 1976).
51. S. W. Thomas, G. R. Tripp, and L. W. Coleman, "Ultrafast Streaking Camera for Picosecond Laser Diagnostics," *Proc. 10th International Congress on High Speed Photography, Paris* (National Assoc. of Technical Research, 1972).
52. J. T. Hunt, R. G. Nelson, and P. A. Renard, in Ref. 12, p. 206.
53. J. T. Hunt, P. A. Renard, and R. G. Nelson, "Focusing Properties of an Aberrated Laser Beam," *Appl. Optics* (to be published, June 1976).
54. A. J. Campillo, R. A. Fisher, R. C. Hyer, and S. L. Shapiro, "Streak Camera Investigation of the Self-Focusing Onset in Glass," *Appl. Phys. Lett.* **25**, 408 (1974).
55. J. T. Hunt and P. A. Renard, in Ref. 12, p. 203.
56. J. Glaze, W. Simmons, and W. Hagen, in Ref. 12, p. 202.
57. E. S. Bliss, "Nonlinear Propagation Studies," in *Laser-Induced Damage in Optical Materials*, edited by A. J. Glass and A. H. Guenther, National Bureau of Standards Special Publication No. 414 (U.S. Govt. Printing Office, Washington, D.C., 1974), p. 7.
58. H. J. Weaver, G. E. Sommargren, and E. S. Bliss, "Self-Calibration and Analysis of Image Formation in the Subnanosecond Domain," *Proc. 18th Annual Technical Meeting Soc. Photo-Optical Instrumentation Engineers* (1974), p. 36.
59. D. R. Speck and E. S. Bliss, in Ref. 10, p. 20.
60. B. R. Strydom, "Effect of Refractive Index Nonlinearity on the Optical Quality of High Power Laser Beams," *IEEE J. Quant. Electron.* **QE-11**, 225 (1975).
61. M. Born and E. Wolfe, *Principles of Optics* (Pergamon Press, London).

5. TARGET DESIGN

Section Editor D. J. Meeker

5. TARGET DESIGN

Several important advances and breakthroughs were made in the area of fusion targets:

- A sequence of improved fusion targets of complex design increased the experimentally measured neutron yield fiftyfold during early 1975. An additional twentyfold increase was achieved when the laser power/energy was doubled. Overall the neutron yield was increased from 10^4 to 10^7 , a sufficiently large number to make possible the first experiments to prove the thermonuclear nature of laser-induced DT neutrons.
- A dozen or so different kinds of fusion targets were developed for testing during 1975. The successful fabrication of these targets, several of which were highly complex, was an important achievement in the program to date.
- Detailed comparison of the diagnostic measurements with calculations made on the LASNEX target design computer code showed generally good agreement. For example, over a range of neutron yields varying from 10^2 to 10^7 , LASNEX predictions were accurate to about a factor of three.
- Major breakthroughs were achieved in the design of advanced targets. A method of damping fluid instabilities by density gradients and low density/mass pushers was developed. As a result of these and other innovations, the laser requirements for fusion reactors were relaxed by large factors in the areas of wavelength, efficiency, and average power. In addition, the fabrication requirements for fusion reactor targets were relaxed by large factors in the areas of surface finish and cost.
- Important advances were made in our understanding of the laser-plasma interaction, particularly in the areas of the laser light absorption, density profile self-steepening, and superthermal theoretical electron spectra. Experiments confirmed many of our theoretical predictions.

The progress of the design, plasma physics, and fabrication parts of the fusion target program are reported in some detail in Secs. 5, 6, and 7.

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5. TARGET DESIGN

5.1 Overview

The design/analysis group made important advances in the design of first-generation laser fusion targets which were tested with operational lasers and performed substantially as predicted; in the design of future targets for Shiva, Shiva Upgrade, and fusion reactors; in the detailed calculation and analysis of laser/plasma experiments; and in the development of the LASNEX magnetohydrodynamic computer program used to design targets and to analyze experiments.

The breakthroughs in the design of future targets that occurred in the last few months of 1975 are not yet completely understood and exploited. It appears that we may be able to create and maintain an optimal density gradient at the ablation surface that strongly damps the growth of fluid instabilities.

The growth of fluid instabilities at the interface between the ablator and the pusher has been greatly damped by use of low-density materials for pushers. Since the density of these pushers is approximately equal to that of the ablator, the Atwood number is small and the rate of growth of fluid instabilities is small.

These more stable, lower density designs may be made relatively more hollow so that the required laser power is reduced, and so that higher target yields can

be achieved with a given laser power. Then the required laser efficiency and average power are reduced. The reduced intensity also permits longer wavelength lasers. Similarly the required surface finish and cost of the target are relaxed. Our current estimates of the laser and target-fabrication requirements for a 1-GWe fusion reactor are as follows:

Laser

Efficiency	1 to 3%
Wavelength	1 to 2 μm
Energy	400 to 1000 kJ
Peak power	400 to 600 TW
Average power	3 to 10 MW
Pulse rate	10/s

Target

Surface finish	100 to 1000 $\text{\AA}$
Cost (maximum allowed)	10 cents

Substantial relaxations have also been achieved in the requirements for fusion reactors driven by relativistic electron beam (REB) machines (both electron and ion), and high-energy accelerators (e.g., 10-to-100-GeV uranium ions).

5.2 Target Design

The design concepts for the targets listed in 1975 were described in the 1975 laser fusion progress report. Plane disk type targets were used to study various effects such as absorption and magnetic fields. These disks had small diameters so that significant optical and x-ray measurements could be made at angles greater than 90° to the laser beam. Fusion targets used glass microspheres filled with low-density DT gas which were driven in the exploding pusher mode. This maximized the ion temperature achieved by the imploded DT and thereby the neutron generation, and made the implosion insensitive to fluid instabilities and surface finish. A variety of targets were designed and tested to provide more complete tests of our theoretical models. Between December 1974 and May 1975 a 1000-fold increase in neutron yield was achieved. Improved target design was responsible for most of this increase (about 100-fold), and the remaining factor of 10 was due to the addition of a second laser beam. The achievement of neutron yields of 10^6 to 10^7 made possible the first experimental determination of the thermonuclear nature of the burn. The excellent agreement between the LASNEX predictions and the diag-

nostic data from a variety of targets imploded under widely varying conditions is a significant accomplishment (Fig. 5-1). The analysis of these experiments is described in Sec. 5.3.

Design of targets for experiments in 1976 and beyond is described in this section. An important objective in the coming year is to generate much higher densities in laser implosions than has been achieved so far ($\sim 1 \text{ g/cm}^3$). Target designs which reach 10 to 30 g/cm^3 with existing lasers appear to be relatively straightforward, but the means for diagnosing these densities are still being developed. The difficulty is that with the small laser energies now available, the pressures which can be generated to drive the implosion are severely limited. In addition, there are severe preheat effects which cannot be shielded out because the targets are so small. Consequently, it is very difficult to achieve both high density and high temperature. These effects also limit the gains which can be achieved with targets for Shiva. To the extent feasible, our very recent breakthroughs in targets designed for Shiva Upgrade and reactors will be described in subsequent reports.

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The success of laser fusion depends on obtaining adiabatic compression of fuel to very high densities and temperature sufficiently high to ignite. These conditions can not be achieved by any existing laser system. To date, the results of laser fusion experiments have been based mainly on the isothermal electron implosion of exploding pusher targets consisting of a thin glass microsphere (wall thickness of less than $1\text{ }\mu\text{m}$) filled with low-density DT gas (initial density of a few mg/cm^3). Maximum DT densities of a few tenths of g/cm^3 and temperatures of a few keV have been achieved in these experiments. The design of these targets was discussed in last year's progress report. This study describes targets which can compress fuel to much higher densities using the capabilities of existing Nd:glass laser systems at LLL.

One-dimensional LASNEX simulations show that the maximum fuel density obtained for all the target designs depends strongly on the number of suprathermal electrons produced. The three-temperature (3T) and suprathermal models are used in these calculations. Suprathermal electrons do not exist in the 3T model. But very energetic electrons may be generated by inhibited transport. In the suprathermal model, 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. The

suprathermal electron spectrum is characterized by a temperature α which is 6 times the thermal electron temperature. Since the direction of the laser light is everywhere normal to the density gradient in one-dimensional calculations, the results are insensitive to the $0.8\rho_c$ requirement. Suprathermal x rays are also calculated in this model. But the results indicate that the x-ray preheat effect is negligible.

Two examples of high-density targets are shown in Fig. 5-2. Figure 5-2a represents a solid, $30\text{-}\mu\text{m}$ -radius, CD_2 pellet enclosed by a $3\text{-}\mu\text{m}$ -thick gold tamper-pusher and CH_2 ablator. The gold shell also acts as an electron preheat shield. This target is irradiated by a 0.25-TW , 0.5-ns , $1.06\text{-}\mu\text{m}$ laser pulse. The ablator thickness is varied in a series of LASNEX calculations. We show, in Fig. 5-3, the results using the suprathermal model. The increase in the CD_2 density and the decrease in temperature with increasing ablator thickness clearly indicate that the electron preheat effect is reduced by the increased electron absorption in the ablator. A maximum CD_2 density of about $25\text{ g}/\text{cm}^3$ is obtained. The drop in the density profile is correlated with the decrease in the laser energy/target mass.

Figure 5-2b shows a thick-wall glass microsphere containing DT gas at a density of $2 \times 10^{-3}\text{ g}/\text{cm}^3$. A

Fig. 5-1. Comparison of calculated and measured neutron output for various laser fusion target designs. Different designs are designated by the letters A-L.

Fig. 5-2. Two high-density targets. (a) CD_2 pellet. (b) Glass microsphere.

Fig. 5-3. Variations in CD₂ density and temperatures as a function of CH₂ ablator thickness for a 0.25-TW, 0.5-ns laser pulse.

100-J, Gaussian temporal profile, 1.06-μm laser pulse is used to implode the target. The laser pulse width is varied. Figure 5-4 shows the calculated results for the 3T and suprathermal models. Large differences in the DT densities as well as the neutron yields are observed. DT densities in excess of 10 g/cm³ are obtained with a 1-ns laser pulse under either the 3T or the suprathermal model. Furthermore, experimental results using this target design with laser pulses of 300- to 700-ps pulse

durations can, perhaps, be used to test the validities of the two models used.

The results of this study show that targets can be designed to compress fuel to densities of 20 to 30 g/cm³ with existing Nd:glass laser systems. But the low calculated fuel temperatures and neutron yields will make the diagnostics very difficult.

Y.L. Pan

5.2.2 FIRST-GENERATION TARGET DESIGNS FOR THE SHIVA LASER

The target geometry just discussed is designed to produce a high density in the fuel at peak compression with existing laser systems. In general, these low-power lasers are capable of attaining high fuel densities or temperatures, but it is difficult to attain both. The Shiva laser system, although producing higher power, will exhibit the same problem, but to a lesser degree. First-generation target designs for the Shiva laser system that incorporate this characteristic are described below.

A cryogenic DT shell with 20 TW of absorbed power can give a thermonuclear yield of several times

the absorbed energy if the energy can be deposited into a Maxwellian distribution of electrons on a target with a 10- to 100-Å surface finish. Using the laser pulses indicated in Table 5-1, a shell of DT with an i.d. of 250 μm and 90 μm thickness is impulsively accelerated to minimize the effects of Rayleigh-Taylor instability. Its calculated performance under various physical models is given in Table 5-2. If the energy is absorbed into a superthermal spectrum, the target performance is severely degraded, as shown. Recent Janus experiments are matched fairly well by a physical model that assumes an $\alpha \sim 4$ and some inhibition of electron

Fig. 5-4. Variations in DT density and neutron yield as a function of the laser pulse width and physical model.

Table 5-1. Laser pulses for an impulsively accelerated DT shell

Time (sh)	Power (W)	Pulse
0.0	6×10^{10}	Constant power
.05	6×10^{10}	
.25	3×10^{11}	
.27	3×10^{11}	Constant power
.3525	1.5×10^{12}	
.3675	1.5×10^{12}	
.3875	5×10^{12}	Linear ramp
.450	2×10^{13}	
0.470	2×10^{13}	Constant power

conduction, the last column in Table 5-2. Alpha is the ratio of the effective temperature of the superthermal electrons to that of the main body electrons. Electron conduction inhibition in these calculations is based on a model for the onset of ion-acoustic turbulence, although such inhibition could come from magnetic fields as well. As shown at the top of Table 5-3, with a pure DT target less than 9% of the absorbed energy was accounted for by inverse bremsstrahlung. The rest must be accounted for by nonclassical processes which produce superthermal electrons. The inverse brems-

strahlung could be enhanced both by using a higher Z ablator and by frequency doubling. The combination of these two could lead to a considerable performance improvement.

For the first generation of Shiva targets, we have assumed that 10 TW of absorbed power is achievable and that only 1- μ m light will be available. The superthermal electrons result in a drop in the driving pressure one achieves. They also preheat the fuel which then is harder to compress. Within the constraints of this model, it is possible to pursue two lines of experiments, one which gives a larger yield but lower density than the bare DT shell and the other which gives higher density but lower yield.

Gas-filled glass shells, similar in design to those used in the Janus laser, give thermonuclear yields of about 1/2% of the absorbed laser energy. This is much better performance than such targets currently being used, because the laser energy is better matched to the target size and the ρr of the fuel is an order of magnitude higher. Mean fuel temperatures of greater than 10 keV are calculated. Such a target has the virtue of being able to tolerate large asymmetries in the absorbed energy and can be imploded without the necessity of producing a low-density corona prior to the implosion.

A ball and shell target design, shown in Fig. 5-5, for 10 TW absorbed power, is capable of producing high densities. The inner gold shell acts as a pusher and a preheat shield. Using the pulse shape of Table 5-3, mean fuel densities approach 150 g/cm³ with a yield of 4×10^{10} neutrons. As shown in Fig. 5-5, the inner ball is supported by a low-density foam. If it could be levitated in density 10^{-4} g/cm³ gas atmosphere, the yield might be an order of magnitude higher. However, if a Maxwellian electron spectrum is generated, and a gas fill between ball and shell is used, then the target yields about one-fifth of breakeven.

The requirements of a highly symmetric implosion, together with fluid instability growth, impose certain constraints on the levels of surface perturbations and illumination nonuniformities which can be tolerated. The tolerances required, based on 2-D simulations using LASNEX, are summarized in Table 5-4 for spherical harmonic mode numbers of 2, 8, and 80. The $\ell=8$ mode is expected to correspond to the worst wavelength for a 20-beam system.

Illumination uniformity requirements are quite severe for the ball and shell target in the absence of a preformed low-density corona, as indicated in Table 5-4. LASNEX calculations indicate that the implosion pressures must be uniform to $\pm 1\%$ to achieve the densities indicated above. Since asymmetries of ± 10 to 20% in laser intensity are expected, some corona is going to be necessary. This is the function of the

Table 5-2. Performance of a cryogenic DT shell. Energy absorbed nonclassically = 8.5 kJ. Input energy = 9.3 kJ

α	3T	1	2	2	4	4
Inhibited conduction	No	No	No	Yes	No	Yes
Yield	23.0 kJ	8.0 kJ	0.53 kJ	3.28 J	0.131 kJ	1.55 J
$\rho_{\text{max}}^{\text{r}}$	0.91	0.78	0.20	0.057	0.046	0.037
Max avg fuel ρ	1280.0	990.0	135.0	11.7	9.7	5.6
Max avg fuel temp	9.2	5.6	3.2	1.33	3.5	1.21
Max fuel velocity	7.7×10^7	7.6×10^7	7.2×10^7	3.8×10^7	6.5×10^7	3.8×10^7
T_{max} (at ρ_c)	4.5	4.3	4.1	9.5	4.0	8.7

Table 5-3. Laser pulses for ball and shell with atmosphere

Time (sh)	Power (W)	Pulse
0.0	10^{11}	Constant power
.01	10^{11}	
.4	10^{13}	Constant power
.42	10^{13}	
.43	5×10^{12}	Linear ramp
0.61	2×10^{13}	

outermost glass shell in Fig. 5-5.

A corona, or atmosphere, is a region of some thickness beyond the ablation surface that is penetrated supersonically by the energy deposited by the laser. This region allows electron conduction to smooth asymmetries in the absorbed energy before that energy is used to generate hydrodynamic motion of the target. To perform this function, the material in the corona must be raised to some temperature. Theoretical calculations for a constant density corona, at a density just above the critical density for the laser being used,

indicate that for a given thickness atmosphere, the required temperature is proportional to λ^{-1} , where λ is the laser wavelength. Similar estimates indicate that the energy required to heat the corona is proportional to λ^{-3} and that the shock generated by the prepulse used to heat the atmosphere is proportional to $\lambda^{-7/3}$. It is this last effect which makes use of high-density atmospheres very difficult. Certain goals, such as the implosion of a DT shell to a density of 1000 g/cm³, can only be achieved if the initial shock is limited to about 1 Mbar. But heating a 300- μ m-thick atmosphere at the critical density of 1- μ m light to the required temperature results in a 40-Mbar shock. For such implosions, a 2- μ m laser will probably be required for the early part of the implosion. Because the double shell target shown in Fig. 5-5 is not a low entropy implosion and because the low-density foam between shells cushions the shock, it can survive the initial large shock generated by the explosion of the outer shell. Initial 2-D calculations indicate we can probably tolerate $\pm 10\%$ asymmetries in absorbed power using an atmosphere generated in this fashion, as shown in Table 5-4.

Several targets intermediate between those discussed here have been considered. If a single thick glass shell is used, the fuel will implode to higher density and

Table 5-4. Tolerances for surface finish and illumination nonuniformity for ball and shell targets

Tolerance/Mode	$\ell = 2$	$\ell = 8$	$\ell = 80$
Surface finish, inner ball ($\text{\AA}$, rms)	150	150	100
Surface finish, shell ($\text{\AA}$, rms)	50	50	30
Illumination symmetry, without atmosphere (% rms)	2	1	1
Illumination symmetry, with atmosphere (% rms)	5	10	30

Fig. 5-5. Ball and shell target design.

lower temperature than for a thin glass shell. A similar effect is obtained by coating a high Z material on the inside of a glass shell. Both of these get higher density than the exploding glass shell but lower density than the

double shell configuration.

J. D. Lindl
W. C. Mead

5.3 Analysis of Experiments

Laser/target-interactions experiments performed in the laser fusion program are carefully simulated by the target design group with two-dimensional magnetohydrodynamic computer codes. The results serve both as an aid to the experimenter in planning his diagnostics and as a check on the existing physics models in LASNEX, LLL's major laser fusion code. Typical calculations representing the varied spectrum of problems studied by the design group are presented here, including a study of laser interaction on disk and slab

targets with emphasis on absorption mechanisms, x-ray emission, and effects of self-generated magnetic fields. A discussion of ion temperature determination from measured alpha emission is also included, an important contribution to answering the question of true thermonuclear burn. Finally, target designs are discussed with specific examples of glass microspheres, spherical targets embedded in foam, and ball-on-plate geometries.

5.3.1 COMPARISON OF LASNEX CALCULATIONS WITH EXPERIMENTAL RESULTS OF PARYLENE DISK IRRADIATIONS AT 1.06 μm

Irradiating Parylene disks with a Nd 1.06-μm laser in the intensity regime of 10¹⁵ to 10¹⁶ W/cm² allows one to study laser light absorption, scattering, and plasma transport processes. Such experiments have recently

been performed at LLL.¹ The laser beam was focused via an f/1.1 lens into a Parylene disk target of 150 μm o.d. and 10 μm thick. Pulses of 60 to 150 ps FWHM with an energy of 5 to 15 J were applied in nominal

focal spot diameters of 90, 30, and 10 μm . Analysis was carried out using LASNEX both with a ring beam having a 2:1 intensity ratio and with a smooth beam. The simulation results discussed below are insensitive to this change in beam profile, except for a change in the angular distribution of scattered light. Unless otherwise noted, the following calculations use parameters $f_{\text{dump}} = 0.2$ to 0.4, $\rho_{\text{thresh}} = 0.8\rho_{\text{crit}}$, and $\alpha = 4$ with classical magnetic field transport coefficients.

It is quite easy to show that inverse bremsstrahlung absorption cannot account for the absorption fraction observed in the Parylene disk experiments, particularly for the 10^{16}-W/cm^2 shots. Here we will make a crude estimate of how much energy inverse bremsstrahlung could be expected to absorb.

The classical result for inverse bremsstrahlung heating in a linear density gradient is

$$\frac{I_{\text{ABS}}}{I_0} = \left[1 - \exp\left(-\frac{32}{15} k_0 L \frac{\nu_{\text{cr}}}{\omega_0}\right) \right], \quad (1)$$

where k_0 and ω_0 are the wavenumber and angular frequency of the incoming light, and ν_{cr} is the electron-ion collision frequency at the critical surface. This relation ignores pondermotively-induced density gradient steepening and nonnormal incidence which would reduce the effectiveness of inverse bremsstrahlung. The plot of Fig. 5-6 shows the absorbed fraction vs incident intensity. For this calculation, the scale height obtained in LASNEX, $L \sim 16 \mu\text{m}$, has been used. The Parylene disk experiments, particularly at 10^{16} W/cm^2 , show significantly higher absorption than inverse bremsstrahlung can provide.

Detailed calculations using LASNEX agree with the estimate presented above. When the dump parameter f_{dump} is set to 0.2 to 0.4 and the threshold fractional density is set between 0.5 and 0.8, the absorbed fraction of the incident laser light is essentially equal to f_{dump} , and the absorbed energies are consistent with experimentally observed values. The mean angle of incidence is about 15° , so nearly all the rays have $\rho_{\text{turn}} > 0.8\rho_{\text{crit}}$. The absorption obtained is thus only weakly sensitive to the value chosen for ρ_{thresh} . These values compare favorably with those computed in recent plasma simulations of laser light absorption via parametric instabilities and resonance absorption.

We note that there is some evidence that Brillouin reflection is being limited by the small mass and heat capacity of the underdense plasma,² which has a rather steep gradient in these experiments with a short, rapidly rising pulse. For example, for the 30- μm spot experiments, we calculate that a large reflectivity would persist for only about 15 ps. This is consistent with some of the preliminary optical streak camera measurements.

Fig. 5-6. Estimated fractional absorption vs incident intensity for inverse bremsstrahlung absorption in Parylene disk experiments. A scale height of $16 \mu\text{m}$ was assumed. The estimate shows that classical inverse bremsstrahlung does not account for observed fractional absorption.

The results obtained using LASNEX to calculate the angular dependence of scattered light are shown in Fig. 5-7. The reference calculations—using $\alpha = 4$, magnetic fields with Braginskii transport, and no anomalous flux limit—show adequate agreement with experimental results. This could be fortuitous, since the calculated shape varies with assumed beam profile.

The observed x-ray spectra for the 90- μm and 30- μm spot sizes are shown in Fig. 5-8. The reference calculations, using $f_{\text{dump}} = 0.2$ and 0.4, show agreement with the experiment to within a factor of 5 over the entire spectrum. Note that the presence of suprathermal heated electrons is strongly supported since the $\alpha = 1$ calculations fall several orders of magnitude below the data at high energies.

The calculation of these spectra is nontrivial, since the most intense emission region for 8- to 10-keV x rays is around a density of 0.01 g/cm^3 while that for 1- to 2-keV x rays is at a density of 0.1 g/cm^3 . The time-varying scale height and suprathermal electron populations, and the spatial variation in transport inhibition make the connection between the electron populations in the critical density region and the time-integrated x-ray emission very indirect.

Because of the subtle interplay between absorption, electron heating, and transport, we do not claim high-

Fig. 5-7. Comparison of calculated angular distributions of reflected and refracted light with experimental results for (a) 90- μm and (b) 30- μm cases, showing qualitative agreement with experiments. The calculated distribution depends quite sensitively on assumed beam profile.

precision knowledge of heated electron distribution functions, but rather that qualitative features of the electron heating are understood. At $I = 10^{16} \text{ W/cm}^2$, the mean heated electron energy, θ_h , used in LASNEX is approximately 40 keV; at $I = 10^{15} \text{ W/cm}^2$, $\theta_h \approx 10 \text{ keV}$. These energies are in reasonable agreement with those computed in plasma simulations. For example, the heated electron temperature θ_h due to resonance absorption can be estimated by wave breaking arguments to be

$$\theta_h \approx \frac{mc^2}{2} \left(\frac{v_{os}}{c} \right) \sqrt{k_0 L} \zeta(\tau),$$

where v_{os} is the oscillatory velocity of an electron, L is the scale length near critical, and ζ is the resonance function given by Ginsburg.³ Estimating $\zeta \sim 1$ and using the self-consistent nonlinearly steepened density profile, $\theta_h \sim 350 (v_{osc}) \text{ keV}$. This gives 35 keV for $I =$

10^{16} W/cm^2 and 12 keV for $I = 10^{15} \text{ W/cm}^2$. Again, the principal point is that calculations of known processes give reasonable agreement.

The x-ray microscope diagnostic shows that transport is significantly inhibited. In Fig. 5-9 are shown film density traces parallel to and transverse to the laser beam propagation direction for an unfiltered channel with response from 0.2 to 2.0 keV. As discussed in Ref. 1, the x-ray microscope viewed the target edge-on, and the laser light plane of polarization was at 45° to the line between the target and the microscope. The parallel direction shows the time-integrated emission across the density gradient. This turns out to be insensitive to conduction inhibition. In the direction transverse

Fig. 5-8. Comparison of calculated x-ray spectra with experimental results for (a) 90- μm and (b) 30- μm cases. The $\alpha = 1$ calculations are shown dashed, and disagree by several orders of magnitude with the data at 50 to 100 keV. The x-ray spectrum is adequately simulated only when suprathermal electron generation is assumed.

Fig. 5-9. Comparison of calculated and observed traces of x-ray images. The parallel direction scans represent the log of the x-ray emission intensity vs position along the beam axis, with the beam incident from the left in the figure. The transverse scans were taken along the line perpendicular to the beam axis containing the point of greatest emission intensity. The calculations without magnetic fields or other conduction inhibition (dashed lines) do not agree well with any of the images obtained experimentally.

to the incident beam, a significant difference is observed between calculations with and without inhibition, as shown in the figure. The calculations without magnetic fields are clearly inconsistent with experiment. The agreement between the reference calculations and the experimental shots selected is the best observed, and is somewhat fortuitous. Other shots show deviation from axial symmetry and, particularly for 90- μm cases, a somewhat narrower FWHM. Calculations with inhibition from either magnetic fields or anomalous conduction are consistent with the experimental results, within the level of uncertainty introduced by possible beam spot size variations.

For the 90- μm case, the reference LASNEX calculated FWHM is 84 μm , while the experimental values ranged from 55 to 80 μm with mean and standard deviation of $67.0 \pm 9.0 \mu\text{m}$. For the 30- μm case, the reference calculation FWHM is 34 μm , while the experimental result is $37.0 \pm 7.0 \mu\text{m}$.

The data obtained from Faraday probe time-of-flight measurements on the Parylene disk experiments show significant fractions of ion energy in a small group of fast ions. As shown in Table 5-5, an estimated 70% of the ion energy lies above $E/A = 10 \text{ keV}$ for the 30- μm shots at intensities of 1 to $2 \times 10^{16} \text{ W/cm}^2$. Measurements obtained using a magnetic spectrometer show a

group of fast protons in the energy range of 100 to 200 keV.

Calculations with LASNEX indicate similar blowoff behavior. The calculated ion distributions show 22% of the ion kinetic energy above 50 keV for the 90- μm case. For the 30- μm case, the reference calculation indicates 66% of the ion kinetic energy above 50 keV. These numbers are in rough agreement with the data, with the necessary proviso that uncertainties in both the experiment and the analysis are large. These uncertainties arise from experimental dynamic range problems, the unknown amount of recombination, which may depend upon the ion energy, and from the single-species, Lagrangian ion modeling in LASNEX.

Both transport inhibition and suprathermal electron populations play a significant role in determining the amount of energy in fast ions. In Table 5-5 are summarized results showing the variation of hot ion production with modifications of transport and suprathermal electron production.

The hot ions are produced by acceleration through the ambipolar potential ($e\phi \sim \theta_n$) which builds up quickly as electrons try to leave the target. Since the electron heat flow into the target is inhibited, they can lose a large fraction of their energy to this fast ion

Table 5-5. Ion energy distribution depends upon electron distribution and transport inhibition. Fraction ion energy above $E/A = 10$ keV —

	90 μm	30 μm
Experiment ^a	0.5 ± 0.2	0.7 ± 0.2
Ref. calc.	0.22	0.66
No inhib.	0.03	0.15
$\alpha = 1$	0.06	0.29

^a Assuming A/Z independent of E .

blowoff. A few simple estimates demonstrate the numbers. The electron heat flux carried into the target is $I_{ej} = n_e \theta_e v_{th,e}$. The energy flux carried off by hot ion expansion is $I_{im} = 5/2 n_e \theta_e v_{th,e}$ (we have crudely estimated this on the basis of an isothermal expansion). The ratio of the ion to the electron energy flux is, then, about $5V/m/M f_{im}^{-1}$. For the 30- μm spot example previously discussed, $f_{im} \approx 1/90$ for electrons of 10 keV or greater. Hence, our estimate gives about 80% of the absorbed energy being lost to fast ion expansion. Of course, this estimate is a bit higher than the calculations show (-66%) because we have neglected the

energy flux carried by lower energy electrons which are less inhibited and because we have also neglected the energy flux by electrons through the holes in the magnetic field.

The most significant conclusions which can be drawn are the following:

1. We observe laser light absorption which is enhanced relative to expectations based on inverse bremsstrahlung, and which is consistent with plasma simulations.
2. The enhanced absorption is coupled with generation of suprathermal electrons.
3. Transport inhibition, such as would be produced by thermoelectrically generated B fields, plays an important part in determining plasma behavior.

With these hypotheses, we have been able to simulate optical energy distribution and balance, x-ray spectral and spatial emission, and ion energy distribution with accuracy sufficient to gain an understanding of detailed plasma processes.

W. C. Mead
W. L. Kruer
J. D. Lindl
H. D. Shay

5.3.2 COMPARISON OF RECENT EXPERIMENTAL RESULTS ON X-RAY EMISSION TO LASNEX CALCULATIONS

As stated in Sec. 5.3.1, magnetic fields and instability mechanisms strongly affect the x-ray emission from laser-irradiated targets. Recently, Naval Research Laboratory (NRL)¹ and LLNL² reported the results of x-ray measurements from short-pulse Nd laser shots on thick polyethylene slab targets with intensities approaching 10^{16} W/cm². We present here a comparison of these results to LASNEX calculations, with particular emphasis on the predicted slope of the x-ray data.

In Fig. 5-10 are shown the NRL data together with data from the LLNL series. Although the analysis of the LLNL data is not complete, it appears that the LLNL thermal spectrum (below 10 keV) tracks the NRL data (with scaling for energy on target) but the high energy x-ray emission is much larger. Box calorimeter measurements indicate only 30 to 40% of the incident energy was absorbed in the Livermore experiments, whereas NRL observed 80% absorption with the use of burn paper.

Calculations with the LASNEX code show for both sets of x-ray data that there is a pronounced change in slope at about 5 keV, with the slope below 5 keV characteristic of a bremsstrahlung emission from plasma of a 1.2 to 1-keV thermal electron temperature. Figure 5-11 shows an initial set of calculations using a

laser absorption of 25% at 0.8μ . There are two curves listed. Both include self-generated magnetic fields, but in the first example, the ALPHA parameter (which is

Fig. 5-10. X-ray data (1 to 100 keV) from two sets of experiments: (a) NRL, (b) LLNL.

the multiplier on T_e for the instability-generated electron spectrum) was 4, and the second case $\text{ALPHA} = 1$, i.e., except for transport effects, it is like a three-temperature calculation. The first calculation agrees quite well with the data and, in particular, has the sharp break in the x-ray spectrum characteristic of the two-temperature instability electron distribution. The slope of the tail is controlled by magnetic field effects and the ALPHA parameter. The second calculation, with no superthermals, is high at low energies and low above 10 keV. It shows little evidence of the break in slope that is almost universally observed in short-pulse, high-intensity laser experiments. In all of the calculations so far, the absorbed laser energy is about 25 to 30% of that incident; hence, raising the amount absorbed (as discussed later) would only enhance the x-ray emission. Also it might be mentioned that the peak T_e near ρ_c was less than 2 keV; the only technique that produced 50-keV temperatures was to eliminate electron conduction altogether.

Since the suprathermal tail was too hot before, some calculations were run with a new absorption model (20% above $0.9\rho_c$) and an $\text{ALPHA} = 4$. Two of these are shown in Fig. 5-12, with and without magnetic fields. One sees that the effect of the magnetic field is to lower the thermal emission below 1 keV by about 2 times and increase the apparent temperature of the suprathermal tail. In fact, the $\text{ALPHA} = 4$ case with the magnetic field problem is very close to an $\text{ALPHA} = 12$ case without the magnetic field. Figure 5-13 shows the radial field variation at the peak of the

Fig. 5-11. Comparison of NRL data (curve a in Fig. 5-10) to calculations assuming that 0.4-J laser energy was absorbed. (a) Three-temperature calculation. (b) Multigroup electrons and photons ($\text{ALPHA} = 4$).

Fig. 5-12. NRL data (curve a in Fig. 5-10) with a different absorption model (20% dumped at $0.9\rho_c$) and using $\text{ALPHA} = 4$. (a) Without magnetic fields. (b) Self-generated magnetic fields.

laser pulse; the characteristic peak at 25 to 30 μm off-axis with a "hole" of low magnetic field on-axis acts as a conduction channel. Figure 5-14 shows the magnetic isoplots for Fig. 5-12. Note that even though the laser beam profile was smooth there is visible a clear ring effect in the magnetic field generation. The distance from ρ_c to solid density is only about 10 μm in these calculations, giving a density scale height of a few micrometers; hence the problem of inhibiting electron conduction (in order to suppress the x-ray emission) over such short distances is severe.

Finally, since the NRL group believes that their absorption is about 80% instead of the 25 to 30% that these calculations indicate, some runs were tried with the absorption set to 80% above $0.9\rho_c$ resulting in 1.2 J absorbed. In Fig. 5-15 the results for two of these runs are shown, again with and without magnetic fields. In these cases 65 to 80% was absorbed and the zeroth-order effect was to increase the x-ray emission by 10 times. Again, the magnetic field lowers the thermal emission (by 3 in this example) and generates a hotter spectrum of suprathermals. In either case, the x-ray output is greatly above that observed. The greater suppression of thermal emission is due to the stronger field generations and presence of a barrier (above ρ_c) in the central region of the beam.

The LLNL slab experiments were run at the same and higher energies (2 to 5 J) as NRL, and observed similar (scaled) results to NRL below 10 keV, but generally a very flat spectrum above 10 keV—much above the NRL data (although with large variability). The 1.2 J

runs (Fig. 5-10) agree below 10 keV quite well; above that, the calculations show a lower tail temperature and do not show marked sensitivity to beam variations. Hence it is yet unclear what is causing the large variations; if the high-temperature tail is correct, one may have to invoke some mechanism of conduction inhibition beyond classical magnetic fields.

In summary, the currently used LLL absorption parameters give about 30% absorption and good agreement with the NRL data using a two-temperature

electron distribution model. To get a hotter suprathermal tail requires less electron conduction, as the LLL data indicates, and since such modifications always strongly affect the low-energy thermal emission, one of the best experimental checks would be to get an absolute integral (to 1.5 keV, say) of the total x-ray emission to about 20% as well as the higher energy spectral measurements.

D. S. Bailey

Fig. 5-13. Radial variation of magnetic field for curve b of Fig. 5-12 at approximately the peak of the laser pulse. The sequence of curves is in the direction of increasing Z . Time, 30.7 ps.

Fig. 5-14. Magnetic field isoplot for curve b of Fig. 5-12 near peak of laser pulse.

5.3.3 CALCULATIONS OF SELF-GENERATED MAGNETIC FIELDS IN PARYLENE DISK EXPERIMENTS

Laser/plasma interaction experiments are being carried out at LLL and elsewhere to investigate the strength and spatial extent of magnetic fields generated in laser plasmas. Here we discuss the utility of a 2-D fluid code in experimental design. For example, LASNEX calculations show a time window during which megagauss magnetic fields extend beyond the Nd critical density over a region 10 to 40 μm in extent for pulses of 100 ps duration and energies of the order of 1 J. This time window is the optimum for measuring dc magnetic fields.

Experiments have been planned at LLL to measure self-generated magnetic fields using the Faraday rotation of frequency-quadrupled 1.06- μm laser light. The LASNEX code was used during the planning of these experiments and has provided valuable information in establishing the conditions under which the thermoelectric fields can be measured. Suspected thermoelectric fields have been inferred from experiments that have been carried out at NRL.⁶

In the LLL experiments, the target chosen for γ -radiation is the finite Parylene disk illustrated in Fig.

Fig. 5-15. NRI data (a) LLL data (b) and two higher atmospheric calculations (1.2 ps): (c) without magnetic fields; (d) magnetic fields included.

5-16. The finite disk allows for unequivocal measurements of quantities such as specific energy delivered to the target and provides a known means for comparison to ion probe diagnostics. In addition, the finite disk provides a simulated one-dimensional geometry for the blowoff on-axis during the laser pulse since the hydrodynamic time scale is less than or comparable to the laser pulse length. Furthermore, it provides for axial symmetry that can be correlated with code calculations.

The dominant magnetic source term in LASNEX is the $\nabla \ln n \times \nabla T$ term:

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left[\vec{v} \times \vec{B} + \frac{c}{en_e} \left(\nabla P_e - \frac{1}{c} \vec{J} \times \vec{B} - \vec{R} \right) \right],$$

$$\frac{\partial \vec{B}}{\partial t} \approx \nabla \times \frac{c}{en_e} \nabla P_e \approx \nabla \times \frac{c}{en_e} \nabla n_e kT,$$

$$\frac{\partial \vec{B}}{\partial t} \approx \nabla \ln n_e \times \nabla T \lesssim 0.1 \text{ MG ps}^{-1}.$$

The growth rate equation, $\partial \vec{B} / \partial t$, includes the convective losses in $\vec{v} \times \vec{B}$, the source term in ∇P_e , the $\vec{J} \times \vec{B}$ loss term, and the resistive losses in $\vec{R}$. The dominant source term is ∇P_e .

Under typical conditions, these source terms lead to field growth rates of up to 0.1 MG/ps. Fields of the order of 1 MG are predicted for many laser experiments. Since the source term is proportional to the gradient of the logarithm of the number density, which is relatively fixed in these experiments, the dominant terms in the growth rate can be expected to be the gradient of the temperature and the angle between the gradients.

This speculation appears to be confirmed in calculations that simulate two different laser beam spatial profiles and, therefore, two different spatial temperature gradients. Figure 5-17 illustrates these calculations. The ring source beam profile has a much steeper gradient and correspondingly higher magnetic field growth rate. The Gaussian beam predicts lower fields, of the order of 300 kG. These fields would be marginally observed using the Faraday rotation apparatus at LLL and are consistent with observations to date on the Monojoule laser system.⁷

The rapid growth rates of the fields means that they are created early in time during the laser pulse. In addition, the low collision rates in the underdense region of the plasma means that the fields diffuse relatively slowly and, consequently, the main losses in field intensity in the blowoff are hydrodynamic (convective).

We can see this in a quantitative way by examining the relative sizes of terms on the right-hand side of a simplified equation for $\vec{B}$:

$$\frac{\partial \vec{B}}{\partial t} \approx \frac{c}{e} \nabla \ln n \times \nabla T + \nabla \times (\vec{v} \times \vec{B}) - \frac{c^2}{4\pi e} \nabla^2 \vec{B}.$$

The first term on the right is the source term, the second term represents convection of the field by the fluid velocity $\vec{v}$, and the third term represents resistive diffusion of the field. The relative sizes of the resistive diffusion term and the $\nabla n \times \nabla T$ source term are

Fig. 5-16. The finite Parlyne disk proposed for magnetic field experiments.

$$\frac{(c^2/4\pi\sigma)\nabla^2 B}{(c/e)\nabla \ln n \times \nabla T} \approx \left(\frac{\Omega_e \nu_{ei}}{\omega_p^2} \right) \frac{c^2}{v_t^2} \approx 0.5\%,$$

for $T_e = 500$ eV, $n_e = 10^{21}$, and $B = 1$ MG. Here σ is the plasma conductivity, $\Omega_e = eB/m_e c$ is the electron gyrofrequency, ν_{ei} is the electron-ion collision time, ω_p is the electron plasma frequency, and $v_t = (T_e/m_e)^{1/2}$ is the electron thermal velocity. Thus, resistive diffusion is a very small effect. Even if the plasma resistivity were enhanced by anomalous processes, one would need a huge enhancement, $\nu_{ei} \sim \omega_p$, in order for resistive diffusion to be important in the equation for B .

Similarly, we may compare the convection term with the $\nabla n \times \nabla T$ source term:

$$\frac{\nabla \times (V \times B)}{(c/e)\nabla \ln n \times \nabla T} \approx \left(\frac{L}{\rho_L} \right) \frac{V}{v_t},$$

where L is a typical scale length for changes in macroscopic plasma parameters, $\rho_L = c/v_e$ is the electron Larmor radius, and V is the bulk plasma or hydrodynamic velocity. If we estimate $V \sim c_s$, the ion sound speed, then the convective term is greater than or equal to the $\nabla n \times \nabla T$ source term if

$$L \geq (M_i/m_e)^{1/2} \rho_L.$$

For a hydrogen plasma with $T_e = 500$ eV, $B = 1$ MG, this condition is $L \geq 20 \mu\text{m}$.

Generally, the plasma scale length L becomes longer, as the laser pulse proceeds. We may crudely estimate the scale length by $L = c_s \Delta t$, where Δt is the elapsed time since the laser was turned on. Then for our example above, the condition for convection to be comparable with the $\nabla n \times \nabla T$ source term can be written as

$$L \approx c_s \Delta t (M_i/m_e)^{1/2} \rho_L.$$

For the numerical parameters quoted above, this inequality is satisfied for $\Delta t \geq 100$ ps. This substantiates our statement that convection becomes important in the B equation, at times later in the laser pulse.

Since the field dissipates on a hydrodynamic time scale, and since the laser pulse length is comparable to hydrodynamic time scales, the fields should be observable for several pulse lengths. This allows for field probe measurements to be made after the laser pulse is off. Thus, any laser-induced steepening that could confuse the experimental results can be expected to relax into smooth density gradients. Furthermore, significant fields can still be observed within the vicinity of the Nd critical density.

Fig. 5-17. Beam profiles found in laser illuminations. (a) Gaussian beam with shallow temperature gradients and smaller fields: 1 J, 130 ps. (b) Ring beam with higher ∇T ; B_{max} is significantly higher, leading to 1-MG fields.

Figure 5-18 is an illustration of these effects. The calculation is of a 1-J, 150-ps laser pulse on a 150- μm Parylene disk. These conditions represent low-energy Janus shots with a 75- μm -diam spot in a ring spatial profile. Two megagauss fields are predicted that remain stationary in space during the time of interest.

The temperature contours are at 100, 300, and 500 eV. The temperature contours are relatively flat in the center of the laser beam, since the higher temperatures in the interior provide excellent thermal conductivity and smooth laser variations. The high gradients evident in both magnitude and direction (for the cross product in the source term) are very evident at the edge of the laser beam.

The resultant magnetic field intensity contours are toroidal in spatial shape and are chosen to be 200, 700,

Fig. 5-18. Plasma conditions at laser peak power. The Lagrangian mesh in cylindrical symmetry about the z axis illustrates isodensity, isotherm, and isofield profiles. The LI graph shows the beam profile used in the calculation.

and 2000 FG. The fields are sufficiently long lived that a temporal window exists after the laser pulse, during which the code predicts that field measurements can be made without large changes in the field intensity or spatial distribution. This observation leads to a criterion on the length and time delay of the 40 probe beam in a Faraday rotation experiment. It will also, hopefully, lead to less ambiguous interpretation of the Faraday probe measurements.

Estimates of the density penetration of the probe beam were also made using the LASNEX ray-tracing package. Figure 5-19 illustrates the perpendicular probe beam and demonstrates that the probe should sample close to the Nd critical frequency without substantial refractive losses.

In conclusion, then, LASNEX predicts observable magnetic fields of the thermoelectric variety in our Janus laser experiments. The steep spatial beam profile has been shown to be an advantage in generating high field growth rates. The fields are observable in a time window lasting roughly a hydrodynamic time scale. Therefore, they can be viewed after the generating pulse is turned off.

G. H. Dahlbacka
W. C. Mead
C. E. Max
J. J. Thomson

5.3.4 COMPUTER SIMULATION OF LASER-DRIVEN IMPLOSION OF DT-FILLED GLASS MICROSPHERES

The slab experiments just described provide valuable insight on absorption mechanisms of laser light. Implosion targets, specifically thin-walled glass spherical targets, provide additional information about the laser light absorption model and the presence of magnetic fields because of the highly curved nature of the

absorption/conduction region. More importantly, however, these spherical target experiments yield information about implosion symmetry, target stability, and thermonuclear burn conditions.

The agreement between calculation and experiment is determined by several laboratory measurements. The

optical energy balance is a good estimate of the energy absorbed by the target, and the scattered light angular distribution is useful in determining the profile and positioning of the laser source. The x-ray spectrum is important in determining the electron conduction and distribution of laser-heated electrons, and as an estimate of the laser energy absorbed. One of the most useful diagnostic tools is the x-ray photomicrograph which gives time-integrated information about local temperatures, and more important, a measure of the compression and the compressional point within the target system. The neutron production is important in verifying the compression (density) and DT ion temperature of the fuel.

It is this set of measurements that is used to evaluate a model using the relevant physics, as is best understood for this class of targets; namely spherical glass shells of high aspect ratio ($\sim 70:1$) that are heated rapidly with a subsequent violent implosion/explosion.

Here we present the calculations and comparisons for two experimental configurations: two-beam simultaneous irradiations and one-beam irradiations. All target and laser parameters were similar for both cases; the microsphere diameter was about $85\text{ }\mu\text{m}$ with a wall thickness of approximately $0.5\text{ }\mu\text{m}$ and a DT gas density of 2 mg/cm^3 . Each beam of the laser delivered

about 15 J in a 75-ps FWHM Gaussian profile. All laser parameters, the absorption model, the electron transport model, and hydrodynamic physics were identical for both calculations.

The two-beam simultaneous experiment is the least sensitive to variations in the physics assumptions. The imploded state shows a dominant intrusion of the glass shell into the fuel region from a position corresponding to the most intense portion of the laser beam. The majority of the neutron-producing reactions occur in the fuel just ahead of this spike due to strong local $p\text{-}dV$ work. The shape of this jet is somewhat influenced by the inclusion of the magnetic field physics but does not affect the simulated measurements to a large degree, with one exception.

Figure 5-20 is the measured and calculated x-ray spectrum for which only the portion above $h\nu = 10\text{ keV}$ is altered by the magnetic fields. It appears that the more uniform heating of the sphere does not greatly inhibit the electron conduction except near the waist; this will be contrasted to the case of the one-sided implosion later.

A very good agreement between experiment and calculation is obtained for the x-ray photomicrograph. Figure 5-21 is the microdensitometer scan of the data together with a profile of the contour along the axis of

Fig. 5-19. 4ω probe picture 250 ps after peak of main laser pulse. The mesh simulates a $0.25\text{-}\mu\text{m}$ probe light incident from the radial direction. Since the z axis is an axis of symmetry in the code, on this plot the rays reflect at the axis, travel back in the r direction and are refracted by the existing plasma density gradient. In reality the rays would continue through the z axis in their original direction.

Fig. 5-20. X-ray spectrum for simultaneous beams.

the laser beams. The corresponding computer-generated representation is also shown along with the dimensions of the interesting features.

A particularly interesting experiment to calculate is the one-sided irradiation of an 85- μm -diam ball with a 0.5- μm wall thickness. About 15 J in a 75-ps FWHM Gaussian laser pulse was focused on the target, with 3.5 ± 0.5 J being absorbed. Two calculations give considerably different results, depending primarily on the inclusion/exclusion of self-generated magnetic fields.

Figure 5-22 shows the angular distribution of scattered laser light. Experimental data points are shown for both the reflection in the plane of the laser polarization and perpendicular to it. The asymmetry between the two components most likely arises from the strong polarization dependence of resonance absorption. The line is the calculated distribution which is in agreement with the data, and verifies the approximations used in determining the input laser beam profile.

The thermoelectric generated magnetic fields are

Fig. 5-21. Microdensitometer scan and contour profile of the simultaneous irradiation experiment showing symmetric compression.

Fig. 5-22. Angular distribution of scatter laser light; laser incident from right.

strongest near the outer edge of the laser beam; it is here that the gradients of the density and electron temperature are the largest. Figure 5-23 shows the electron temperature contours; for the two calculations the effect of the magnetic field is to keep the back of the ball from being heated by conduction. However, the conduction towards the laser axis is not as severely inhibited because of the smaller temperature gradients where the interior portion of the laser source is being absorbed.

The simulation of the x-ray photomicrograph for the region between 2.0 and 3.3 keV is shown in Fig. 5-24 together with a densitometer trace drawn along the laser

axis, and the corresponding simulated pictures from the magnetic field calculation. The interesting features are that the implosion appears symmetric about the laser axis and that the region of highest x-ray emission comes from the initial position of the pusher. Indeed, the front of the shell has been translated in a distance of about 1 ball diameter. The experimental point of compression is a few micrometers behind the center, and the calculated position is 35 μm . This discrepancy is most likely due to too severe a reduction in transport coefficients.

The delay of one beam relative to the other provides some insight into the role of the electron conduction model and the behavior of the exploding pusher. From the experimental x-ray photomicrograph, the point of compression can be found relative to the initial center of the target system. Upon delaying one laser beam 42 ps relative to the other, a shift of 9 μm is measured; and for an 84-ps delay, 18 μm is measured. These two points together with the simultaneous experiment can be used to calculate an average velocity of the DT/glass interface. Figure 5-25 is a plot of the compression offset from the center of the target against the relative beam delay. The average velocity is computed to be about 0.21 $\mu\text{m}/\text{ps}$, which agrees well with the calculated value.

It has been demonstrated here that self-generated magnetic fields play an important role in determining the character of the implosion/explosion of the target. There may be, in fact, much stronger conduction inhibition arising from additional magnetic field source terms, different magnetic field diffusion coefficients, and/or inhibition from plasma fluctuations and in-

Fig. 5-23. Electron temperature contours with (a) and without (b) magnetic fields present.

Fig. 5-24. X-ray photomicrograph for the region between 2.0 and 3.3 keV (a), its computer simulation from the magnetic field calculation (b), the densitometer trace drawn along the laser axis (c), and its computer simulation from the magnetic field calculation (d).

stabilities. It has been suggested that there may be additional large magnetic fields present due to the nonaxial symmetry of the experiment and/or a large effect arising from the resonant absorption process which is dependent on the incident electric field and plasma density gradient.

There is also some indication that the absorption model (resonance absorption and parametric instabilities) may be insufficient without the inclusion of polarization effects and the self-steepening of the density gradient.

J. T. Larsen

Fig. 5-25. Plot of the compression offset from the center of the target against the relative beam delay.

5.3.5 ANALYSIS OF LASER-FUSION EXPERIMENTS DETERMINING THE ION TEMPERATURE OF BURNING DT THERMONUCLEAR FUEL

To ascertain whether the 14.1-MeV neutrons observed in the laser irradiation of DT-filled glass microspheres are generated in thermonuclear burn or reactions between a small number of fast ions, LLL has conducted experiments observing the spectral broadening on particle reaction products.⁸ These data establish an upper limit of 15 to 16 keV to the energy of the interacting ions, consistent with a temperature of 3.2 to 3.7 keV. We present here as well calculations of a nonthermal component to the broadening and demonstrate that the inferred thermal broadening is consistent with 1.6 to 2.0-keV ion temperatures calculated with the Lagrangian MHD code LASNEX. Furthermore, the observed spectral shift of several hundred keV is consistent with the calculated collisional energy loss incurred in exiting the heated glass shell.

Lawrence Livermore Laboratory has recently conducted a number of glass microsphere implosions which successfully produced millions of neutrons per shot.^{8,9} With the aid of LASNEX,¹⁰ we can calculate the alpha-particle reaction product spectra as detected in these experiments. Figure 5-26 illustrates schematically the experiment. A glass microsphere roughly 80 μm in diameter with a 0.6- μm wall thickness was filled with DT gas (the thermonuclear fuel) to a density of approximately 2 mg/cm³. This microsphere is irradiated simultaneously with two laser beams, each having an energy of roughly 13 to 15 J and each having a temporal width of about 75 ps. Each beam, focussed with an f/1.1 lens, intersected the glass microsphere at a diameter of about 60 μm . The radial profile of the beam at the position of the glass microsphere was not uniform; rather, there was roughly a 2:1 intensity difference across the beam such that the most intense portion of the beam was actually at the outer edge. The beam then took on a ring appearance. Shown also in Fig. 5-26 is a direction of the alpha-particle line of sight by the dotted line.

The data obtained from the alpha-particle detector can be summarized as follows: the alpha-particle spectrum was shifted by 250 keV down from the 3.52 MeV of the initial alpha-particle energy and the spectral width was roughly 280 keV. Brysk¹¹ has derived the relationship between the spectral width of the reaction products and the ion temperature of this interacting species. With this relationship we may infer an upper limit on the burn temperature of 2.4 keV. The significance of these two points is that the thermonuclear reactions took place within the glass shell and that they probably took place as a consequence of the interaction of ion species having relatively low energies — consistent with temperatures expected on the basis of

crude hydrodynamic arguments. In short, these data suggest that the burn took place in compressed matter and is true thermonuclear burn. We can refine these inferences considerably by referring to the results of LASNEX calculations, specifically, the temperature, density, and velocity profiles at the time of peak thermonuclear burn.

Figure 5-27 illustrates the conditions predicted by LASNEX at the time of peak thermonuclear burn.⁸ The r axis is the radius and the z axis is the distance along the laser axis of focus, which is the axis of revolution for the 2-D hydrodynamical LASNEX calculation. The initial radius of the microsphere, 40 μm , is shown at the left. Since the problem is symmetric, we have represented only the right half. The r axis is, then, a plane of symmetry. The dark line illustrates the interface at this time between the DT fuel and the glass pusher. A strong jet generated by the intense portion of the ring beam has imploded the fuel to an asymmetric configuration. The greatest ion temperatures, and hence the most intense burn, occur immediately ahead of this jet as shown by the hatched region. Electron isotherms are shown in Fig. 5-28a. The entire problem at this time shows very gradual gradients in the electron temperature. Isodensity contours are shown in Fig.

Fig. 5-26. Schematic of the glass microsphere implosion.

Fig. 5-27. Conditions predicted by LASNEX at the time of peak thermonuclear burn.

5-28b. Note that the peak compressions predicted for the fuel are on the order of a few tenths g/cm^3 . This represents a compression of perhaps 50- to 100-fold above the initial density. As discussed by Larsen,⁹ this implosion configuration is roughly consistent with the observed x-ray micrographs. Note also that there are shallow density gradients at this time. Any inferences we might make concerning the energy loss of the alpha-particle reaction products are functions of density and temperature. Since the gradients in these variables are small, we do not expect that estimates of alpha-particle losses will sensitively depend on the details of the calculation. At this time the jet is still imploding with velocities approaching 10^7 cm/s so that the alpha particles are generated in matter having high hydrodynamic velocities. The temperatures in the most intensely burning regions range between 1.5 and 2 keV.

With the aid of a few simple calculations performed by hand from the data provided from the LASNEX computation, we can make a few statements concerning the alpha-particle spectra. Let us first enumerate the broadening mechanisms. From ion temperatures of 1.5, we would anticipate thermal broadening of 200 keV on the basis of the relationship derived by Brysk.¹¹ Since alpha particles can be born on either side of the fuel region, energy losses across the fuel region appear as a broadening mechanism. In this experiment we would anticipate a broadening of about 30 to 90 keV from this mechanism. The Doppler shift from the imploding fuel adds another 60 keV.

There are a number of additional mechanisms which contribute very weakly. Energy straggling in SiO_2 is less than 20 keV. The burn lasts for only a few tens of

picoseconds, during which time there is little change in the ρR in the pusher. While the fuel has been compressed in excess of 50-fold, the ρR of the pusher has only gone up perhaps a factor of 2 or 3, so that, at the time of peak compression, it is only a few times 10^{-4} g/cm^2 . As a consequence, the temporal variations in the energy loss of alpha particles exiting through the glass is very small. Likewise there are predicted to be few spatial inhomogeneities which would also contribute to the broadening. Multiple scattering would only deviate the path of the exiting alpha particle by a few degrees; similarly, curvature because of the magnetic field is

Fig. 5-28. Electron isotherms (a) and isodensity contours (b) at the time of peak thermonuclear burn.

small; and so, as a consequence, these will have little effect in lengthening the path of some alpha particles. (The magnetic field seen in this calculation is rather large—on the order of several megagauss. But its spatial extent is so limited that it cannot bend the alpha particles by a large amount.) If these widths are added, for example, in quadrature, then we might expect a total spectral width of roughly 270 keV. This value is very close to the observed value. It is a moot point as to how to add these effects, and clearly, the correct approach is to calculate in detail the trajectory of sample alpha particles. We have done this. We may also infer from the LASNEX computation an energy loss at the time of peak burn of about 350 keV for the alpha particles exiting through the SiO₂ along the alpha-particle-detector line of sight. If there is a large electrostatic potential at the time of peak burn, its effect is unknown to us and that remains a deficiency in this logic. If the sheath potential were 50 kV, a reasonable value, the predicted collisional energy loss is corroborated by the data.

Table 5-6 lists quick estimates of the dominant mechanisms contributing to the alpha-particle spectrum. A code has been written which uses the results of the LASNEX calculation for data and calculates the alpha-particle spectrum in complete detail. The data drawn from LASNEX are the intrinsic variables, such as the velocities, temperatures, and electron and ion densities as functions of both position and time. This code is termed, then, a postprocessor code since it uses these data simply in a passive mode, tracking particles out through the Lagrangian mesh. The tracking algorithm is Monte Carlo. The sites of the reactions and the initial directions of the reaction products are chosen in Monte Carlo fashion. Likewise, the initial alpha-particle energies are distributed in Gaussian fashion with the widths and centroids as given by Brysk.¹¹ At every point, the proper transformation from the matter frame to the lab frame is observed so that Doppler shifts are automatically computed. A Monte Carlo algorithm computes, on a point-by-point basis, energy straggling and path deviation because of multiple scattering. dE/dx for each particle is computed continuously along its path. The treatment for the energy loss of free electrons and ions is a modified version of Spitzer's treatment.¹² Modifications are principally in $\ln A$ —a superior version of the Debye length, quantum mechanical treatment of small impact parameters, and the inclusion of plasma Cerenkov radiation for large impact parameters. The stopping power for bound electrons is based on a modified version of the semiempirical relationship given in the CEA report of Williamson, Boujot, and Picard.¹³ The principal modification is again in the logarithm; the mean ionization potential for the bound electrons is changed as the degree of ioniza-

Table 5-6. Dominant mechanisms contributing to the alpha particle spectrum

Broadening mechanisms			
Thermal	$\theta_i \approx 1.5\text{-}2.0 \text{ keV} \div \Delta E$	$\approx 120 \text{ keV}$	
Energy loss across fuel		$\approx 60 \text{ keV}$	
Doppler shift from hydrodynamic motion		$\approx 20 \text{ keV}$	
Energy straggling in SiO ₂		$\approx 20 \text{ keV}$	
Temporal, spatial in energy loss in SiO ₂		$\leq 20 \text{ keV}$	
Path lengthening from multiple scattering and B		small	
	Adding in quadrature	$\approx 280\text{-}300$	
Energy shift			
Loss across SiO ₂		$\approx 210\text{-keV}$	
Electrostatic Potential's		?	

tion of the atom is altered. Bending because of magnetic fields is also computed on a point-by-point basis.

Figure 5-29 illustrates the results of the alpha-particle code when applied to the LASNEX calculation shown earlier. This spectrum, influenced by thermal broadening alone, would be number one. When Doppler effects are added in, the width increases as shown in the middle graph. And finally, when energy loss mechanisms, principally across the fuel volume, are included, we have the final spectrum shown in the bottom graph. The spectral width is close to those observed experimentally.

What inferences may we draw from the alpha-particle spectrum? The alpha-particle spectrum is consistent with burn occurring at a temperature of roughly 1.8 keV in compressed matter on the interior of the glass shell. The LASNEX calculation would predict a compression of roughly 100-fold. The agreement between the predicted and experimental alpha spectra implies that we are observing true thermonuclear burn and not reactions resulting from freely accelerated ions. Because the relevant density and temperature profiles are relatively insensitive to many of the assumptions in LASNEX, we cannot use these experimental results to draw any conclusions about, for example, the spectrum of the superthermal electrons or the presence or absence of hydrodynamic instabilities. In this sense, the experiments, while strongly suggesting true thermonuclear burn, do not provide a critical test of our predictive code LASNEX or of laser fusion in general.

H. D. Shay
J. T. Larsen
G. B. Zimmerman
J. H. Nuckolls

Fig. 5-29. LASNEX-CPMC code prediction for the alpha spectrum.

5.3.6 INTERACTION OF 1.06- μm LASER LIGHT WITH SPHERICAL TARGETS IMBEDDED IN LOW-DENSITY FOAM

A target designed to study the coupling effects of 1.06- μm laser light to a glass shell consists of the spherical glass shell embedded in low-density foam. Experimentally, poor coupling of the absorbed energy to the spherical capsule was observed, resulting in a barely detectable neutron signal. The x-ray micrograph shows that the electron conduction in the target was strongly inhibited. Calculational results are presented here, indicating that the inhibited electron conduction may be the result of large spontaneously generated magnetic fields.¹⁴ Calculations including the magnetic field are seen to agree reasonably well with the experiment.

Novel fabrication techniques¹⁵ were required to produce the target shown in Fig. 5-30. A 44- μm o.d.

spherical glass shell with a 0.6- μm wall thickness contained equimolar DT gas at a density of 2 mg/cm³. The target ball was imbedded in foam of density 0.08 g/cm³. The dimensions of the foam and position of the ball are shown in the figure. The total target mass was about 15 mg. The experiment using this target was performed at the LLL Janus laser facility.¹⁶

A representation of the Janus laser beam profile is shown in Fig. 5-31. Preliminary characterization studies indicated that the spatial intensity distribution of the beam was approximately constant from its center out to some radius where the intensity rose sharply to a value of about 2 to 4 times its central value. The intense region extended roughly 10 μm beyond this, then fell off fairly rapidly. In other words, the beam profile

Table 5-7. Janus beam experimental summary

Energy on target	18 J
Pulse length	113 ps
Energy absorbed	3 to 5 J
Neutrons produced	200
Energy reflected and transmitted	6 J
Energy refracted	7 to 9 J

Fig. 5-30. Foam target. (a) Target design. (b) Schematic of target design.

Fig. 5-31. Janus laser beam. (a) Beam shape at target. (b) Spatial intensity distribution.

looked much like a bright ring with a roughly uniform and less intense central region. As is seen, the spot size chosen for this shot was roughly $70 \mu\text{m}$ at the plane of the target face. The placement of the circular ring beam on the target is also shown in Fig. 5-31. The intent was to place the ring, which contained most of the energy, concentric to the target ball.

An experimental summary is given in Table 5-7. The actual laser energy on target was 18 J delivered in a 113-ps FWHM near Gaussian pulse. Transmitted and back-reflected light was collected by the back-imaging lens and focusing lens located at the rear and front of the target chamber. This energy is measured by calorimeters and totaled about 6 J in this experiment. Light back-reflected or scattered at large angles will not be collected by the lenses. A number of photodiodes

were arrayed at various locations around the target chamber to give an estimate of the scattered or refracted energy. An analysis of the diode data resulted in an estimate of 7 to 9 J of light refracted or scattered at large angles. The resultant absorbed energy was 3 to 5 J. The neutron yield was barely detectable. An estimate for the neutron count of 200 was obtained from two different detectors, each registering signals with the appropriate timing for neutron time-of-flight.

The neutron yield was somewhat puzzling, considering the incident energy on target. When the energy balance data became available, the poor coupling of the energy to the capsule was revealed. The x-ray microscope provided interesting information, as seen in Fig. 5-32. This is a color-enhanced photomicrograph of the foam target response to the laser pulse. The ring structure of the beam is clearly evidenced by the pattern of the relatively intense x-ray emission from the target. No emission can be seen from the back of the target, indicating that it remained relatively cold. The glass shell cannot be seen, nor is an intense compression spot in evidence; hence, it appears that the energy was absorbed at the face of the foam and was trapped there. A postshot calculational study of the experiment was undertaken using the LASNEX code. The target geometry was as described in Fig. 5-30.

The LASNEX computer program, it will be remembered, is a flux-limited, multigroup diffusion photonics and electronics magnetohydrodynamics code. The ray-trace computational subroutine¹⁷ was used to describe the laser beam and its subsequent interaction with the target. A source of 100 rays was tracked through the calculations and provided a reasonable description of the energy deposition. The light energy was absorbed classically via inverse bremsstrahlung up to half the

critical density. At this point, dumpall was used to deposit 20% of the ray energy locally and put it into the suprathermal electron distribution given by $\exp \times (-1/2M_e V_e^2/kT_e)$. The suprathermal electron spectral parameter α was given a value of 4 in these calculations and seems appropriate to reproduce the measured x-ray spectrum, as will be seen shortly. The target calculation does not appear to be strongly sensitive to the above chosen values of deposition parameters, within reasonable limits.

The measured x-ray emission from the target provided the only other diagnostic data available for post-shot analysis. The light-energy balance has been previously described. It should be pointed out that a more complete and sophisticated diagnostic package has been developed and employed subsequent to the shot in question. As previously mentioned, the time-integrated spatial response of the target is measured by the x-ray microscope.¹⁸ The resolution of the instrument was thought to be less than 5 μm . The integrated x radiation above 1 keV was measured by a few x-ray calorimeters¹⁹ placed in the target chamber.

The calculated radiated energy was found to be in rough agreement with the calorimeter data. Perhaps the diagnostic data that has received the most attention is the measured x-ray spectrum. The spectral range from approximately 2 to 100 keV is covered by two detector arrays. The "seven shooter"²⁰ is an array of seven silicon PIN diodes fitted with K-edge transmission filters appropriate to the energy range of interest. Each filter transmits x rays in a preferential way, with energies just below its absorption edge. Signals from the seven channels are combined by an unfolding process to provide an absolute spectrum. The seven shooter covers the 1- to 10-keV spectral range. The "four-shooter"²¹ is an array of four photomultiplier tubes with suitable scintillator materials. Spectral coverage in the 10- to 100-keV range is provided by this detector array. The resultant measured spectrum for the experiment is shown in Fig. 5-33.

Two calculated spectra are compared directly with experiment. The calculations represent a controlled numerical experiment. The control is the magnetic field including the Bohm diffusion approximation. The calculated and measured thermal portions of the spectra are in close agreement. This portion of the spectrum is associated with the energy absorbed by the target and indeed, the absorbed energy in each calculation was 3.2 J, a value in reasonable agreement with that from the detected energy balance. It is seen, however, that the high-energy tail of the calculated spectrum, when the magnetic field is not taken into account, is in poor agreement with experiments. A comparison of the two calculations revealed a number of interesting differences. The spatial distribution of the absorbed energy

Fig. 5-32. Color-enhanced photo micrograph of the x-ray microscope data showing the foam target response to the laser pulse.

Fig. 5-33. Calculated and measured x-ray spectrum from the foam target.

was significantly affected by the magnetic field. The calculated value of the field was several megagauss, sufficient to inhibit the electron conduction into the foam. Exclusion of the magnetic field resulted in calculated electron temperatures of at least 300 eV everywhere around the glass shell. This had two adverse

effects on the calculated results. The neutron yield was too high due to the increased implosion energy deposited in the target shell. Additionally, electron temperatures this high should have made a detectable difference in the x-ray microscope data. To check this, theoretical x-ray micrographs were constructed for each calculation using a postprocessor called TDG.²⁷ A comparison of these theoretical isodensity contours with experiment is made in Fig. 5-34.

In each case, a horizontal densitometer scan is taken through the center of the relevant contours. As is seen, the FWHM of the calculated densitometer scan is detectably different from experiment if the magnetic field is excluded. This is at least consistent with other calculational evidence presented. It should be noted that a vertical scan through the contours shows a double peak consistent with the ring beam.

To briefly summarize, then, this experiment may suggest the presence of spontaneously generated magnetic fields of sufficient intensity to inhibit the transport of the energy in the target in some cases. The source terms for the fields, in this case thermoelectric plasma gradients probably associated with discontinuities in the laser beam, should be recognized and, if possible, minimized. It should be noted that the principal effect of the magnetic field on this study acts to limit the electron conduction. Other as yet unknown anomalous conduction mechanisms in the plasma could conceivably have a similar effect on the coupling efficiency; hence, further work on spontaneously generated magnetic fields should play a significant role in future laser fusion experiments.

A. R. Thiessen

5.3.7 ANALYSIS OF THE BALL-PLATE LASER FUSION TARGET EXPERIMENTS

In this section, we present the two-dimensional computer simulations of the ball-plate experiments carried out at LLL. These simulation results are in approximate agreement with the experimental space- and time-integrated x-ray spectra, x-ray microscope data, neutron yields, and laser energy absorptions.²¹ The effects of magnetic fields and other parameters on the simulation results will be discussed.

Three parameters were used to characterize the laser absorption due to plasma instabilities. Two dumpall parameters were used to model the energy absorption, and a single variable was used to define the electron temperature. The values, as well as the selection procedure for these parameters, are discussed below.

Geometrical ray tracing is used to calculate the focal, refractive, and reflective properties of the laser pulse. Assume that a ray is reflected in a linear density gradient slab (Fig. 5-35). The plasma density, ρ_i , at the

turning point of the ray in the plasma can be determined. If ρ_i is equal to or greater than $0.8\rho_c$, where ρ_c is the critical density for the laser radiation, then 25% of the energy carried by the ray is absorbed at the turning point. The energy so absorbed is placed in the superthermal electrons. In these simulations, the superthermal electron spectrum is characterized by a temperature α which is 6 times the thermal electron temperature. The selection of the values for these parameters is guided by the theoretical work of Estabrook, Valeo, and Krueer.²⁴ Theoretical uncertainties can increase the magnitude of the absorption by about 15%. In addition, the value of α can vary between 3 and 12. It should also be noted that the results of computer simulations are, to some extent, insensitive to small variations in the values of these parameters because of the finite zone size and small density scale length found in most calculations.

Fig. 5-34. Comparison of theoretical and measured density contours.

The limitations of two dimensions, no polarization, and calculation of magnetic field due to only the thermal electrons in LASNEX influence the calculated laser absorption, density scale length, temperature gradient, and magnetic field strength. These effects can give high calculated neutron yields, and high calculated thermal and low superthermal x-ray spectra. The magnitudes of the effects will depend strongly on the experimental conditions.

The physical inputs required by LASNEX are: (1) target dimensions and compositions and (2) energy, spot size, convergence angle, and spatial and temporal intensity profiles of the laser pulse.

The ball-on-plate target consisted of a 55- μm diam, 0.5- μm -thick glass microsphere containing DT gas at

density $2 \times 10^{-3} \text{ g/cm}^3$. This microsphere was attached to a 0.7- μm -thick, 120- μm -average-diam glass plate by a 10- μm -diam, 3- μm -thick glue joint. A 14-J, 90-ps FWHM laser pulse extending over 350 ps with a 4:1 ring spatial profile was focused on the target in the calculation. The ring was assumed to be about 60 μm in diameter at the center of the microsphere and had a 12° convergence angle (Fig. 5-36).

The ball-on-plate target consisted of a 55- μm -diam, 80- μm -diam, 0.6- μm -thick glass microsphere containing DT gas at density $2 \times 10^{-3} \text{ g/cm}^3$ and a glass plate located at the equatorial plane of the microsphere. This was accomplished by cutting a 90- μm -diam circular hole in the 0.7- μm -thick, 160- μm -average-diam glass plate and gluing the microsphere at the edge of the

● Nonclassical absorption - dumpall

25% absorbed
at
0.8 critical density (ρ_C)

● Superthermal electron temperature

$$\alpha = 6$$

Fig. 5-35. Parameters used to model the laser absorption due to nonclassical processes.

hole. A 10- μm -diam circular ridge around the edge of the hole was formed in the laser cutting process. Note that there existed a circular gap averaging 5 μm between the microsphere and the glass plate. In our calculation, the focusing of the laser beams on the two sides of the target, as well as other characteristics of the two laser beams, were assumed to have been identical. Each laser beam was assumed to have had 15 J of energy in a 79-ps FWHM pulse extending over 280 ps with a 2:1 ring spatial profile. The ring was assumed to be about 55 μm in diameter at the center of the microsphere and had a maximum convergence angle of 20° (Fig. 5-36).

We see in Table 5-8 that the calculated and experimental energy absorptions for the two targets are consistent with each other. But the estimated experimental errors for these data are large. Therefore, a more meaningful comparison requires better experimental measurements.

A comparison of the neutron yields (Table 5-9) shows that the calculated neutron yields for both target experiments are high. As discussed before, this effect can be the result of the limitations in the LASNEX code.

Figure 5-37 shows that the calculated and experi-

(a)

(b)

Fig. 5-36. Physical parameters used in the LASNEX calculations for the (a) ball-in-plate and (b) ball-on-plate targets.

Table 5-8. Calculated energy absorptions

	Ball-on-plate	Ball-in-plate
Experiment	3 ± 2 J	6 ± 4 J
LASNEX	2 J	6 J

Table 5-9. Calculated neutron yields

	Ball-on-plate	Ball-in-plate
Experiment	$1 \pm 0.5 \times 10^4$	$8 \pm 4 \times 10^5$
LASNEX	1×10^5	8×10^6

mental x-ray spectra for the ball-in-plate target agree surprisingly well. Using a value of 4 for α would lower the superthermal spectrum in the 20- to 100-keV range, and the slope would be more parallel to the experimental spectrum.

We show in Fig. 5-38 the comparison between the experimental x-ray spectrum and that calculated from LASNEX simulations when the magnetic field effects were turned on and off for the ball-on-plate target. As in the case of the ball-in-plate target, the experimental x-ray spectrum is in good agreement with the calculated spectra obtained when the magnetic field effects were included. Large deviations in the superthermal portion of the x-ray spectrum were observed between the data and the calculated results without magnetic field. This is in agreement with the results of Thiessen²⁵ for the foam target.

The fact that we simulate properly the implosion shapes for the two ball-plate targets can be demon-

Fig. 5-37. Calculated and experimental x-ray spectra for the ball-in-plate target.

Fig. 5-38. Comparison of the experimental x-ray spectrum for the ball-on-plate target with spectra calculated from LASNEX simulations with the magnetic field effects both on and off.

strated by comparing our calculated results with the x-ray microscope data. Figure 5-39 shows this comparison along the symmetry axis of the two targets. The location of the plate as well as the consequences of laser misalignment are clearly observed in the ball-in-plate target. The positions as well as the widths of the compression peaks are in approximate agreement.

We have shown that LASNEX two-dimensional simulation results of two ball-plate targets are in approximate agreement with the available data.

Y. L. Pan

Fig. 5-39. Comparison of (a) ball-on-plate and (b) ball-in-plate target implosion shapes along the symmetry axis; 3-μm resolution.

5.4 Theory and Code Development

Most of LLL's laser fusion computer calculations are done on LASNEX, a two-dimensional magnetohydrodynamic code written by George Zimmerman, Dave Bailey, and Dave Kershaw. A continual updating of the physics and models in LASNEX occurs as we gain new

understanding of the laser/plasma interactions. Two areas recently investigated are described here, including a semi-Eulerian hydrodynamics option for LASNEX and a description of angle-dependent absorption of laser light.

5.4.1 DEVELOPMENT OF THE LASNEX COMPUTER PROGRAM

The LLL two-dimensional hydrodynamic-energy-transport code LASNEX²⁶⁻²⁸ has been modified to allow material motion relative to the mesh lines. In the past this program has been purely Lagrangian—the mesh always moved with the matter, even in shearing or turbulent regions. Often this created very small or badly distorted zones which could lead to inefficient and inaccurate calculations. By allowing some material flows to pass through the mesh, we have realized a reduction in both the computer time and the amount of human intervention required to perform complex laser fusion calculations.

After the normal Lagrange time step is completed, a new mesh is established, and all physical variables are

mapped onto it. The overlaying procedure is similar to that used in Ref. 29 and conserves mass momentum and internal energy. Kinetic energy is conserved only if velocity gradients are well resolved by the mesh.

There is no single "best" method of establishing the new mesh. We have chosen a relaxation method that favors a pure Lagrange calculation except in regions that would cause zone distortion. In addition, the mesh is constrained to be Lagrangian on material interfaces and in regions of steep density gradients. These constraints help to minimize the numerical diffusion inherent in the overlaying procedure.

We have used the semi-Eulerian hydrodynamics option in LASNEX to calculate several laser fusion

Fig. 5-40. A purely Lagrangian calculation of a ball and disk target after absorption of 1.0 J of laser light. Some manual zone straightening was required.

targets. As an example, Figs. 5-40 and 5-41 show a ball and disk target after 1.0 J of laser light is absorbed. At this point, exploding pieces of the ball and disk have collided together and matter is squirting out from between them. Figure 5-40 is from a pure Lagrange calculation which had already required manual zone straightening several times. The calculation that produced Fig. 5-41 used semi-Eulerian hydrodynamics and ran to completion with no human intervention. The pictures shown are at different times because the

semi-Eulerian calculation absorbed laser energy at a faster rate. This is due at least in part to numerical diffusion which increases the density scale height and reduces the temperature. On the other hand, the pure Lagrange calculation suffers from errors caused by severe zone distortion. It is difficult to ascertain which of these calculations more closely represents the actual experiment.

G. B. Zimmerman

Fig. 5-41. A semi-Eulerian calculation of the same target as in Fig. 5-40. This calculation allows material to flow through the mesh but may suffer from numerical diffusion errors.

5.4.2 ANGLE-DEPENDENT ABSORPTION

The current picture of laser/plasma coupling near the critical surface is that the component of electric field in the plane of incidence of an incoming light ray near the turning point can excite plasma waves at the critical region and thereby transfer energy to the plasma. This process, known as resonant absorption, has been studied on a small scale, spatial and temporal (Debye length, electron plasma period), by the plasma theorists using simulation codes; they have extracted

results that can be applied on the much larger scales in a hydro code. Basically they have presented results for the absorption averaged over incident polarizations as a function of the incident angle (as referred to vacuum based on a linear slab model) which controls how close the turning point is to the critical surface, and the resulting electron spectrum of the absorbed energy.

The current absorption model in LASNEX used to absorb energy at the turning point is shown in Fig.

Fig. 5-42. The absorption efficiency vs angle of incidence. (a) Previous model in LASNEX. (b) Present model. The points are from a series of two-dimensional computer simulations with the electric vector of the light in the plane of incidence, $I = 10^{10} \text{ W cm}^{-2}$, and $T_e = 4 \text{ keV}$ initially. The dashed line is an estimate (based on these simulations) of the net absorption efficiency for light incident with an equal mix of polarizations.

5-42a. The model assumes a constant absorption from normal incidence to some cutoff angle, and the energy goes into a Maxwellian (of ALPHA times T_e) at the turning point. The new model (depicted in Fig. 5-42b as presently predicted by plasma simulation codes) now allows an arbitrary specification of the absorption vs incident angle and hence can be adjusted to mock up

changes in polarization, etc., that can affect the absorption. The electron spectrum is still done in the same way as before, since it appears to be a fair representation of the electron heating.

D. S. Bailey

5.5 Electron and Ion Beam Targets

The possibility of attaining high power levels from relativistic electron beam accelerators in the form of charged particles has prompted several studies to determine the feasibility of using electrons or ions as a source to implode fusion targets. The areas summarized here include multiple-shell targets designed for fusion

gains of unity or greater, targets designed to produce thermonuclear yield from existing electron beam machines, a study of instabilities for both electron and ion beam targets, and a description of electron beam deposition in high Z plasmas.

5.5.1 LOW-POWER MULTIPLE-SHELL FUSION TARGETS FOR USE WITH ELECTRON AND ION BEAMS

Previously published designs by Clauser and Sweeney^{30,31} for fusion targets driven by energetic charged particles rely mainly on single-shell configurations. Kirkpatrick *et al.*³² have published a double-shell design but use a very unrealistic deposition scheme. The work reported here shows how one can make use of more complex target configurations and shorter range particles to lower the power and energy require-

ments.

Electron-beam and ion-beam targets have absorption shells about 1 range thick, essentially because there is no ablation front which propagates through the shell. This occurs for two reasons:

- There is little density or temperature dependence in the range, so except for spherical convergence effects the beam deposits in the same mass throughout the

implosion. Since some of the mass moves inward and some moves outward, the convergence effects are small.

- The matter temperatures achieved are only a few hundred electron volts at most and electron conduction is inefficient at carrying the energy beyond the matter where it is absorbed.

Since the required input energy is approximately proportional to the target mass, targets imploded with long-range particles are going to require large energies and high power. To significantly reduce the required power and energy, we must reduce the range of the particle carrying the energy.

Single shells of high Z material can be used with particles such as 1-MeV electrons, which have a long range, to achieve fusion breakeven. For these long-range particles, the thermal radiation generated by the hot plasma is substantially self-trapped, thus limiting the radiation losses. For example, in a typical target with 1-MeV electrons on gold, radiation losses are about 40% of the input energy. For 1-MeV electrons on iron, the losses are about 20%. On the other hand, for 100-keV electrons or 10-MeV alpha particles on gold, virtually all of the input energy is radiated away as thermal x-rays. Such targets may be useful as x-ray sources but not for implosions. To limit the thermal x-ray losses to a tolerable value, these short-range particles, which are necessary for breakeven at low energies and powers, must be absorbed in low Z and, hence, low-density materials. Even in CH_2 , using 10-MeV alpha particles thermal x-rays result in about a 50% loss of input energy. This loss can be limited to about 20% by using LiD or LiH.

Low Z materials are very poor pushers and tampers. Unless a target can be designed which achieves sufficient velocity to ignite without a pusher, a layer of high Z material must be added for a pusher. With double-shell targets, we can use a low Z , low-density material for the outer shell. This allows us to increase the radius while keeping down the mass and maintaining a sufficiently small aspect ratio that fluid instabilities can be tolerated. The high Z pusher-tamper layer needed for ignition and efficient burn at the low velocities we are generally able to generate with e-beams or i-beams is placed at a much smaller radius. This keeps its thickness sufficient to survive fluid instability and also to act as a preheat shield against photons or high-energy electrons and ions. If we tried to put a high Z pusher against a low Z exploding ablator, it would be very thin, making it very susceptible to preheat and fluid instability.

The larger radius of a double-shell design at a given energy also reduces the focusing requirements of the beam. The penalty one pays for this advantage is larger convergence ratio $R_0/R_{\min}$. Here R_0 is the initial radius

of the outer shell, and $R_{\min}$ is the minimum radius of the fuel. The convergence ratios for the various double-shell designs given below are about 100, implying a 1% uniformity of deposition. By contrast, convergence ratios of various single-shell designs that have been published are 20 to 30, implying a uniformity of 3 to 5%.

The lowest power, double-shell i-beam breakeven target designed to date is shown in Fig. 5-43. This target and all others to be presented here have been calculated using the LASNEX¹⁰ computer code written by George Zimmerman of LLL. This target gives a theoretical yield of 65 kJ with 45 kJ of 9-MeV alpha particles which have a range of 0.0114 g/cm². The pellet requires a peak power of 11 TW. The target performance characteristics and pulse shape are given

Fig. 5-43. Pellet imploded with 9-MeV alpha particles.

in Table 5-10. The energy deposition profile includes range straggling and 5 mrad of beam divergence from finite temperature and scattering at the source. The source is assumed to be 10 cm from the target. Also, for this target, the range of the ions was varied linearly with the power, a crude attempt to model a constant impedance machine. When the photon transport is represented by a single group diffusion model, this feature of the deposition profile does not significantly affect the peak power required compared to that which would be required for a constant range profile. Its principal effect is to keep the higher energy thermal photons from leaking out of the outer shell and getting into the inner gold shell, thus degrading the implosion.

Recent 2-D calculations indicate that the design shown in Fig. 5-43 will not survive Rayleigh-Taylor instability. The target can be redesigned to have a more rapid early acceleration and a thicker outer shell. These modifications will probably result in about a factor 2 increase in required power, but other comments above will not be affected.

In comparison with single-shell targets for longer range particles, the advantage of a double-shell target is not so obvious. Since the outer shell must have the same g/cm^2 as the single-shell target, its larger radius means it must have more mass. For example, the target shown in Fig. 5-44 for use with 1-MeV electrons has about twice the radius of a breakeven single-shell target. The iron mass is about 3 times that of a breakeven single shell.³⁵ Because of the velocity multiplication on the gold, the average implosion velocity is about half, and its radius twice that of the single shell,

Table 5-10. Properties of 9-MeV alpha driven target —

Time (ns)	Power (TW)	Range (g/cm^2)
0.0	0.11	0.000114
6.8	1.1	0.00114
13.6	11.1	0.0114

Power and range vary linearly between listed values

Input energy (kJ)	46.0
Yield (kJ)	66.0
ρ (DT) (g/cm^2)	0.33
ρ (Au) (g/cm^2)	2.0
V_{max} (Au) (cm/s)	3.20×10^7
V_{max} (LiD) (cm/s)	2.25×10^7
Burn temp (keV)	17.0

Fig. 5-44. Double-shell target driven by 1-MeV electrons.

so we might expect similar power and a somewhat greater energy input than for the single shell. The double-shell design in Fig. 5-44 achieves a little over breakeven at 250 TW with 4.5 MJ input, about a 50% increase in energy and 50% decrease in power relative to a single-shell target.

J. D. Lindl
R. O. Bangerter

Existing electron beam accelerators are characterized by tens of kilojoule beam energies and pulse lengths typically in excess of 50 ns. The resulting power is thus substantially below the 250 TW and 4.5 MJ required for breakeven fusion.³ However, if targets could be designed for existing machines, then a greater understanding of beam/target interactions and implosion physics could be gained, allowing refinement of designs for future machines and targets. A particular target approach that addresses the problem of long pulse widths and low power is described here, and supporting code calculations predict thermonuclear burn conditions in such a pellet imploded by present-day accelerators.

The range of parameters considered for this design was restricted to beam voltages of 1 MeV and pulse widths of 50 ns, with zero rise and fall time. Total beam energy was varied from 10 to 100 kJ. The target is characterized by a relatively large diameter, i.e., 1 cm, and a shell thickness equal to one-third the classical range of 1-MeV electrons. The interior of the shell is filled with low-density DT gas, and the shell itself is composed of either gold, copper, or lithium. The electron beam is also 1 cm in diameter and is restricted to flow in the axial direction, with a uniform current density in the radial dimension. The advantages of using a larger beam include: (1) relaxation of the superpinch requirement, and (2) a larger energy content of the incoming beam compared to a superpinched beam.

The thin shell of the target allows the use of a different mechanism for imploding the capsule than suggested for breakeven targets. The shell itself acts as an isothermally heated pusher causing faster implosion velocities than would be attainable from a shell with a thickness equal to a classical range. The shell allows the 1-MeV electrons to penetrate to the fuel; and, in fact, a large portion of the incident beam passes right through the target. The result is an axially flowing current through the pellet which both heats the plasma and forms a B_0 field inside the shell. This concept was first suggested by Physics International³⁴ and separately reported by Rudakov of the Kurchatov Institute.³⁵

The existence of the magnetic field depends strongly on the location and magnitude of the return current. If the return current flows through the fuel region, the magnetic field inside the shell is greatly reduced. However, if the return current flows outside the gas, several effects become important. Normally, a long output pulse would allow the gas to cool by thermal conduction to the shell wall as the pellet is imploding. The net magnetic field coupled to the beam-heated plasma

reduces the thermal conduction to the wall, which for this design is the maximum loss term. The self-field of the beam can also increase the alpha deposition at burn time if the Larmor radius of the alpha particles is less than the radius of the sphere of fuel. Thus, the incident beam explodes the shell, preheats the gas, and, depending on the return current path, can reduce thermal conduction to the walls and increase alpha deposition.

To ensure the implosion of the target occurs with good symmetry, one must determine the shell thickness and material that allows the beam to uniformly heat the shell and still deposit a significant fraction of the input energy. The best material appears to be lithium, as it has a very low scattering angle for 1-MeV electrons, allowing the beam to pass through the shell essentially unchanged in direction; but the shell still absorbs a large fraction of the beam energy.

To determine the heating effects of the incoming electron beam, LASNEX was run with the hydrodynamic motion turned off. The resulting fuel temperatures represent beam heating only, as there was no compression by the shell. The temperatures ranged from 0.5 eV at 10 kJ to 5.4 eV at 100 kJ of beam input energy for the lithium shell. Although only a few electron volts of preheat exists, adiabatic compression of the gas would cause significant ion temperatures in the fuel.

True adiabatic compression cannot be achieved at these beam energies and implosion times, but the thermal losses can be greatly reduced by the magnetic field induced by the penetrating beam. Following the method of Braginskii,³⁶ we can show that the thermal conductivity varies as $\rho^2/B^2\eta^{1/2}$. For a 100-kJ beam and no current neutralization the thermal conduction can be reduced by a factor of 10^5 .

One question that must be addressed is the diffusion time of the magnetic field through the shell. Using the conductivity of lithium at room temperature yields a diffusion time of the order of 1 μ s, long compared to typical implosion times of 150 to 350 ns. Thus the field should remain trapped in the plasma long enough to prevent thermal losses during implosion.

Implosion calculations using LASNEX were done for an incoming flux of 1-MeV electrons with a 50-ns pulse width, and total beam energy ranging from 10 to 100 kJ. Thermal conduction losses were reduced by amounts consistent with the incoming beam current and particular fuel density. Figure 5-45 shows the expected output from a 1-mm-thick lithium shell plotted as a function of input beam energy. The range of data shown in Fig. 5-45 extends from 10^2 neutrons at 10 kJ to 7×10^{10} neutrons at 100 kJ, and represents a pellet

optimized in both initial fuel density and shell thickness. Peak yield occurs at $\rho = 10^{-7} \text{ g/cm}^3$; however, this density requires a large compression ratio and thus a more stringent beam uniformity than a target with a higher density. Therefore, if beam irregularities cannot be removed, a higher fuel density is suggested even though lower outputs are predicted.

Varying the shell thickness reveals an optimum occurring at 1 mm of lithium. Although the implosion velocity should increase as the shell thickness is reduced, the thinner shells absorb much less of the incoming beam and therefore do not provide as much output.

The second curve plotted in Fig. 5-45 indicates the yield expected from a target with an inner diameter of 3 mm. Although the neutron output is greatly increased, this geometry requires that the same beam energy be made available in an area approximately 10 times smaller than the 1.0-cm beam.

Output characteristics for the optimum lithium shell design are shown in Fig. 5-46. The highest values of ion temperature noted are 2 keV with implosion velocities of $4 \text{ cm}/\mu\text{s}$. The densities obtained at maximum compression are 0.2 g/cm^3 , yielding a ρr of 0.001 g/cm^2 . The time to maximum compression is typically several hundred nanoseconds due to the large shell diameter and low implosion velocity; but this is desirable as it removes the uncertainty of the neutron flux being caused by beam/target interactions.

D. J. Meeker
J. H. Nuckolls

Fig. 5-45. 14-MeV neutron output as a function of input beam energy for two sizes of lithium targets, (a) 1.0 cm diameter; (b) 3 mm diameter.

5.5.3 STABILITY OF ELECTRON AND ION BEAM TARGETS

The preceding target design does not suffer from hydrodynamic stability because the isothermally heated pusher explodes, thus removing sharp density gradients in the continually expanding shell. In typical pellets designed to give a net energy gain this condition does not exist, as a cold, dense pusher is accelerated by an ablating outer surface.

The familiar phenomenon of Rayleigh-Taylor insta-

bility occurs when two fluids of density ρ_1 and ρ_2 ($\rho_1 \neq \rho_2$) are placed in contact and accelerated in a direction normal to the interface and directed toward the denser fluid. Specifically, let us assume an acceleration a along the z axis. If a perturbation of the form $\eta_0 \sin kx$ is applied to an interface at $z = z_0$, the amplitude η at time t is given by

$$\eta = \eta_0 e^{\gamma t}, \quad (1)$$

where

$$\gamma = \sqrt{\alpha k a} \quad (2)$$

and

$$\alpha = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

is the Atwood number. In this case we assume that the fluid of density ρ_2 occupies the region $z > z_0$ so that exponential growth occurs when $\rho_2 > \rho_1$ and $a > 0$.

Equation (1) is valid for $\eta < \lambda = 2\pi/k$. For $\eta < \lambda$ the growth rate becomes more nearly linear in time.³⁷

We consider only spherical fusion targets. In this case, we expand the perturbation in spherical harmonics of order ℓ and replace k in Eq. (2) by $k = \ell/r$, where r is the radius of the interface.

There are at least three cases in typical electron- and ion-beam fusion targets where Rayleigh-Taylor instability is likely to play an important role. These are shown in Fig. 5-47.

Case I occurs when an initially uniform spherical shell is heated on the outside by an electron or ion beam. The region in which the beam is deposited expands, producing a low-density medium which accelerates the denser material lying inside of the beam

deposition region. It might be expected that Eq. (2) would not be valid in this case, since one does not expect a density discontinuity but a more gradual density transition. If the density transition between ρ_1 and ρ_2 is exponential, such that

$$\rho = \begin{cases} \rho_1 & z \leq z_0 \\ \rho_1 e^{\beta(z - z_0)} & z_0 < z < z_1 \\ \rho_2 & z_1 \leq z \end{cases},$$

where z_1 is chosen to insure the continuity of ρ , it can be shown³⁸ that we must make the replacement

$$k \rightarrow \frac{k\beta}{K + \beta}$$

in Eq. (2).

Case II can occur in target designs having an initial density discontinuity.

Case III occurs near the end of an implosion when the pressure in a relatively light fuel region becomes sufficiently great to decelerate the dense pusher surrounding the fuel.

We have studied Case I instability for electron- and ion-beam targets using LASNEX.³⁹ Multiple scattering and bremsstrahlung strongly influence electron deposition but are unimportant in ion deposition. This can

Fig. 5-46. Lithium pellet implosion characteristics.

Fig. 5-47. Three possible cases of Rayleigh-Taylor instability.

result in rather different density profiles for the two cases. Figure 5-43 compares the density profiles produced by irradiating gold with 1-MeV electrons and 10-MeV protons. In the electron case, $k \gg \beta$ for k values of interest so that relation (3) gives $k \rightarrow \beta$ resulting in a comfortably small growth rate. By contrast, the ion case has a large value of β so that

ion-beam targets are quite subject to Case I instability. This imposes rather severe constraints on the design of ion-beam targets. Nevertheless, we calculate that 10-MeV proton beams can still produce fusion energy at lower beam power levels than 1-MeV electrons.

R. O. Bangerter

5.5.4 INTERACTION OF RELATIVISTIC ELECTRON BEAMS WITH HIGH Z PLASMAS

To properly model the electron-beam deposition that occurs in targets such as those just discussed, a set of relativistic multigroup diffusion equations has been derived for the study of electron-beam/target interactions. Included are transport, Coulomb collisions, electric and magnetic fields, bremsstrahlung, and hydrodynamic motion of the background plasma. LAS-NEX, the laser fusion code, has been modified to include these equations and will be used for modeling electron beam fusion.

Basic Equations

The relativistic Boltzmann equation with the collision term derived by Mosher⁴⁰ is taken as a starting point:

$$\frac{\partial f}{\partial t} + \frac{c^2 \vec{p}}{\epsilon} \cdot \frac{\partial f}{\partial \vec{x}} - e(\vec{E} + \frac{c\vec{p}}{\epsilon} \times \vec{B}) \cdot \frac{\partial f}{\partial \vec{p}} = -\frac{\partial \Gamma}{\partial \vec{p}}, \quad (1)$$

where

$$\text{number of electrons} = \int d^3\vec{x} d^3\vec{p} f(\vec{x}, \vec{p}),$$

$$\epsilon = \sqrt{(mc^2)^2 + (pc)^2},$$

$$\gamma = \epsilon/mc^2,$$

$$\Gamma = \frac{-m\gamma}{p^3} \sum_{k=1}^n C_k \ln \Lambda_k \left[\sum_j (\delta_{ij} p^2 - p_i p_j) \frac{\partial f}{\partial p_j} + 2\gamma \frac{m_e}{m_k} p_i f \right],$$

Fig. 5-48. Comparisons of density gradients produced by 10 MeV protons and 1 MeV electrons.

$k = 1$ is electron scattering and $k = 2, \dots, n$ is scattering off the various ion species, and

$$C_k \ln \Lambda_k = 2\pi n_k Z_k^2 r_0^2 (m_e c^2)^2 \ln(b_k^{\max}/b_k^{\min}).$$

Since high Z plasmas are assumed, it is reasonable to make the diffusion approximation. But since the background plasma is in motion it is important when making the diffusion approximation to assume near isotropy in the local rest frame of the moving matter rather than in the laboratory rest frame. Taking the $\int d\Omega'$ (zeroth moment) of Eq. (1) and neglecting terms which are smaller by factors of v/c , v/u , $m_e/m_i \ll 1$, we get,

$$\begin{aligned} \frac{\partial n}{\partial t} + (\vec{v} \cdot \vec{\nabla}) n = -\vec{\nabla} \cdot \vec{F} + \frac{1}{3} p \frac{\partial n}{\partial p} (\vec{v} \cdot \vec{v}) \\ + \frac{e}{(pc)^2} \frac{\partial}{\partial p} (\epsilon p \vec{E} \cdot \vec{F}) + \frac{2m_e}{p^2} \frac{\partial}{\partial p} (\gamma^2 n c_e \ln \Lambda_e), \end{aligned} \quad (2a)$$

where all primes have been dropped and from now on all unprimed quantities (except for x , t , and v) are assumed to be local matter rest frame quantities.

Similarly, taking the $\int d\Omega' u'$ (first moment) of Eq. (1), neglecting terms smaller by factors of v/c and $1/Z^2$, and assuming that on time scales of interest the flux equation (first moment equation) is always relaxed so that $\partial F/\partial t$ may be neglected, we get,

$$\begin{aligned} -\frac{2m_e \gamma}{p^3} (\sum C_k \ln \Lambda_k) \vec{F} - \frac{e}{m \gamma c} (\vec{F} \times \vec{B}) \\ = \frac{1}{3} u^2 \vec{\nabla} n - \frac{e \vec{E}}{3m \gamma} p \frac{\partial n}{\partial p}. \end{aligned} \quad (2b)$$

Equations (2a) and (2b) are our basic equations for modeling the evolution of the relativistic electrons in electron-beam interactions with a high Z plasma target.

Physical Significance of the Various Terms

It will prove convenient to use a different normalization. Define

$$np^2 dp = \eta de,$$

$$\vec{F} p^2 dp = \vec{\Phi} de,$$

or

$$n = \eta / (p m \gamma),$$

$$\vec{F} = \vec{\Phi} / (p m \gamma),$$

so that

$$\text{number of electrons} = \int d^3 \vec{x} de \eta(\epsilon, \vec{x}, t).$$

Then Eqs. (2a) and (2b) become, after some rearrangement,

$$\begin{aligned} \frac{\partial \eta}{\partial t} + \vec{v} \cdot (\vec{v} \eta) = -\vec{\nabla} \cdot \vec{\Phi} + \frac{(\vec{v} \cdot \vec{v})}{3} \frac{\partial}{\partial \epsilon} (p u \eta) \\ + \frac{\partial}{\partial \epsilon} (e \vec{E} \cdot \vec{\Phi}) + \frac{2}{m_e} \frac{\partial}{\partial \epsilon} \left[\left(\frac{c_e \ln \Lambda_e}{u} \right) \eta \right], \end{aligned} \quad (3a)$$

and

$$\begin{aligned} -\frac{2(m \gamma)^2}{p^3} [\sum C_k \ln \Lambda_k] \vec{\Phi} - \frac{e}{c} (\vec{\Phi} \times \vec{B}) \\ = \frac{1}{3} p u \vec{\nabla} \eta - \frac{e \vec{E}}{3} p^3 \frac{\partial}{\partial \epsilon} \left(\frac{\eta}{p m \gamma} \right). \end{aligned} \quad (3b)$$

The transport term in Eq. (3a), $-\vec{\nabla} \cdot \vec{\Phi}$, makes a multigroup diffusion treatment vital. Mosher¹¹ has shown that in a spatially homogeneous plasma a monoenergetic beam stays monoenergetic as the average energy decreases due to collisional energy loss. However, in a spatially inhomogeneous plasma such as

an electron beam target, electrons will transport into the target, reach a certain density, and then reflect out again. The electrons just coming in for the first time will have a much higher energy than those at the same location that are coming out from the target and have undergone considerable energy loss. Thus, at a given point in space, the electron distribution will be far from monoenergetic, as is borne out by Monte Carlo computer simulations,* and η will in general be an arbitrary function of ϵ .

The $(\nabla \cdot v)/3(\partial/\partial\epsilon)(pu\eta)$ term is just a Doppler shift of the electrons to compensate the $P_e \cdot dV$ work done by the beam electrons on the matter.

The $\partial/\partial\epsilon (eE \cdot \Phi)$ term is the energy loss of the beam electrons due to ohmic heating of the background plasma.

The $(2/m_e)(\partial/\partial\epsilon) [C_k \ln \Lambda_k / u] \eta$ term is the beam energy loss due to collisions with thermal electrons.

Equation (3b) is a multigroup version of Ohm's law. The coefficient of the flux, $[-2(m\gamma)^2/p^3] [C_k \ln \Lambda_k] = R(\epsilon, x)$, is the resistance. The forces driving the flux are

$$\frac{-e}{c} (\vec{\Phi} \times \vec{B}) ,$$

the $(1/c) (J \times B)$ force, where $J = Ie\Phi =$ current density per unit energy, $pu\vec{\nabla} \eta/3$, the $-\nabla p_e(\epsilon)$ force, where $p_e(\epsilon) = pu\eta/3 =$ electron pressure per unit energy, and $(eE/3) p^3 (\partial/\partial\epsilon) (\eta/(pm\gamma))$ which is just the multigroup form of the electric field force as can be seen from

$$\frac{e\vec{E}}{3} \int p^3 \frac{\partial}{\partial\epsilon} \left(\frac{\eta}{pm\gamma} \right) d\epsilon = -e\vec{E} \int \eta d\epsilon = -e\vec{E} n_e .$$

Finally, the effects of bremsstrahlung are included by adding to Eq. (3a) an additional term of the form

$$n_i \left[\int_0^\infty dk \eta(\epsilon + k) u_k \frac{d\sigma}{dk} - \eta(\epsilon) u \int_0^\epsilon dk \frac{d\sigma}{dk} \right] ,$$

where n_i is the ion density, k is the photon energy, $u_k = c [(\epsilon + k)^2 - (mc^2)^2]^{1/2} / (\epsilon + k)$, and $d\sigma/dk$ is the bremsstrahlung cross section.⁴³

For a typical high Z plasma, e.g., Pb, above 15 to 20 MeV more energy is lost through bremsstrahlung than through scattering of plasma electrons. Even at 1 MeV in Pb, bremsstrahlung losses are 10% of the total energy loss. Therefore bremsstrahlung is an important loss mechanism. This term is also important for diagnostic purposes and for the study of preheat problems.

Numerical Questions

The computer code LASNEX¹⁰ already incorporates a complete description of the thermal background plasma, so only the numerical coding of the superthermal beam electron equations need be discussed.

The basic point is that one requires fully implicit differencing [i.e., all quantities on the right-hand side of Eq. (3a) are evaluated at the end of the time step] so that when the time step gets much larger than the relaxation time, the code will calculate the steady-state solution (with the given electromagnetic fields, background plasma conditions, and boundary conditions).

D. S. Kershaw

*These simulations were done with a relative electron beam entering a static high Z plasma using the computer code SANDYL.⁴²

References

1. R. A. Haas, D. W. Phillion, M. J. Boyle, H. N. Kornblum, and V. C. Rupert, *Bull. Am. Phys. Soc.* **20**, 1246 (1975).
2. W. L. Kruer, E. J. Valeo, and K. G. Estabrook, *Phys. Rev. Letters* **35**, 1076 (1975).
3. V. L. Ginsburg, *The Propagation of Electromagnetic Waves in Plasma* (Pergamon Press, New York, 1964), p. 260.
4. B. H. Ripon *et al.*, *Phys. Rev. Letters* **34**, 1313 (1975).
5. H. Ahlstrom, *Bull. Am. Phys. Soc.* **20**, 1230 (1975).
6. J. A. Stamper and B. H. Ripin, *Phys. Rev. Letters* **34**, 138 (1975).
7. D. T. Attwood, D. W. Sweeney, and L. W. Coleman, *Bull. Am. Phys. Soc.* **20**, 1266 (1975).
8. H. G. Ahlstrom, V. W. Slivinsky, K. G. Tirsell, E. K. Storm, S. S. Glaros, and D. E. Campbell, "Experimental Determination of DT Ion Temperatures in Laser Fusion Targets," *Bull. Am. Phys. Soc.* **20**, 1267 (1975); *Phys. Rev. Letters*, **35**, 1083 (1975).
9. J. Larsen, "Computer Simulation of Laser-Driven Implosion of DT-Filled Glass Microballoons," *Bull. Am. Phys. Soc.* **20**, 1267 (1975).
10. G. B. Zimmerman, and W. L. Kruer, *Comments in Plasma Physics and Controlled Thermonuclear Fusion* **2**, 85 (1975).
11. H. Brysk, *Plasma Phys.* **15**, 611 (1973).
12. L. Spitzer, *Physics of Fully Ionized Gases* (John Wiley and Sons, New York, 1967), pp. 120-136.
13. C. F. Williamson, J. P. Boujot, and J. Picard, *Tables of Range and Stopping Power of Chemical Elements for Charges Particles of Energy .05 to 500 MeV*, Centre d' Etudes Nucleaires de Saclay, Rapport CEA-R3042 (1966).
14. J. A. Stamper and D. A. Tidman, *Phys. Fluids* **16**, 2024 (1973).
15. J. A. Rinde and R. R. Stone, *Preparation and Fabrication of Low-Density Microcellular Foam Laser Targets*, Lawrence Livermore Laboratory, Rept. UCRL-51708 (1975).
16. *Laser Program Annual Report-1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975).
17. See Ref. 16, p. 368.
18. *Laser Fusion Program Semiannual Report-July-December 1973*, Lawrence Livermore Laboratory, Rept. UCRL-50021-73-2 (1974), p. 93.
19. See Ref. 16, p. 439.
20. See Ref. 16, p. 310.
21. V. W. Slivinsky, H. N. Kornblum, and H. Shay, "Determination of Suprathermal Electron Distribution in Laser-Produced Plasmas," *J. Appl. Phys.* **46**, 5 (1975).
22. See Ref. 18, p. 74.
23. J. F. Holzhrichter *et al.*, "Laser Implosion and Fusion with Ball-on-Plate and Ball-in-Plate Targets," *Bull. Am. Phys. Soc.* **20**, 1266 (1975).
24. K. Estabrook, E. Valeo, and W. Kruer, *Phys. Fluids*, **18**, 1151 (1975).
25. A. R. Thiessen, "Interaction of 1.05 μ m Laser Light with Spherical Targets Imbedded in Low-Density Foam," *Bull. Am. Phys. Soc.* **20**, 1230 (1975).
26. *Laser-Fusion Program Semiannual Report-January-June 1972*, Lawrence Livermore Laboratory, Rept. UCRL-50021-72-1 (1972), p. 107.
27. See Ref. 18, p. 69.
28. See Ref. 16, p. 368.
29. F. H. Harlow and A. A. Amsden, *J. Comp. Phys.* **16**, 1 (1974).
30. M. A. Sweeney and M. J. Clauser, *Appl. Phys. Letters* **27**, 483 (1975).
31. M. J. Clauser, *Phys. Rev. Letters* **35**, 848 (1975).
32. R. C. Kirkpatrick *et al.*, *Nuclear Fusion* **15**, 333 (1975).
33. J. D. Lindl and R. O. Bangerter, "Low Power Multiple Shell Fusion Targets for Use With Electron and Ion Beams," *Bull. Am. Phys. Soc.* **20**, 1352 (1975).
34. Physics International, Inc., private communication.
35. M. V. Babykin, Ye. K. Zavoisky, A. A. Ivanov, and L. I. Rudakov, *Nuclear Fusion, Supplement 1972*, pp. 75.
36. S. I. Braginski, *Reviews of Plasma Physics*, **1** (Consultants Bureau, New York, 1965), p. 205.

37. An exact description of large-amplitude Rayleigh-Taylor instability is extremely complex. See W. P. Crowley, Lawrence Livermore Laboratory, Rept. UCRL-72656 (1970).
38. R. LeVier, G. Lasher, and F. Bjorklund, Lawrence Livermore Laboratory, Rept. UCRL-4459 (1955).
39. R. O. Bangerter, J. L. Lindl, C. E. Max, and W. C. Mead, *Bull. Am. Phys. Soc.* **20**, 1352 (1975).
40. D. Mosher, *Phys. Fluids* **18**, 846 (1975).
41. See Ref. 40, Appendix A.
42. H. M. Colbert, SANDYL, Sandia Lab. Pub. SLL-74-0012 (May 1974).
43. W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, 1954) pp. 245-254.

6. PLASMA PHYSICS

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6. PLASMA PHYSICS

Calculations of laser plasma interactions have progressed to the point where specific correlations with experiments have been obtained in several important areas.

- Two-dimensional simulations of resonance absorption and instability heating in nonlinearly steeped density profiles have predicted net absorption efficiencies of about 20 to 30%. These predictions are in semiquantitative agreement with recent measurements. The observed polarization dependence of the scattered light was also predicted.
- The absorption calculations have been extended to include focused light beams. Several mechanisms which can lead to regimes of improved light absorption have been examined. These include short-wavelength ion turbulence and critical surface breakup.
- Calculations have demonstrated a reduction in Brillouin scattering due to the limited mass and heat capacity of the underdense plasma. The results are consistent with the time-dependent reflectivity observed in some recent experiments with high-intensity light. Stimulated scattering may play a larger role in the overall energy balance in future experiments with longer pulses and more uniform irradiation.
- Calculations have also emphasized the importance of self-generated magnetic fields in the inhibited energy transport encountered in the experiments. The magnitude of these fields, their sources, and several mechanisms for nonclassical electron diffusion have been examined.

LASER FUSION

6. PLASMA PHYSICS

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6. PLASMA PHYSICS

6.1 Overview of Plasma Theory and Simulation

Recent experiments have underlined the important role of plasma effects in determining the performance of a laser-irradiated target. Characteristic plasma effects both calculated and observed are (1) nonclassical and polarization-dependent absorption of the laser light, (2) generation of very energetic electrons, (3) sizable energy losses to fast-ion expansion, (4) inhibited energy conduction, and (5) time-dependent reflectivity. Our calculations of these plasma effects have progressed to the point where reasonably quantitative comparisons with the data have been obtained in several important areas. A brief overview of our present understanding is given here, and important current directions of study are outlined.

6.1.1 LASER LIGHT ABSORPTION

Two-dimensional simulations¹ of resonance absorption and instability heating in nonlinearly steepened density profiles have predicted absorption efficiencies consistent with recent measurements. These calculations were carried out with our principal tool for plasma simulation—a two-dimensional computer code which solves the full set of Maxwell's equations and uses relativistic particle dynamics.² These results are very briefly summarized in Fig. 6-1, which is a plot of absorption efficiency (due to plasma waves) vs angle of incidence for a plane wave obliquely incident on an inhomogeneous plasma slab. The points are simulation results for Nd laser light with its electric vector in the

plane of incidence and with an intensity of 10^{16} W/cm². The dashed line is an estimate, based on this data, of the absorption efficiency due to plasma waves for laser light obliquely incident with an *equal* mix of polarizations. Hence the dashed line takes into account the fact that only about half the light energy is incident on the target with the proper polarization for resonance absorption. Note that this absorption efficiency ranges from about 15 to 30% and is polarization-dependent.

In several hundred experiments³ at Livermore using a wide variety of targets and Nd laser light with intensities ranging from about 10^{15} to 10^{17} W/cm², net absorption efficiencies of about 15-45% have been measured. Classical inverse bremsstrahlung is estimated to account for an absorption efficiency of only 10-15%, depending on the target and the intensity. Hence classical processes are inadequate to account for the experimental results, especially in the experiments with intensities above 10^{16} W/cm². However, as is evident from Fig. 6-1, the simulations of absorption due to plasma waves are quite consistent with this data, particularly when the small classical absorption is added.

In many of these experiments, in particular those where the targets were small Parylene disks,⁴ detailed measurements of the reflected light using arrays of photodiodes have shown that the light is not simply missing or refracting around the target. In addition, there also appeared to be a polarization dependence to the absorption. On the average, photodiodes in the plane defined by the polarization vector and the target normal collected about half as much light as did the corresponding diodes in the orthogonal plane. Using the estimates in Fig. 6-1 and taking into account the average angle of incidence of light focused with an $f/1.1$ lens, we estimate this same one-half ratio.

This correspondence between the data and the calculations is encouraging, and we are continuing to improve our models of the absorption processes both to make the comparisons more quantitative and to seek

Fig. 6-1. The nonclassical absorption efficiency vs angle of incidence. The points are from a series of 2-D computer simulations with the electric vector of the light in the plane of incidence. $I = 10^{16}$ W/cm² (Nd), and $\theta_0 = 4$ keV initially. The dashed line is an estimate (based on these simulations) of the nonclassical absorption efficiency for light incident with an equal mix of polarizations. See Ref. 1.

out regimes of optimum absorption. Especially important questions addressed are (1) processes which can modify the dependence of the nonclassical absorption on angle of incidence, such as critical surface rippling and light filamentation, (2) absorption by short-wavelength ion turbulence produced by subsidiary effects such as heat transport instabilities, and (3) complications introduced by realistic focusing optics. Each of these topics is discussed in more detail in the following sections of this report.

Energy Transport Limitation and Its Causes

The experimental evidence for transport inhibition has been rapidly accumulating and is especially clear in the Parylene disk experiments.⁴ This inhibition is evidenced by the spatial extent of the x-ray emission, the fraction of the absorbed energy spent in fast ion expansion, and the level of the high-energy x rays. We give here an estimate for how transport inhibition affects the energy loss to fast ions and then discuss our progress in understanding the mechanisms responsible for the inhibition.

Laser light energy is absorbed near the critical density surface into hot electrons. These electrons produce two effects. They carry energy into the target, and they generate fast ion expansion via the ambipolar potential that is set up to keep the electrons from leaving the target. The fraction of the electron energy which goes into either process clearly depends on the relative rates, which can be estimated as follows. The energy flux transported by electrons into the target can be expressed as

$$I_e = n\theta_e v_e f_{in},$$

which is the free-streaming value times an inhibition factor, f_{in} ; here n is the heated electrons' density, θ_e their temperature, and v_e their thermal speed. Note that the free-streaming estimate assumes that the mean free path is greater than the scale length. The energy flux carried off by fast ion expansion can be expressed as

$$I_i = \frac{5}{2} n\theta_e v_a,$$

where v_a is the acoustic speed determined with the hot electron temperature. This estimate is based on a 1-D isothermal expansion. The fraction of the absorbed energy lost to fast ion blowoff is then

$$F = I_i / (I_e + I_i) \\ \approx 2.5v_a / (2.5v_a + f_{in}v_e).$$

If the conduction is relatively uninhibited so that maximum transport is obtained, then $f_{in} \approx 1$, and Eq. (1) shows that only several percent of the energy is directly lost to fast ion expansion. Physically this is due to the small electron/ion mass ratio, which means that the electrons can carry energy into the target much more rapidly than the ions can expand outward. (Note that we are here discussing a "thick" target.) On the other hand, if the conduction is strongly inhibited, the energy conduction speed can be reduced to the characteristic hydrodynamic speed ($\sim v_a$). Then $f_{in} \approx \sqrt{m/M}$ (where m/M is the mass ratio), and Eq. (1) shows that about two-thirds of the energy is lost to fast ion expansion. The Parylene disk experiments indeed show such a large fast-ion component.

What produces this marked energy transport limitation? Our studies show that the most promising mechanism is self-generated dc magnetic fields.^{5,6} There are many source terms for such fields; the best known is the one which arises when the density and temperature gradients are not parallel. This effect can be simply illustrated by using the one-fluid plasma equations. Neglecting the magnetic field pressure and resistive diffusion and treating the pressure as a scalar,⁷ we then obtain

$$-\frac{1}{c} \frac{\partial B}{\partial t} = \nabla \times E \\ \approx \nabla \times \left[\frac{u \times B}{c} - \frac{1}{ne} \nabla p_e \right].$$

Here u is the plasma flow velocity and $p_e = n\theta_e$, where θ_e is the electron temperature. Equation (2) shows that $B = 0$ whenever $\nabla \times (\nabla p/n) \neq 0$, which occurs when $\nabla n \times \nabla \theta_e \neq 0$.

To show that a sizable inhibition is possible via these fields, consider here a crude order-of-magnitude estimate. Setting $\partial B/\partial t = 0$ and denoting all gradient lengths by L , we find with Eq. (2) that $|B| \approx (c/u)(\theta_e/eL)$. The energy flux carried by electrons across the field can be expressed as $I_e = 3/2 \theta_e D \partial n/\partial x$, where D is the diffusion coefficient. We conservatively take Bohm-like diffusion ($D \approx \omega_{ce}^{-2} r_{ce}^2$; ω_{ce} is the electron cyclotron frequency and r_{ce} the gyro-radius). Combining these estimates then gives $I_e \approx n\theta_e u$; that is, the characteristic energy flow speed is of the order of the acoustic velocity rather than the electron thermal velocity.

For quantitative results, it is essential to address many important questions—the size and extent of the self-generated fields, how electrons diffuse across them, and other mechanisms for their generation. Significant progress has been made on each of these questions. The extent and magnitude of the magnetic

fields due to $\nabla n \times \nabla \theta_e$ has been analyzed for several targets, and we find that their magnitude can be estimated by balancing the source term with magnetic field convection, $(\mu \times B)/c$. The conditions for the use of classical diffusion for electron transport across these fields have been examined, and the enhancement of this diffusion by magnetic field inhomogeneities has been calculated. In addition, the generation of additional dc magnetic fields by resonance absorption of a focused light beam has been computed. Lastly, an experiment has been designed to directly measure the magnetic fields. More details are given elsewhere in this report.

Transport inhibition by ion turbulence has also been examined. The nonlinear evolution of the ion-acoustic drift instability has been computed in 2-D simulations, and the self-consistent effects of this ion turbulence on other transport coefficients have been included in a fluid description.⁸ Particularly important effects identified are (1) the self-consistent ion heating, which can control the level of the ion fluctuations, and (2) the return current scattering by these fluctuations. On the basis of our present understanding, the ability of this ion turbulence to strongly inhibit the energy conduction appears doubtful but deserves further investigation.

Stimulated Reflectivity in Underdense Plasma

Instability-generated reflectivity does not appear to be playing a dominant role in recent Livermore experiments. Our calculations show that this reflectivity principally occurs due to the colder electron component (with a temperature of about 1 keV) which streams in from the overdense plasma. Two effects then reduce the reflectivity. First, a sizable fraction of the plasma in the underdense region is very hot due to the inhibited energy transport. Secondly, momentum deposition by the intense reflecting light readily pushes back the colder plasma component, steepening its density profile and turning off the induced reflectivity.⁹

An example of this time-dependent reflectivity is

shown in Fig. 6-2. This is a plot of induced reflectivity vs time from a 1-D calculation assuming effectively 10 μm of 1-keV plasma in the underdense region. This choice is motivated by LASNEX calculations of the 30- μm -focal-spot Parylene disk experiments. Note that the stimulated reflectivity turns off in a time of about 15 ps, consistent with some of the recent time-resolved measurements.

Fig. 6-2. A calculation of induced back reflection vs time from a 1-D hybrid code. The initial conditions were $13.5\lambda_D$ of uniform plasma at a density of $1/3n_{cr}$ with $T_e = 1$ keV and $T_e/T_i = 5$ initially. These conditions were motivated by a simple estimate of the amount of plasma in the underdense region in the 30- μm -focal-spot-diameter Parylene disk experiments.

The major uncertainty in these calculations comes from not knowing the amount of colder plasma component. This depends on details of the energy transport inhibition and the distributions produced by the heating processes. We are still concerned about the possibility of large induced back- and sidescatter in future experiments with longer pulse lengths, larger focal spots, and hence longer gradients (and perhaps less inhibited transport).

W. L. Kruer

6.2 Light Scattering

6.2.1 STIMULATED SCATTERING AND THE STRUCTURE OF THE QUARTER-CRITICAL SURFACE

This report is part of our continuing study of parametric instabilities in the neighborhood of the quarter-critical region. Last year¹⁰ we discussed the thresholds for the high frequency instabilities which occur at quarter-critical and below: $2\omega_{pe}$ decay and Raman back- and sidescattering where ω_{pe} is the electron plasma frequency. These instabilities consist of the

decay of the incident electromagnetic wave (frequency ω_0) into an electron plasma wave and either another electron plasma wave ($2\omega_{pe}$ instability) or a scattered electromagnetic wave (Raman). Brillouin scattering, which occurs throughout the underdense region, is the decay of the incident laser light into an ion acoustic wave and an electromagnetic wave. With simulations

in the transverse magnetic polarization, we showed that the principal hydrodynamic effect of the $2\omega_{pe}$ instability is a steepening of the density gradient through the quarter-critical region. We also see the emission at $3\omega_s/2$, which has been used experimentally to locate the quarter-critical surface.

This year, we report on the complementary problem, simulations with transverse electric polarization. In this polarization, sidescattering is accessible but the $2\omega_{pe}$ instability is not. With our code ZOHAR,² we simulate a plasma slab, typically 9 vacuum wavelengths in the x or open-sided direction and 14 vacuum wavelengths in the y or periodic direction. The large y dimension reduces biases caused by the periodicity; this consideration is especially important in studying sidescattering. Density gradient scale lengths are typically 30 vacuum wavelengths where

$$L \equiv \rho_{crit} \left(\frac{d\rho}{dx} \right)^{-1}$$

and ρ_{crit} is the plasma critical density. The simulated region has a density gradient from 0.075 to 0.325 (where ρ_{crit} is 1), encompassing the quarter-critical region. For incident intensities $\sim 2 \times 10^{16}$ W/cm and plasma temperatures ~ 5 keV, Raman and Brillouin back- and sidescattering both occur.

We monitor the Fourier modes of the transverse electric field so that the spectrum, direction, and point of origin of the scattered light components can be determined. Raman sidescatter is strongest in mode 7: the production point for 90° sidescatter into this mode is at $\rho = 0.14$, or at the low density end of the slab. However, the angle of exit from the slab is only 52° . Raman sidescattering is evident but weaker in modes 1 through 6. The 90° scattering points for these modes are closer to quarter-critical, and these modes exit the slab at angles less than 52° . Brillouin sidescatter is most vigorous in mode 12. This scattered light, whose 90° production point is at the high density end of the slab, would be detectable at an angle of 57° . This refraction of the scattered light is significant for diagnostic purposes. Some of the light collected back into a small f number lens may actually be due to sidescattering rather than backscattering.

Density profile changes produce a time dependence in the scattering amplitude which is apparent in the mode histories. Late in the run, a density depression develops just below the quarter-critical surface. As evident in Fig. 6-3, the quarter-critical surface has broken up. This cavity scatters the transmitted light, and the interference patterns contribute to the rippling of the critical surface. A probe inside this cavity shows that the frequency of the trapped light has shifted down to $\sim 0.28\omega_{pe}$. (The frequency of the decay electromag-

Fig. 6-3. Ion density contours showing the hole below the quarter-critical surface which is indicated by the heavy contour.

netic wave in Raman scattering has a lower limit of $\omega_s/2$.) This shift is similar to the behavior of the trapped light in cavities formed near critical density. (See Sec. 6.3.1.)

These results are not simple extrapolations of 1-D simulations of Raman and Brillouin scattering. In those problems, only backscattering occurs. For similar parameters, a trough forms at quarter-critical, somewhat analogous to the density striations which develop at the critical surface. One might expect this trough to be sausage unstable in two dimensions and to lead to a rippled quarter-critical surface. However, sidescattering hinders trough formation. The cratered quarter-critical surface does develop—but without a trough—the intermediate state which might be inferred from 1-D results.

A. B. Langdon
B. F. Lasinski

The efficiency with which intense laser light is absorbed is one of the most important questions for laser fusion applications. Of particular concern is the possibility that intense light may be reflected in the underdense plasma by the Brillouin and Raman instabilities. Linear theory¹¹ indicates that the thresholds for these instabilities are readily exceeded, and computer simulations¹²⁻¹⁵ have shown that a large reflection can then occur in the nonlinear state. Reflection via the Brillouin instability is especially dangerous, since the principal energy transfer is from the incident light wave to the scattered one. However, there is at present very little correlation between experiment and theory. For example, experiments have typically shown a net back reflection of the order of 20% for incident light intensities of $\geq 10^{16}$ W/cm² (for 1.06- μ m light).¹⁶⁻²⁰ Indeed this back reflection is sometimes observed to decrease with increasing intensity.

We present theoretical estimates and computer simulations which show that a large induced reflection of intense light can occur, but that this reflection is often limited by momentum and energy deposition due to reflection of the light in the underdense plasma. This momentum deposition drives a reflection front supersonically through the underdense plasma. Consequently, the induced reflection persists for a limited time which depends both on the intensity and the amount of plasma present in the underdense region. We compare our results with some recent experimental results obtained at the University of Rochester in which a large and time-dependent reflection has been observed.¹⁶

The basic physical processes can be simply illustrated by appealing to an idealized model. Assume that the reflection length (ℓ) is much less than the density scale length (L) of the underdense plasma. Analytic calculations of this reflection length in both the weakly²¹ and the strongly²² damped acoustic wave limits show that this condition is easily obtained. Further assume that the ion wave damping decrement satisfies the inequality $\nu_i > c_s/\ell$, where c_s is the sound speed. Then the ion waves deposit their momentum and energy in the interaction region. Computer simulations have shown that, even if the ion waves are initially weakly damped, they become heavily damped in the nonlinear state due to ion trapping.^{12,13}

Finally, assume that the energy density of the electromagnetic wave exceeds the kinetic energy density of the plasma. This assumption is motivated by simulation studies²³ of laser light absorption. These studies indicate that near the critical density (n_{cr}) the plasma electron energy distribution consists of a relatively cold main body with a temperature of ~ 1 keV due to inverse

bremstrahlung plus a lower-density, very hot tail due to various collective heating mechanisms. Since this lower-density hot tail is rather ineffective in reflecting the light, we neglect it here. For a main body temperature of 1 keV, our last assumption is satisfied when the intensity $I > 2 \times 10^{15}$ W/cm² for 1.06- μ m light.

With these assumptions, consider the macroscopic behavior in the frame moving with the reflection front. As illustrated in Fig. 6-4, take total light and plasma reflection from opposite sides of the front, and designate the incoming (reflected) plasma density and velocity by n^+ (n^-) and v^+ (v^-). Number and momentum conservation then give

$$n^- v^- = n^+ v^+ \quad (1)$$

and

$$M(n^- v^{-2} + n^+ v^{+2}) = 2 \frac{E_L^2}{8\pi} \quad (2)$$

where M is the ion mass and $E_L^2/8\pi$ is the light pressure. Of course, the momentum fluxes of the particles can be described more accurately as second moments of a distribution function, but Eq. (2) will suffice for these estimates. If we crudely estimate $v^- \sim v^+$, then the velocity of the front relative to the incoming (upstream) plasma is

$$v^+ \sim \mu(n_{cr}/n)^{1/2} v_{os} \quad (3)$$

where μ is the electron-ion mass ratio, and v_{os} is the oscillatory velocity of an electron in the laser light field. The time required for this reflection front to propagate through the underdense plasma is then

$$t_r \approx L/(\mu v_{os}), \quad (4)$$

Fig. 6-4. A sketch of a very simple model of the light-plasma interaction in a frame moving with the reflection front.

where we have assumed a linear profile with scale length L . Hence t_r gives an estimate for how long a large reflection can persist.

Our principal point is that the secular momentum and energy transfer due to the damping ion waves introduces a new time scale. For high intensity light, the reflection front is not stationary relative to the higher density regions but propagates through the underdense plasma in a time $\sim L/\mu v_{os}$. In contrast, the time for instability growth and saturation is $\sim \lambda_0/\mu v_{os}$, where λ_0 is the free-space wavelength.

Our estimates have been confirmed by computer simulations of Brillouin backscatter. In these simulations we propagate intense laser light from a vacuum into an initially uniform slab of underdense plasma. This simplification of initially uniform density does not alter the basic results, since the threshold intensities set by gradients can be far exceeded and since our momentum and energy balance arguments depend essentially on the net amount of plasma in the underdense region. In order to more clearly isolate the physics, we choose the initial plasma density to be $> 0.25n_{cr}$ to exclude the Raman instability, which gives rise to less efficient reflection and can be saturated by a hot electron tail. The simulations were carried out using two different codes—a 1½-D code with particle electrons and ions and a 1-D code with fluid electrons and particle ions.²⁴ This latter code allows us to more economically study long-time behavior, and comparisons show that the results from this code are in reasonable agreement with those from the more complete code. In the simulations the particles are reflected from the left side of the plasma but are re-emitted with constant flux from the right side in order to model a resupply of the simulated plasma by a reservoir of plasma at the initial temperature. This allows us to model the transmission properties of a slab of such plasma without simultaneously modeling the complicated absorption processes occurring near the critical density. Light waves exiting the plasma slab are allowed to freely propagate away.

Here we will briefly discuss a simple example motivated by experiments performed at the University of Rochester. Light of wavelength $1.06 \mu\text{m}$ and intensity $5 \times 10^{15} \text{ W/cm}^2$ is propagated through a $30\lambda_0$ plasma slab with an initial density of $1/3n_{cr}$ and an electron temperature of 1 keV. The electron-ion mass ratio is 0.01 and the initial temperature ratio is 5. The light reflection begins rapidly and rises to an average value of about $\frac{1}{3}$. This reflection principally occurs in about 5 wavelengths, which is several growth lengths as computed theoretically.

However, this is not a stationary state as is clear from our simple model. A large fraction of the plasma is pushed to the right as the momentum and energy deposition from the damped ion waves secularly ac-

cumulates. This is shown in Fig. 6-5, where we plot the plasma density profile (averaged over the $2k_0$ density fluctuations) from several different times in the simulation. The front of strong reflection is proceeding at a velocity of about $0.01c$. This is approximately the rate expected from our foregoing estimates, i.e. $v_r \sim \mu v_{os}$, where $\mu^2=0.01$. We have also carried out several examples with more intense light and find that the speed of the front increases approximately as the square root of the intensity as expected.

As the reflection front moves through the plasma slab, the reflection gradually decreases. This is shown by the plot of transmission vs time in Fig. 6-6. We have averaged this transmission over some short-time relaxation oscillations which occur at roughly the frequency of the ion waves and which were previously pointed out in Ref. 14. Note that the reflection gradually decreases from about 80 to about 15% in a time of $\omega_0 t = 2 \times 10^4$. In agreement with our estimates, this time is $\sim L/(\mu v_{os})$, that is, the time for the reflection front to traverse the system. If we scale to a mass ratio appropriate for deuterium, the reflection persists for a time of about 50 ps.

Finally, we compare our results with some recent experimental results obtained at the University of Rochester.¹⁷ In these experiments a 500 ps pulse of $1.06\text{-}\mu\text{m}$ light (preceded by a prepulse) was focused on a $400\text{-}\mu\text{m}$ -diam cylinder of D_2 , and the time-dependent backreflection was measured. In experiments in which the incident energy was about 100 J and the focal spot diameter was about $60 \mu\text{m}$, a large reflected intensity—as high as 80% of the incident intensity—rapidly onset and slowly decreased over a time of about 60 ps. After this time the backreflection dropped to a much smaller value ($\leq 10\%$). This behavior compares favorably with

Fig. 6-5. The computed ion density profile at (a) $\nu_r t = 0$; (b) $\nu_r t = 480$; (c) $\nu_r t = 1040$; and (d) $\nu_r t = 1520$ ($\nu_r = \omega_0/2\pi$). These results are from a particle simulation: $T_e = 1$ keV and $T_e/T_i = 5$ initially.

Fig. 6-6. The evolution of the light transmission through a $30 \lambda_D$ plasma slab. The transmission has been averaged over relaxation oscillations which have a period of $\omega_0 t \sim 300$. These results are from the hybrid simulation: $T_e = 1$ keV and $T_e/T_i \approx 5$ initially.

that calculated in our simulation. (For this experiment we have estimated a preformed plasma with a density gradient of about $30 \lambda_D$. This corresponds to the same amount of plasma present in a $30 \lambda_D$ plasma slab with an initially uniform density of about $1/3 n_{cr}$.)

Several other features observed in experiments are also consistent with this picture of the reflectivity. First, as the intensity is increased, the large reflectivity persists for a shorter time. This gives rise to a decrease in the net reflectivity of the 500 ps pulse as the intensity is increased. This decrease has been observed in the

Rochester experiments. Furthermore, this decrease in the reflectivity is observed to onset for an $I \sim 2 \times 10^{15}$ W/cm², also as expected, since this is roughly the intensity for which $v_{os} \geq v_{te}$ for the cold main body. On the other hand, in experiments in which there is a short, rapidly rising laser pulse, we estimate little reflectivity of very intense light since there is no sizable preformed plasma which must be displaced when the light reaches high intensity. This may account for the low reflectivity observed in many short pulse experiments with high intensity light. In this regard, it should be noted that there are also critical surface phenomena²⁴ which reduce the flow of cold plasma out from the critical surface and thus help to maintain a large density gradient.

Lastly, note that the frequency shift calculated by such a model is larger than that predicted by linear theory because during the period of large reflectivity the plasma is accelerated inward relative to the higher density plasma. Of course, the net frequency shift observed in the laboratory is a combination of this red shift plus a blue shift due to the overall expansion of the upstream plasma. The increased red shift may be sufficient to yield a net red shift in the frequency of the reflected light.

For simplicity we have discussed backscatter, but similar results should also obtain for sidescatter (the momentum transfer is less by a factor of $\sqrt{2}$). It should be noted that 2-D effects could further reduce the time over which a large reflectivity can occur. For example, the incident light may form narrow filaments, expelling the plasma laterally.²⁵

W. L. Kruer
E. J. Valeo
K. G. Estabrook

6.3 Critical Surface Ripples, Cavities, and Structures

6.3.1 FORMATION AND EVOLUTION OF DENSITY STRUCTURES NEAR THE CRITICAL SURFACE

The behavior of the critical surface strongly affects the absorption of laser light. Using our particle simulation code ZOHAR,² we are studying the formation and evolution of density structures near the critical surface. This work complements and extends the fluid simulations and theoretical analysis of Valeo and Estabrook²⁶ on the formation of "bubbles." They showed that for normally incident light of sufficiently high intensity the density trough which forms near the critical surface

undergoes a "sausage" instability producing a cratering of the critical surface. With ZOHAR, the polarization of the incident light can be varied to infer the three-dimensional behavior of these density structures, and kinetic and high frequency effects are included.

We find that an important aspect of the evolution of these cavities is the downward frequency shift of the trapped light as the cavity expands after initial formation. The simulation of a two-dimensional uniform

homogeneous plasma readily illustrates this property. A transverse electric pump $E \cos \omega_0 t$ produces a well-defined cavity. In this model problem, the formation process may be thought of as the pump wavevector $k_0 \rightarrow 0$ limit of filamentation, leading to the relation-

$$k_{\text{pert}} \lambda_{De} < \frac{1}{\sqrt{2}} \frac{v_0}{c}$$

ship for the linearly unstable modes. Here k_{pert} is the wavevector of the perturbation, λ_{De} is the electron Debye length, c is the velocity of light and v_0 is the electron oscillation velocity in the laser electric field. For the simulation, $v_0 = 0.1c$, $T_e = 1.3 \text{ keV}$, $T_i = 4T_e$, and $\omega_0 \approx \omega_{pe}$ where T_e is the electron temperature, T_i is the ion temperature, and ω_{pe} is the electron plasma frequency.

As the cavity expands, that is, as the ponderomotive force pushes the plasma out, both the light frequency and the total field energy inside the cavity drop accordingly. Figure 6-7 is a plot of the total field energy as a function of time; the field energy (all of it concentrates inside the cavity) drops to ~ 0.6 of its initial value. A spectral analysis gives a frequency shift to $\sim 0.6\omega_0$. The cavity expansion is an adiabatic process in which $E/\omega = \text{constant}$ where E is the oscillation energy and ω is the frequency of the trapped light. The field energy is given up to pdV work as the cavity expands. Rather than the trapped light evolving into a more complicated spatial structure, the dominant effect is the frequency shift.

This frequency shift is also seen in slab geometries. The first problem we discuss in the open-sided system

Fig. 6-7. Total field energy as a function of time for the time interval in which the cavity is expanding.

Fig. 6-8. Probe of the transverse electric field component inside the cavity as a function of time. By $\omega_{pe} t = 200$, the cavity has formed. A spectral analysis shows a frequency shift to $\sim 0.6\omega_0$.

overlaps the work of Valeo and Estabrook. Using their parameters, $V_{0z} = 0.1c$, $T_e = 5 \text{ keV}$, and $T_i = 3T_e$, we find, also, that a trough forms which is sausage unstable producing an isolated cavity approximately one vacuum wavelength in diameter. Figure 6-8 is a plot of the transverse electric field component in the pump mode at a position inside the cavity showing the field buildup as the trough forms and then the subsequent drop as the cavity develops. The frequency shifts down to $\sim 0.6\omega_0$, as in the adiabatic process found in the homogeneous simulation.

To make statements about the three-dimensional behavior of the critical surface, we need to know if cavities also form for pump polarizations more general than purely transverse electric. We have looked at elliptical and circular polarization. The simulation with circular polarization, $V_{0z} = V_{0y} = 0.1c$, but still at normal incidence and with the other parameters the same as in the transverse electric open-sided case, illustrates the new features. As before, a trough forms. Although it exhibits spatial structure in the direction normal to the density gradient, this perturbation of the critical surface develops more slowly and in a different location than in the transverse electric case. And this density depression is no longer a simple cavity completely isolated from the incident light by overdense plasma.

The downward frequency shift is apparent in the transverse electric component as the critical surface cratering develops. As the surface perturbation

evolves, the transverse magnetic component undergoes resonance absorption before an appreciable frequency shift occurs. (The transverse electric component cannot undergo resonance absorption in this geometry.) The dissipation of the transverse magnetic mode accelerates as the density structure forms. Furthermore, a dc component of the magnetic field appears, which may be viewed as a signature of the resonance absorption processes.²⁷ Thus, the density structures formed by the transverse electric component, which does not itself undergo absorption, improve the absorption of the transverse magnetic component.

Relaxing the requirement of normal incidence is another aspect of the problem of the three-dimensional stability of the critical surface. We have done simulations at angles of incidence of 23° and 45°, with transverse electric polarization. The other parameters are the same as in the transverse electric case at normal incidence. The trough forms, but we then see no evidence for the sausage instability at these angles. Instead, Brillouin backscatter occurs along the trough (that is, along the direction perpendicular to the density gradient). The density depressions that do appear are at the antinodes of the standing wave pattern created by the Brillouin backscattering of the light in the trough.

The question of the long-term breakup of the critical surface on a scalelength of one vacuum wavelength needs further work. Experimentally, the stability of the critical surface may be inferred from the angular distribution of the scattered light in the fundamental frequency and higher harmonics. Critical surface breakup causes the scattered light to be more isotropic in the backward hemisphere instead of returning at the specu-

lar angle. Experimental evidence indicates that under some circumstances the critical surface is not smooth, for well-defined specular reflection is not found.²⁸

The stability of the critical surface is an important factor in understanding the absorption process. The possibility of critical surface breakup is then one of the motivations for a parallel study on the effect of a shaped (finite spot size) or filamented beam impinging on a possibly cratered critical surface. In simulations of a plane wave at 10¹⁶ W/cm normally incident on a perturbed critical surface, the absorption is typically ~ 50%. By contrast, for the same parameters but a smooth critical surface, the absorption is as low as 12%. Figure 6-9 shows ion density contours at a time late in the run for the extreme case of a filamented beam incident on the critical surface. The absorption rose to 90% as the filament continued to gouge out a density depression along its path. An incident plane wave undergoing resonance absorption under optimum conditions produces ~ 50% absorption. For a finite spot size beam but with fixed ions to prevent cavity formation, the absorption drops to 16% because resonance absorption is accessible only for the non-normal components of the shaped beam. Therefore, it is the density depression, not the finite spot alone, which raises the absorption.

Thus, the presence or absence of density structures near the critical surface is a key aspect of the laser-plasma interaction problem.

A. B. Langdon
B. F. Lasinski
W. L. Kruer

Fig. 6-9. Ion density contours. The dark line is the critical surface.

There is computational and indirect experimental evidence that the critical surface of a plasma irradiated by a high intensity laser is not smooth but has cavities or ripples. Since most of the absorption occurs near the critical density, greater critical surface for a given volume has the advantage that absorption should be greater than for a smooth surface. Also, light which reflects from the critical surface has a large probability of striking the critical surface, causing further absorption. However, the craters or bubbles may be several wavelengths apart and, consequently, may encourage further Rayleigh-Taylor growth.

The shape of the critical surface is determined by 3-D kinetic effects and, therefore, cannot be completely studied with 2-D computer simulations. However, since computers do not yet exist that can do 3-D simulations in a reasonable time period, we have approached the problem with two different kinds of simulations with two different fixed polarizations of light. If the electric field of the incoming transverse wave is perpendicular to the plane of simulation, then Brillouin sidescatter (as well as backscatter) may occur. Absorption in the form of heating does not occur in the simulation plane since the electric field does not act in that direction. Some energy is absorbed in the bulk motion of the plasma since it is compressed due to momentum deposition of the light as it is reflected. The interference pattern of the reflected light with the incoming light produced strong maxima and minima in the radiation pressure of the light (ponderomotive pressure) which bunches up the plasma. For reasonably high intensities (say v_{osc}/v_{the} greater than 0.25 to 0.5 for density gradient lengths of about 10 vacuum wavelengths of light) the plasma will bunch up so strongly that it will trap the light in a low density trough which is surrounded by plasma of density greater than critical. The trapped light drives a sausage type of instability so that it gathers in small regions and forms what we call "bubbles" in the critical density region. This process was discussed in detail in last year's annual report and in Refs. 26 and 29.

When the electric field of the incoming transverse light is in the plane of the simulation, direct kinetic heating will occur. However, sidescatter does not occur in the direction of the transverse electric field (this is discussed in the following paragraph). If the incoming light wave vector is perpendicular or nearly perpendicular to the critical surface, then the kinetic instabilities, ion acoustic decay, and oscillating two-stream will produce ion acoustic waves or bunching that will still ripple the critical surface with large amplitude for v_{osc}/v_{the} near one. The physical mechanism is quite different from the light trapping mechanism described above. Figures 6-10 and 6-11 are contour and surface plots of the ion density which illustrate the rippling of the critical surface. It is important to emphasize that in this polarization, the ripples come and go with the ion acoustic period since they are caused in large part by ion acoustic waves traveling up and down the critical surface. Ion waves are also driven in both the $+$ and $-x$ direction which break to form fast ions streaming in both directions. These fast ions have been observed in the TRW microwave experiments.³⁰

In a 3-D plasma, the radiation pattern from Brillouin sidescatter will be in the form of $\cos^2$ of the angle between the polarization vector and the detector. There is indirect experimental evidence, which is not conclusive, that this angular dependence may have been seen.³¹ In the experimental irradiation of both ball and flat targets, a 4 to 1 intensity variation of sidescattered light was noticed with the minimum in the direction of polarization. Some of the pattern could be also due to resonant and other absorption mechanisms which would produce the same kind of pattern but with a much smaller intensity ratio than 4 to 1. The simulation code FLUID has shown that with polarization out of the plane, sidescatter soon dominates backscatter and immediately dominates self-focusing in agreement with theory and the experimental evidence discussed above.

K. Estabrook

6.3.3 STABILITY OF THE CRITICAL SURFACE INCLUDING RESONANT ABSORPTION

We have extended the stability analysis of E. Valeo and K. Estabrook²⁶ of the critical surface to include resonantly excited plasma waves.³² We modeled the effect of the electron heating by the resonant fields by including phenomenological collision frequencies. We applied this analysis to a sharp gradient ($L \approx 20\lambda_{De}$) such as results from resonant absorption of high power electromagnetic waves. We find that the critical

surface is unstable. The unstable perturbations are ripples of the steepened surface traveling in a direction perpendicular to the density gradient.

We have written two versions of a two-dimension hydrodynamics code to investigate this instability. In one version, the electromagnetic equations are solved in the $1/\omega_p$ time scale. In the other version, the electromagnetic equations are solved with the common

Fig. 6-10. Surface plot of ion density from a fully kinetic, relativistic, electromagnetic simulation (ZOHAR-2) in which the transverse electric field is in the simulation plane and incident parallel to the density surface n_{cr} . The initial density was a ramp from 0.4 to 1.4 n_{cr} and $v_{inc} = 0.15$, and $v_{th} = 0.088$. The vertical system size is 2.5 vacuum wavelengths, and the system is 10 wavelengths long. Only about half the system length is shown here for clarity. The lengths in x and y are the same. Sidelscatter is not allowed, but a depression can still be seen in the critical surface region beyond $y = 0.6$ and 1.5 wavelengths. About 40% of the total heating is in the x direction by resonant absorption occurring in the cavity and along practically the whole critical surface region which is quite distorted. The density compression right in front of the cavity is slightly above critical.

Fig. 6-11. Same surface as Fig. 6-10 except that it is a contour plot rather than a surface plot. The values of the density are expressed by n/n_{cr} and are inserted into the broken contour lines which follow levels of constant density.

factor $e^{i\omega_0 t}$ removed. Thus the timestep can be on the hydrodynamic time scale. A typical result is shown in Fig. 6-12. The plasma density is given at a time late in the calculation after the instability has saturated. We find that the instability saturates when the density has ripples with a depth of a few Debye lengths. The laser

absorption is increased about 20% by the presence of these ripples.

Wee Woo
John S. DeGroot

6.4 Turbulence Effects On Absorption

6.4.1 LASER LIGHT ABSORPTION BY SHORT WAVELENGTH ION TURBULENCE

Nonlinear steepening of the density profile has been found to substantially reduce the efficiency of parametric instabilities near the critical density in laser-irradiated plasmas.¹ Thus there is considerable interest in other collective absorption processes which are less sensitive to density steepening, i.e., which operate over a wider range of densities. Hence we have investigated the absorption of laser light by short wavelength ion turbulence such as may be generated by several processes involving either the heat flow or the plasma expansion. We find that modest levels of this turbulence can yield absorptions comparable to those found experimentally.

The absorption of high frequency radiation by a given spectrum of ion fluctuations has been calculated by Dawson and Oberman.²³ It is worthwhile to give a

short and physical derivation of their result in order to emphasize the physics. We will give a 1-D treatment for a monochromatic ion density fluctuation, since the extension to three dimensions and to a spectrum of fluctuations is obvious.

Apply an oscillating field of the form $E_0 \cos \omega_0 t$ to a plasma whose density is

$$n_0(x) = n_p + \delta n \cos k_i x.$$

By oscillating electrons between regions of lower and higher density, the applied field produces a source term for high frequency density fluctuations:

$$n_s(x, t) = \frac{eE_0 \cos \omega_0 t}{m \omega_0^2} \cdot \frac{\partial}{\partial x} n_0(x). \quad (1)$$

The self-consistent plasma response to this source term is determined by Poisson's equation, and the time-averaged power per unit volume transferred to the plasma by these fluctuating fields is then readily calculated:

$$P = \frac{\omega_0}{2} \frac{E_0^2}{8\pi} \left(\frac{\delta n}{n_{cr}} \right)^2 \frac{\text{Im} \epsilon_L(k_i, \omega_0)}{|\epsilon_L(k_i, \omega_0)|^2}.$$

Here n_{cr} is the critical density, and $\epsilon_L(k, \omega)$ is the plasma dielectric function. The effective damping rate (ν^*) of the imposed field is now obtained by energy balance ($P = \nu^* E_0^2 / 8\pi$). Generalized to a 3-D spectrum of ion fluctuations, the result for ν^* is

$$\nu^* = \frac{\omega_0}{2} \sum_{k_i} \left(\frac{\delta n_{k_i}}{n_{cr}} \right)^2 \frac{\text{Im} \epsilon_L(k_i, \omega_0)}{|\epsilon_L(k_i, \omega_0)|^2} \cos^2 \theta, \quad (2)$$

where θ is the angle between k_i and E_0 .

Much attention has been focused on the strong

Fig. 6-12. Plasma density as a function of x for various positions in y , at $\omega_0 t = 300$. Parameters: $L/\lambda_{De} = 20$, $eE_0/m\omega_0 v_{the} = 0.5$, $m/M = 100$, $\theta = 20^\circ$.

resonance apparent from Eq. (2) when $\omega_i \approx \omega_{pe}$ and $k\lambda_{De} \ll 1$; that is, when the density is quite near the critical density and the ion fluctuations have a long wavelength (compared to λ_{De} , the Debye length). However, particularly for short wavelength density fluctuations, $\text{Im}(1/\epsilon_i)$ is appreciable in magnitude at plasma densities as low as approx $1/2n_{cr}$. This is illustrated in Fig. 6-13, which is a plot of $\text{Im}(1/\epsilon_i)$ as a function of density for $k\lambda_{De} = 1/2$. Such short wavelength ($\sim 10\lambda_{De}$) fluctuations are of particular interest since they can be spontaneously generated by several subsidiary processes involving either the heat flow or the plasma expansion.

To test the effectiveness of this coupling and also the heated electron distributions which result, we have carried out some simulations with a 1-D electrostatic particle code. Since we will subsequently discuss their generation, we simply imposed ion density fluctuations and then examined the subsequent heating due to an imposed oscillating field of the form $E_0 \cos \omega_i t$. The results are shown in Fig. 6-14, where we plot the anomalous collision frequency versus plasma density. The triangles denote the simulation results, and the solid line is the theoretical prediction using Eq. (2). The agreement is quite reasonable.

Note that the anomalous collision frequency is substantial ($\nu^* \sim 1/200 \omega_{pe}$) over a sizable range of densities, i.e., $0.5 \leq n/n_{cr} \leq 1$. Hence, this coupling is not as sensitive to density profile steepening as is parametric instability heating. In addition, note that a

Fig. 6-13. A plot of $\text{Im } \epsilon_i(k, \omega_i) / |\epsilon_i(k, \omega_i)|^2$ as a function of plasma density. $k = 0.5k_D$ and n_{cr} is the critical density ($4\pi n_{cr} e^2 / m = \omega_{pe}^2$).

modest level has been assumed for the density fluctuation ($\delta n/n_p = 0.1$).

The simulations emphasize another rather important result. As shown by the sample distribution plotted in Fig. 6-15, the heated electron distributions do not have extensive high energy tails. In this example $\omega_i = \omega_{pe}$, but similar results have been calculated for frequencies up to $\sqrt{2}\omega_{pe}$. The principal point is that the driven plasma fields have a low phase velocity ($< 3v_{te}$), and hence the heated electron tail does not extend to very large velocities.

Fig. 6-14. The absorption rate as a function of plasma density. The triangles are simulation results, and the solid line is the theoretical estimate.

Fig. 6-15. A heated electron distribution from the particle simulation. An ion density fluctuation was imposed: $\nabla n = 0.1n_p \cos k_i x$, where $k_i = 0.5k_D$. The driver field has a frequency $\omega_i = \omega_{pe}$ and an amplitude $eE_0/m\omega_{pe}v_{te} = 0.1$.

Fig. 6-16. A portion of ion phase space from a particle simulation at three different times: (a) $\omega_i t = 90$, (b) $\omega_i t = 340$, and (c) $\omega_i t = 990$. The electron-ion mass ratios were 0.01 and 0.02.

Several different sources of this short-wavelength ion turbulence have been examined. Two of these sources are subsidiary to those usually investigated, that is, the fluctuations are not directly driven by the electric vector of the incoming radiation. Rather, they depend on either the heat flow or the plasma expansion.

As recently emphasized, the heat flow can itself drive ion fluctuations.^{34,35} Hot electrons try to stream into a dense target. However, an electric field must be generated to drift in colder electrons in order to prevent charge imbalance. This field induces a drift between the colder electrons and the ions which can drive the ion acoustic instability. Past studies of the nonlinear evolution of the ion acoustic instability have shown that the generated ion fluctuations are broad in angle (when the drift velocity is much greater than the acoustic velocity c_s), and that the magnitudes are limited by ion trapping.^{36,37} The levels can then be estimated by simple wave trapping arguments:

$$v_{tr} = v_p - \sqrt{3} v_{ti}$$

where v_{tr} is the trapping velocity of an ion, v_p the phase velocity, and v_{ti} the ion thermal velocity. This gives

$$\frac{\delta n}{n_p} \approx 1/4 [1 - \sqrt{\frac{3T_i}{T_e}}]^2$$

Assuming $T_e/T_i \approx 10$, the above estimate gives: $\delta n/n \approx 7\%$. It should be noted that not all the fluctuations are effective at coupling the laser light, i.e., $\theta \neq 0$ in Eq. (2). Assuming a broad-angle spectrum, this effective intensity of the fluctuations is reduced by a factor of about 2.

We find that the plasma expansion can also drive short wavelength ion turbulence. This occurs either when the plasma expands out through a cold plasma (left over, say, from a low energy prepulse) or when there are several species with different charge-to-mass ratios participating in the expansion. This latter is very often the case in practice. What can then happen is an ion-ion streaming instability between the different ion species.

Figure 6-16 shows the ion phase space at three different times from a simulation of the plasma expansion using a particle code. The ions were split into two groups—both with the same charge, but with masses a factor of 2 different (such as for H and D₂). As seen in Fig. 6-16a the species first expand independently in a manner which can be estimated by isothermal expansion theory,

$$u_1 = c_1 + \frac{x}{t},$$

$$u_2 = c_2 + \frac{x}{t},$$

where c_1 and c_2 are the appropriate acoustic speeds. However, since $c_2 - c_1 >$ the ion thermal spreads, a strong ion-ion instability developed.

As shown in Fig. 6-16a, the saturation is again determined by ion trapping. The trapping spreads the streams in velocity until the instability is quenched (Fig. 6-16). The fluctuation levels reached are about 10%. Of course, in this 1-D calculation, the ion fluctuations are along the direction of the plasma gradient, that is, in the wrong direction to damp normally incident laser light. However, as in the case of the electron-ion

instability, a significant spreading in angle is expected when the ion-ion instability is well above threshold. This spreading in angle is currently under study.

Other sources of short wavelength ion turbulence are also under study. For example, particle drifts in the inhomogeneous, self-generated magnetic fields readily drive two-stream instabilities. Our goal here has been to illustrate that there are a number of different sources and that fluctuation amplitudes of 5-10% are readily generated.

Finally, we have used our estimates for the effective collision frequency due to this ion turbulence to calculate the absorption in an inhomogeneous, expanding plasma. To do this, we simultaneously solve the wave equation for electromagnetic wave propagation

$$\frac{\partial^2 E}{\partial t^2} + \nu \frac{\partial E}{\partial t} + \left(\omega_{pe}^2 - \frac{c^2 \partial^2}{\partial x^2} \right) E = 0, \quad (3)$$

and the one-fluid plasma equations

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x} nu = 0 \quad (4)$$

$$nm \left(\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} \right) = -\theta_e \frac{\partial n}{\partial x} - \frac{ne^2}{2n\omega_{ce}^2} \frac{\partial}{\partial x} E^2, \quad (5)$$

In our 1-D treatment, E is the electric vector of the light wave, and ν is the effective collision frequency as a function of density ($\nu^* = n_p/n_{cr} \nu$). In Eq. (5), an isothermal fluid has been assumed, and $\partial/\partial x E^2$ describes the momentum transfer between the radiation and the plasma.

To include the absorption due to short wavelength ion turbulence, we used the result predicted by Eq. (2) for a density fluctuation of 7%, and took a mean value of $1/2$ for $\cos^2 \theta$. A density profile with a scale length of $15\lambda_{ce}$ (free space wavelengths) was taken, since this is characteristic of many recent experiments with high intensity light. For $eE/m\omega_{ce}v_e = 0.3$ and including profile steepening near the critical density, the computed absorption was $\approx 10\%$. This absorption is independent of the polarization of the laser light and is comparable in magnitude to that obtained in simulations of heating due to parametric instabilities. We note that net absorptions in the range of 15-50% have been measured in recent laser plasma experiments at Livermore using a wide variety of targets.³ Hence these calculations show that short wavelength ion turbulence can make a significant contribution to the net observed absorption.

R. J. Faehl
W. L. Kruer

6.5 Spherical Geometry

6.5.1 INTERACTION OF FOCUSED LASER BEAMS WITH SPHERICAL TARGETS

The theory of the interaction of intense laser beams with dense plasmas has generally been developed for plane light waves impinging upon planar targets. A more realistic situation for laser fusion is that of a finite-sized, focused beam interacting with a spherical plasma. It is of interest to calculate the amount of energy absorbed by resonance absorption and by inverse bremsstrahlung as a function of lens f-number and focusing in order to interpret experimental results and help design future target systems.

In the previous annual report, we discussed the vector theory of focusing and diffraction of the incoming laser beam. We assume that the beam is axisymmetric and linearly polarized and that the beam intensity as a function of angle is known on some aspherical surface. The beam can then be decomposed in terms of Legendre functions, e.g. the radial components are

$$E_r^{inc} = \frac{1}{ikr} \sum_q a_q P_q^1(\cos\theta) \cos\phi h_q^{(2)}(kr)$$

$$B_r^{inc} = \frac{1}{ikr} \sum_q a_q P_q^1(\cos\theta) \sin\phi h_q^{(2)}(kr),$$

where ϕ is the azimuthal angle, $h_q^{(2)}$ is a spherical Bessel function, and the coefficients, a_q , are determined by the known intensity profile.

The new work we report analyzes the interaction of the beam with a plasma target. We consider a spherically symmetric plasma, with the critical density at radius R_c . For simplicity in analysis, we assume the density gradient is linear in r , with scale length ΔR . Multipole expansions similar to those discussed above are used to describe the fields within the plasma, taking

the free-space solutions as boundary conditions. With this expansion, the spherical harmonics continue to describe the transverse variation of the fields, so that only a 1-D equation describing the radial variation need be solved.

Using Maxwell's equations and the fluid equations for a cold plasma, we find the following set to be solved²⁸:

$$\begin{aligned}\nabla \times \mathbf{E} &= ikB \\ \nabla \times \mathbf{B} &= ike\mathbf{E} \\ \nabla \cdot \mathbf{B} &= 0\end{aligned}\quad (2)$$

where $\epsilon = 1 - \omega_p^2/[\omega^2(1 + i\nu/\omega)]$. These equations neglect the convection and subsequent damping of plasma waves (cold temperature approximation), but they do treat the magnitude of the resonantly absorbed energy correctly.³⁰ The absorption coefficient is due to inverse bremsstrahlung:

$$\nu/\omega = 24.7 \frac{n(r)}{n_c} T^{-3/2} \text{ (eV)}.$$

We may separate the solutions to Eq. (2) into two components, the transverse magnetic (TM) such that $B_r = 0$, and the transverse electric (TE) such that $E_r = 0$. Making an analogy to plane waves, the TM mode corresponds to a plane polarized wave with polarization vector in the plane of incidence, and the TE mode corresponds to a perpendicularly polarized wave. Thus only the TM mode generates resonantly excited waves and loses energy via resonance absorption.

We define potential functions Ψ , χ for the TE and TM modes respectively, and expand in terms of the Legendre functions $P_\ell^1(\cos\theta)$. Thus, for an axisymmetric, linearly polarized beam,

$$\chi(r, \theta, \phi) = \sum_{\ell=1}^{\infty} a_\ell X_\ell(r) P_\ell^1(\cos\theta) \cos\phi, \quad (3)$$

$$\psi(r, \theta, \phi) = \sum_{\ell=1}^{\infty} a_\ell Y_\ell(r) P_\ell^1(\cos\theta) \sin\phi.$$

The polarization vector is defined by $\phi = 0$. The electric and magnetic fields may be found from ψ and χ , e.g.,

$$\begin{aligned}E_\theta &= \frac{1}{ikr} \frac{\partial}{\partial r} \frac{\partial}{\partial \theta} \chi \quad (\text{TM}) \\ &+ \frac{1}{\sin\theta} \frac{\partial \psi}{\partial \phi} \quad (\text{TE}).\end{aligned}$$

Substituting Eq. (3) into Eq. (2), we find that X_ℓ and Y_ℓ satisfy³⁹

$$\left[\frac{d^2}{dr^2} - \frac{1}{\epsilon} \frac{d\epsilon}{dr} \frac{d}{dr} + k^2 \left(\epsilon - \frac{\ell(\ell+1)}{k^2 r^2} \right) \right] r X_\ell = 0$$

$$\left[\frac{d^2}{dr^2} + k^2 \left(\epsilon - \frac{\ell(\ell+1)}{k^2 r^2} \right) \right] r Y_\ell = 0. \quad (4)$$

These equations are analogous to those for a plane-polarized [Eq. (4)] and perpendicularly-polarized wave [Eq. (5)] obliquely incident on a plasma slab with equivalent angle $\sin\theta_0 = \sqrt{\ell(\ell+1)}/kr$.³⁹ This analogy holds only if the latter term is approximately constant; i.e., $\Delta R \ll R_c$, where R_c is the radius of the critical density, a criterion usually well satisfied for present target parameters.

Following the analysis by Ginzburg, Eq. (4) and (5) may be solved in the plasma and matched to the incoming laser beam at the plasma boundary.³⁹ We find that the power absorbed due to resonance absorption is

$$P = \sum_{\ell} P_\ell \frac{\Phi^2(\tau_\ell)}{2\pi}$$

where P_ℓ is the total power in the ℓ th, and $\Phi^2(\tau_\ell)$ is the power absorption function defined by Ginzburg, which depends on the parameter $\tau_\ell = (k\Delta R)^{1/3} \times \sqrt{\ell(\ell+1)}/kr$, (see Fig. 6-17). Thus the power absorbed is a function of ℓ and the plasma gradient length. The intensity distribution of the scattered light may give information on the plasma characteristics. In fact, experimental measurements of scattered light do show an asymmetry between the plane of polarization and the perpendicular plane, an indication of resonance absorption.

Fig. 6-17. Resonance absorption in a medium with a linearly varying dielectric constant.

Figure 6-18 shows the magnitude of the radial electric field at the critical density for a typical case.³⁹ Note that the field, and therefore the absorbed power, is concentrated in lobes in the upper and lower hemispheres. This lack of symmetry is due to the preferred absorption in the direction of the polarization vector and may degrade symmetry of compression.

Figure 6-19 shows the energy absorbed and scattered versus $k\rho$, the distance from the center of the sphere to the geometric lens focus.⁴⁰ For $k\rho = 0$, most of the light energy is concentrated in low ℓ modes, corresponding to nearly normal incidence, which is not efficiently absorbed by resonance absorption (Fig. 6-17). For large $k\rho$, the energy is shared evenly over many ℓ modes. For some intermediate $k\rho$, the energy is mainly in ℓ modes efficiently absorbed, i.e. $\tau\ell \sim 0.5$, leading to the maxima observed in Fig. 6-19. Nonlinear aberrations found in high-power laser systems affect the absorption curve but not its general shape. We are in the process of analyzing the theoretical absorption for the Janus f/1 lens and clamshell systems and the Cyclops f/2.5 lens system.

Fig. 6-18. $\langle E_r \rangle$ on critical surface, $r_c = 100 \mu\text{m}$, $R = 5 \mu\text{m}$, f-number = 0.5, $T = 850 \text{ eV}$. α , β are the angles away from beam center.

Fig. 6-19. Light scattered and absorbed vs position of laser focus, f-number = 0.5, $r_c = 100 \mu\text{m}$, $R = 5 \mu\text{m}$, temperature = 4000, 850 eV.

One possibility for increasing the symmetry of light absorption is to go from linear polarization to circular polarization. A circularly-polarized beam is a sum of two orthogonal linearly polarized beams with a phase difference of 90° . We decompose the beams, as before, so that the fields from one beam have the factor $\cos \phi$ and from the other have the factor $e^{i\pi/2} \sin \phi$. Adding the fields, the azimuthal dependence is $(\cos \phi + i \sin \phi) = \exp(i\phi)$. Therefore, the power is now independent of ϕ , and the energy is absorbed in a circular pattern rather than in lobes. It is simple to show that the amount of power resonantly absorbed is equal for linear or circular polarization.

J. Erkkila
A. Glass
J. J. Thomson
C. E. Max
J. Tull

6.6 Energy Transport

6.6.1 THEORETICAL ASPECTS OF LASER-GENERATED dc MAGNETIC FIELDS

We have continued our investigation of laser-generated dc magnetic fields in plasmas and their effect on plasma transport properties. This section consists of

three parts: 1) an extension of our previous analysis of resonance absorption B fields to focused beams in spherical geometry; 2) a consideration of the adequacy

of the classical or Braginskii transport model as used in LASNEX to describe the effects of $\nabla n \times \nabla T$ magnetic fields; and 3) discussion of anomalous diffusion due to random B-field fluctuations, a phenomenon that is not included in the present LASNEX model.

Resonance Absorption Fields in Spherical Geometry

Last year, we discussed the magnetic field generation due to resonance absorption of laser light for the case of a plane wave incident on a plasma slab.^{27,40} For parameters typical of laser fusion, the source term for the growth of dc B fields can be very strong, of the order 1-10 MG/ps. However, in the more realistic case of a focused beam incident on a spherical target, this source term would be expected to be smaller since the illumination is more symmetric.

The general expression for the magnetic field source term due to the time-averaged radiation pressure is

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \frac{c}{en} \nabla \cdot \mathbf{P}_R \quad (1)$$

where $\mathbf{P}_R$ is the radiation pressure tensor and n the local density.^{27,40} Elsewhere in this report, we discuss the analytical treatment of a focused laser beam on a spherical target. Briefly, the incoming beam is decomposed in Legendre functions $P_\ell^m(\cos\theta)$. The radial potential function, $r\chi_\ell(r)$, satisfies an equation similar to that of a plane wave incident on a slab with incident angle $\sin\theta_0 = \sqrt{\ell(\ell+1)}/kR_c$, where R_c is the radius of the critical surface. We may then solve for the fields in the plasma using well-known techniques.

Substituting the resulting expressions into Equation (1), we find the following general results:

1) There are three components to the dc B field, B_θ , B_ϕ , and B_r , where ϕ is the azimuthal angle. 2) B_ϕ is the strongest field, with growth rates in the ratio $B_\theta : B_\phi : B_r = 1 : 2\pi(k\Delta R)^{1/3}/kR_c : (\nu/\omega) \times (\Delta R/R_c) \sim 1 : 10^{-2} : 10^{-3}$ for typical values (ΔR is the plasma scale length, ν is the absorption rate). 3) Typically $B_\phi \sim 10^{-2}$ MG/ps for laser fusion parameters. This is considerably smaller than for the planar case, but may still reach megagauss levels in a 100 ps pulse.

It should be noted that in these results hold only in the linear regime. It has been shown that the critical surface may ripple at high laser powers, leading to an enhancement of resonance absorption and the associated dc magnetic field.⁴⁰

Limitations of the Classical, Braginskii Transport Model in Describing Laser-Generated Magnetic Fields

We have examined the conditions under which the classical transport model,¹¹ used in LASNEX, should give a good description of heat and particle flows in laser-generated $\nabla n \times \nabla T$ magnetic fields. Figure 6-20 shows the geometry for $\nabla n \times \nabla T$ fields. There are three types of constraints necessary for the classical transport picture to be accurate. The first set of constraints involves the sizes of microscopic parameters such as mean free path and electron Larmor radius, relative to macroscopic plasma scale lengths. The second type of constraint is due to the occurrence of collisionless drifts in strongly magnetized plasmas. The third constraint is the absence of large fluctuations in

Fig. 6-20. Geometry for generation of $\nabla n \times \nabla T$ magnetic fields. The rate of growth of the dc magnetic field is $\dot{\mathbf{B}} = (c/en) \nabla n \times \nabla T$.

either the electric or magnetic fields, which lead to enhanced diffusion.

Let us consider first whether typical plasma conditions in the vicinity of laser-generated magnetic fields satisfy the necessary inequalities regarding microscopic plasma properties. We shall discuss strongly magnetized plasmas, for which $\Omega_e \tau_{ei} \gg 1$ ($\Omega_e = eB/m_e c$ is the electron gyrofrequency, and τ_{ei} is the electron-ion collision time). In this case, the requirements that classical transport be valid are:

$$\begin{cases} L_{\perp} \gg \rho_L \\ L_{\parallel} \gg \lambda_{mf} \end{cases}$$

Here $L_{\perp}$ and $L_{\parallel}$ are respectively macroscopic field length scales perpendicular and parallel to B . The electron Larmor radius is $\rho_L = v_e/\Omega_e$, and λ_{mf} is the electron mean free path. LASNEX calculations for current experiments show that typical parameters in the maximum field region are $T_e \sim 300-500$ eV, $B \sim 3$ MG, giving $\rho_L \sim 0.1 \mu\text{m}$. Since macroscopic field scale lengths $L_{\perp}$ are generally several μm , the first condition, $L_{\perp} \gg \rho_L$, is well satisfied in the maximum field region. The second condition, $L_{\parallel} \gg \lambda_{mf}$, is not in general satisfied, especially for the blowoff region and the suprathermal electrons. LASNEX deals with this situation by using flux-limited transport where appropriate.⁴²

The second kind of constraint arises because particles execute drift motions across B field lines, in a collisionless, strongly magnetized plasma. If these drifts cause particles to sample regions whose macroscopic parameters differ widely, some of the basic assumptions of classical transport theory may be violated. For example, if particles from a cooler region drift into a hot one, the distribution function in the hot region will no longer be the local Maxwellian assumed in all the transport coefficients.

Consider for example the gradient- B drift, which gives electrons a cross-field drift velocity $v_D \sim v_i (\rho_L/L)$. Here L is the scale length for changes in B . According to the above arguments, classical transport should be valid if $v_D \tau_{ei} \ll L$, or

$$L \gg \sqrt{\rho_L \lambda_{mf}}$$

This limit is most severe when the laser focal spot is very small, causing gradients in B to be steep. For example, the experiment of Ref. 43 reported a scale length for B of $L \sim 10 \mu\text{m}$ at the edge of the maximum field region. With parameters⁴³ $T_e \sim 10^4$ eV, $B \sim 4$ MG, and $n_e \sim 10^{19} \text{ cm}^{-3}$, one obtains

$$\frac{L}{\sqrt{\rho_L \lambda_{mf}}} \sim \frac{10 \mu\text{m}}{100 \mu\text{m}} \sim 0.1.$$

whereas this ratio should be greater than unity for classical transport to be valid.

We conclude that the steep gradients characteristic of very small laser focal spots may violate this second type of constraint necessary for classical transport to apply.

A third condition necessary for classical transport to apply concerns field fluctuations. The classical theory breaks down in the presence of large-amplitude field fluctuations. In the case of strongly turbulent electric fields, one obtains Bohm diffusion, which exists as an option to classical transport theory in LASNEX. Another potentially important source of departure from classical transport theory is large fluctuations in the B field, which we consider in the next section.

Anomalous Diffusion Due to Small Scale B Fluctuations

There are several sources of small-scale B fields, some of which are not contained in the present LASNEX code. Some examples of these sources are: 1) $\nabla n \times \nabla T$ fields around a self-focused light filament or hot spot, 2) $\nabla n \times \nabla T$ fields at composition discontinuities, such as a DT-glass interface, 3) resonance absorption fields, and 4) magnetic instability fields. These sources may cause essentially random fluctuations in the background $\nabla n \times \nabla T$ field, leading to enhanced diffusion.

We have considered this effect by a quasilinear calculation. In the absence of strong electric fields, the Vlasov equation is

$$\frac{\partial f}{\partial t} + \underline{v} \cdot \nabla f + (q/m)(\underline{v}/c) \times (B_0 + \delta B) \cdot \nabla_v f = 0. \quad (2)$$

Here B_0 is the static background field and δB the stochastic component. Equation (2) may be written schematically as

$$(L_0 + L')f = 0$$

where L_0 is the averaged Vlasov operator, and L' the stochastic part. Averaging,

$$L_0 f_0 + \langle L' f' \rangle = 0$$

Subtracting the averaged equation from the full equation,

$$L_0 f' + L' f_0 + L' f' - \langle L' f' \rangle = 0 \quad (3)$$

In the spirit of quasilinear theory, we neglect the last two terms in Eq. (3), and obtain

$$f' = L_0^{-1} L' f_0. \quad (4)$$

The operator L_0^{-1} involves integration in time backwards along the trajectory defined by L_0 . In our case it is a helix defined by the background field B_0 . We assume $\delta B \ll B_0$. The averaged equation becomes

$$L_0 f_0 + \langle L' L_0^{-1} L' \rangle f_0 = 0. \quad (5)$$

The generalized diffusion operator is thus

$$\langle L' L_0^{-1} L' \rangle.$$

The diffusion coefficients in the fluctuating fields δB are then calculated by using expressions for L_0 and L' from Eq. (2). Our main results can also be derived from a heuristic argument that shows the physical basis of the effect. Since

$$\frac{\Delta v}{\Delta t} \sim (e/mc) \underline{v} \times \underline{\delta B},$$

a 90° scattering time may be defined as

$$\tau_{90}^{-1} \sim \frac{\Delta v^2}{v^2 \Delta t^2} \Delta t = \delta \Omega^2 \Delta t,$$

where $\delta \Omega$ is the cyclotron frequency ($e \delta B / m c$) and Δt is the duration of one scattering event, $\Delta t \sim \min(\Omega_0^{-1}, \delta \Omega^{-1})$. Now consider cross-field scattering (perpendicular to B_0):

$$D_{\perp} = \Delta x_{\perp}^2 \tau_{90}^{-1}.$$

But the trajectory is shifted by a Larmor radius, ρ_L , during scattering. Therefore,

$$D_{\perp} = \rho_L^2 \delta \Omega^2 \Delta t = v_{\perp}^2 \left(\frac{\delta B^2}{B_0^2} \right) \min(\Omega_0^{-1}, \delta \Omega^{-1}). \quad (6)$$

Next, consider the parallel diffusion. The particle freely streams along the field line which is deformed by δB , thus affecting the particle parallel velocity or displacing the particle sideways. In either case

$$D_{\parallel} \sim v_{\parallel}^2 \tau_{90} \sim \frac{v_{\parallel}^2}{\delta \Omega^2 \Delta t} \sim \frac{v_{\parallel}^2}{\Omega_0^2} \left(\frac{B_0^2}{\delta B^2} \right) \min(\Omega_0, \delta \Omega), \quad (7)$$

a result which is well known in the theory of cosmic rays.¹¹ The quasilinear calculation shows that this diffusion is due to resonant scattering from fluctuations with scale lengths λ satisfying $(2\pi/\lambda)v_{\parallel} \sim \Omega_0$. Hence $\lambda \sim$ a few μm for $T \sim 0.5$ keV, $B \sim 1$ MG.

We are investigating these processes in more detail in order to see whether they will significantly affect our present understanding of plasma transport properties.

C. E. Max
J. J. Thomson
W. Manheimer
G. Dahlbacka
W. C. Mead

6.6.2 ANOMALOUS dc RESISTIVITY

We have discovered a new mechanism for anomalous dc resistivity.¹⁵ This problem is important to the heat conductivity of the laser-heated electrons streaming into the corona. Charge neutrality at the critical surface demands a return current of thermal electrons. This return current is unstable if the electron drift velocity is above a threshold value¹⁶ which is a function of the electron-to-ion temperature ratio. We have modeled this effect in our particle simulation codes by calculating the electric field required to hold the electron drift velocity constant. We have run electron drift velocities from 0.5 to $2 V_{the}$, where V_{the} is the electron thermal velocity, $V_{the} = \sqrt{kT_e/m}$.

Our results indicate that the anomalous resistivity is due to the formation of localized, extremely large amplitude ($\delta n/n \approx 1$), ion waves. A typical result for ion density from the 1-D results as shown in Fig. 6-21.

The low-frequency potential also has large (several T_{ion}) jumps at these localized structures. The electrons are accelerated over these potential jumps and heated by the interaction with the ion waves. The maximum resistivity is $\nu_{eff} \approx 0.01 \omega_{pe}$ for this calculation. The effective collision frequency is a rapidly increasing function of V_d/V_{the} for $V_d \leq 2V_{the}$. At $V_d \approx 2V_{the}$, we find $\nu_{eff} \approx 0.05 \omega_{pe}$. We find an almost complete lack of runaway electrons. The 2-D calculations show that the 1-D results are qualitatively correct. The electron heating is mostly along the drift velocity, showing that the effect is essentially 1-D in contrast to the accepted theories of anomalous dc resistivity.¹⁷

Art Walstead
John DeGroot
Chris Barnes

6.7 X-Ray Line Spectra

6.7.1 X-RAY LINE SPECTRA DIAGNOSTIC THEORY

Introduction

Diagnosis of laser-produced plasma under conditions appropriate for target implosion experiments has required the development of a new class of experimental apparatus. The targets are small (shells of $100\text{ }\mu\text{m}$ or less diameter which have wall thicknesses of $0.1\text{--}1\text{ }\mu\text{m}$), the experimental times are short (implosion times $\tau \approx r/c_s$, with sound speeds $c_s \approx 2 \cdot 10^7\text{ cm/s}$ at a temperature of 1 keV , are about $100\text{--}200\text{ ps}$), and the energy fluxes are large (laser intensity approx 10^{14} to 10^{16} W/cm^2). In fact, the characteristic times and lengths during the last important compression phase are even shorter, about 10 ps and $5\text{ }\mu\text{m}$, respectively.

Current diagnostics depend heavily on analysis of x-ray emission from these targets. Presently, most of the emphasis has been placed on broad-band time- and space-integrated continuum measurements⁴⁷ which are used to help determine energy absorption and the spectrum of high energy electrons which can be created by collective absorption processes. Additionally, spatially resolved, time-integrated measurements of x-ray fluxes by pinhole cameras provide useful information about the amount and symmetry of compression.⁴⁸

This work presents the results of our attempts to interpret the line portion of the x-ray spectrum in the $1\text{--}4\text{ keV}$ region. The experiments to date have been done with glass targets, from which the strongest emitter in this energy range is Si. Small amounts of Na (3%) and Ca (4%) are also present along with traces of other materials. Sodium lines (near 1 keV) are almost always present while calcium lines (near 4 keV) appear above the continuum only erratically.

Since the current observations are space and time integrated,⁴⁹ our approach has been to try to characterize the emitting region by a single density N , temperature T , plasma scale length L and duration of emission τ . If no such set of parameters can satisfactorily model the data, then we expect that additional information is obtainable, but only through the use of a more sophisticated model. This analysis is also a prerequisite to interpretation of future experiments in which spatial and temporal resolution is obtained through the introduction of selected materials into the target.

The plan of this section is as follows: Part 2 develops the basis for temperature measurements; Part 3 discusses the calculation of density and temperature-dependent emission lineshapes; Part 4 discusses the important effects of opacity; and Part 5 uses the results

of these calculations to interpret data obtained at Livermore. (See Sec. 8.5.6.)

Fig. 6-21. Ion density as a function of position at time of maximum resistivity ($\omega_{pe}t = 440$). Parameters: $V_{d1} = V_{the}$, $M/m = 100$, $T_e/T_i = 100$.

Temperature Measurements

Ionization State. The appearance of strong lines resulting from transitions within a given ionization state immediately provides upper and lower bounds on the electron temperature which can sometimes differ by less than a factor of two. Except at very high electron densities (densities high enough so that the electrons are degenerate) the ground level ionization potential χ_{ii} of the most abundant ionization state ranges from $\chi_{ii}/T_e \sim 5$ at $Z = 1$ to $\chi_{ii}/T_e \sim 1$ at $Z = 25$. In the moderate Z range of interest (the average nuclear charge $Z = 10$ for Si glass), the ratio $\chi_{ii}/T_e \approx 3$. As shown below, the minimum electron temperature is expected to be at least > 200 eV. This is about half of the 523 eV ionization potential of Li-like Si. The ionization potentials of the He-like (2.44 keV) and H-like (2.67 keV) Si ions are several times larger than those of any other charge state. Therefore, for the temperatures and Z 's of interest, the ions spend most of their life in the He-like, H-like, or fully stripped state. In order to bound the temperature during emission, we have solved the ionization rate equations including collisional ionization³⁰ and radiative³¹ and three-body recombination. The He-Li, H-He and H⁺-H population ratios vs temperature are shown for several density values in Fig. 6-22 a, b, and c, respectively.

Intensity Ratios. A direct temperature measurement is obtainable through comparison of line intensity ratios only if the line center optical depths are much less than unity. As we shall show below, the optical depth is large for the first several members of the principal series so that temperature measurements based on line ratios are most easily interpreted if the lines are from high series members. Since the H-like ionization potential is several times the temperature during emission, most accurate temperature values come from a comparison of He/H high series members, whose line center opacity is small except at very high density. In order to determine the upper level populations, we use the fact that for electron densities

$$n_e > A_n/K_{in}(T, Z) \quad (1)$$

with

$$A_n = \sum_{m < n} A_{nm}, \quad (2)$$

the total spontaneous emission rate from level n , and $n_e K_{in}(T, Z)$, the collisional ionization rate, Saha equilibrium with the ground level of the next higher ionization state obtained. Thus, when inequality (1) is satisfied, this ratio is

$$\frac{n_{Z+1,1} n_e}{n_{Z,n}} = 2 \left(\frac{2\pi m T_e}{h^2} \right)^{3/2} \frac{g_{Z+1,1} \exp\{-\chi_{ni}(Z)/T\}}{g_{Z,n}}$$

Fig. 6-22. Ratio of successive ionization state populations for Si vs the electron temperature T_e for several values of the electron density n_e .
a) He-like to Li-like ratio.
b) H-like to He-like ratio.
c) Ratio of fully stripped to H-like Si.

Here $g_{Z,n}$ is the statistical weight of the n th level of ionization state Z , $\chi_n(Z)$ is the ionization potential from the level n , and the other symbols have their usual meanings.

For emission in optically thin lines, the intensity is simply

$$I_{n1}(Z) = A_{n1}(Z) n_{Z,n} \tau \quad (4)$$

and the intensity ratio between high series members of successive ionization states is

$$\begin{aligned} \frac{I_{n1}(Z)}{I_{n'1}(Z-1)} &= \frac{A_{n1}(Z) n_{Z,n}}{A_{n'1}(Z-1) n_{Z-1,n'}} \\ &= \frac{n_{Z+1,1}}{g_{Z+1,1}} \frac{g_{Z,1}}{n_{Z,1}} \frac{g_{Z,n}}{g_{Z-1,n'}} \end{aligned} \quad (5)$$

The ratio $n_{Z+1,1}/n_{Z,1}$ is obtainable for an assumed density and temperature from Fig. 6-22.

Continuum Measurements. The slope and height of the edge of the He and H free-bound continuum is used to check the value of the temperature determined from line intensity ratios. Additionally, a comparison of opacity-corrected line intensities to the continuum intensity is used to determine the plasma density and extent.

Density Determination

Continuum Measurements. If the electron temperature and the extent of the emitting region are known, then the average density can be determined from an absolute measurement of the free-bound continuum intensity. The total energy emitted per steradian is

$$\begin{aligned} E(\text{erg/sr}) &= \int_V d^3x \int dt \sigma(n, T) \\ &\approx V \tau \sigma(\bar{n}, \bar{T}) \end{aligned} \quad (6)$$

with the emission rate per unit volume σ given by^{31, 32}

$$\sigma = 1.6 \cdot 10^{-25} Z^4 n_e n_i T(\text{keV}) \text{ergs/cm}^3/\text{s}.$$

The duration of emission τ is experimentally³³ observed to be equal to the laser pulse width. Although absolute intensity measurements are nontrivial, the total radiated energy varies with the square of the density, a fact which should make it possible to determine the density accurately to within a factor of a few.

Linewidth Calculations. The fluctuating plasma microfields which arise both from single particle en-

counters and from collective oscillations perturb the radiating ions and give rise to a lineshape which must be convoluted with the natural and Doppler-broadened linewidths in order to determine the complete lineshape. We present here only the results of calculations of electron and ion broadening of the He-like resonance line and high principal series members of both He- and H-like ions.³⁴

The resonance line is principally broadened by collisions with electrons which occur so rapidly that they are considered instantaneous in the theory (the impact approximation). That is, the interaction time

$$\tau_i \approx \rho/v, \quad (8)$$

for a collision with impact parameter ρ between a radiator and an electron with velocity v is much smaller than the maximum inverse frequency shift $\Delta\omega$ which occurs during the collision

$$\Delta\omega\tau_i \ll 1. \quad (9)$$

The result of an average over a large number of such collisions is to yield a random diffusion of the radiator wave function phase and consequently a Lorentz lineshape

$$I(\omega) = \frac{1}{\pi} \frac{w}{(\omega - \omega_0)^2 + w^2} \quad (10)$$

with a width w which is obtainable analytically in the high temperature

$$T_e \gg \hbar\omega_{01}/Z \quad (11)$$

straight classical path approximation as

$$w = 3 \left(\frac{2\pi m}{T_e} \right)^{1/2} \left(\frac{\hbar}{m} \right)^2 \frac{n_e}{(Z-1)^2} n^2 (n^2 - \ell_M^2) \frac{\ell_M \lambda}{2\ell + 1}. \quad (12a)$$

Here ℓ_M is the quantum number of the larger of the two orbital angular momenta states which are coupled by the radiator-electron interaction in the dipole approximation. (For 2^1p broadening $\ell_M = 1$.) The factor

$$\lambda = \ell_n \left\{ \left[\frac{2}{3} \frac{2\ell + 1}{\ell_M (n^2 - \ell_M^2)} \right]^{1/2} \frac{T_e}{\hbar\omega_{01}} (Z-1) \right\} \quad (12b)$$

is the logarithmically dominant term in the high temperature limit. The line center frequency ω_0 also suffers a small shift which we neglect here.

The effect of encounter, between radiators and the relatively slowly moving ions is included in the theory by neglecting their motion entirely (quasi-static approximation) and taking a statistical average over their

positions. Such an approach is valid when the inverse of condition (9) applies, and it usually does for ions.

There are two effects of the ion microfields which concern us. One is the mixing of dipole forbidden (2^1s-1^1s) and allowed (2^1p-1^1s) transitions. This results in emission near the frequency of the forbidden component. The intensity of this emission relative to that of the allowed component is

$$I \equiv \frac{I(2^1s-1^1s)}{I(2^1p-1^1s)} = 9 \left(\frac{ea_0}{Z\hbar\omega_{01}} \right)^2 \int dF F^2 w(F) .$$

$$= 9 \left(\frac{ea_0}{Z\hbar\omega_{01}} \right)^2 \langle F^2 \rangle . \quad (13)$$

In Eq. (13) the notation $\langle \rangle$ has been introduced to designate the field strength average.

There are no detailed calculations of ion microfield strengths available for the high densities and charge states under consideration. The Holtzmark calculation is not expected to apply because the potential at a mean particle spacing

$$\alpha \equiv \frac{Z^2 e^2}{r_{av} T_i} \quad (14a)$$

is generally large. Setting $1/r_{av} = (4\pi n_i/3)^{1/3}$, and expressing T_i in Kev, we have

$$\alpha = 2.3 \times 10^{-10} \frac{Z^2 n_i^{1/3}}{T_i(\text{keV})} . \quad (14b)$$

For $Z = 13$, $T_i = 0.4$ keV, $\alpha = 1$ at $n_i = 10^{21} \text{ cm}^{-3}$. For $\alpha \gg 1$, a simple model allows an estimate of the mean field strength E . Consider a one-dimensional chain of ions with mean spacing Δ . Each ion oscillates about its equilibrium position with an excursion δ , such that the potential due to the other ions $\phi(\delta) \approx T_i$. After a little algebra, the estimate

$$E = \left(\frac{T_i}{2\Delta^3} \right)^{1/2} \quad (15a)$$

is obtained for the mean field strength. Associating Δ with r_{av} , we have finally

$$E(\text{esu}) = 5.79 \times 10^{-5} T_i^{1/2}(\text{keV}) n_i^{1/2} . \quad (15b)$$

The other effect of the ion microfields is to broaden the high series members through the linear Stark effect. The half-width of such lines of principal quantum number n is⁵⁵

$$\Delta E = \frac{2}{3} n(n-1) \frac{ea_0}{Z} \langle F \rangle \quad (16)$$

Effects of Opacity

The atomic absorption cross section $\sigma(\nu)$ is expressed in terms of the absorption oscillator strength f_{ij} and the line absorption profile $\phi(\nu)$ as

$$\sigma(\nu) = \pi e^2 f_{ij} \phi(\nu) , \quad (17)$$

with $\phi(\nu)$ normalized so that

$$\int_{-\infty}^{\infty} d\nu \phi(\nu) = 1 . \quad (18)$$

We assume for the moment that $\phi(\nu)$ has a single maximum at the line center frequency ν_{ij} . In the absence of spontaneous and induced emission, radiation of frequency ν_{ij} suffers an exponential attenuation in energy density

$$\exp(-k_i x) \quad (19)$$

with

$$k_i = \frac{n_i \pi e^2}{mc} f_{ij} \phi(\nu_{ij}) \quad (20)$$

as a result of propagating a distance x through a density n_i of scatterers in the i th state. Generally, the quantity $k_i(\nu)x$ is the optical depth at frequency ν corresponding to the physical length x . For example, the line center optical depth for a Lorentz linewidth γ in a plasma of $\sim$ length L is

$$\tau_0 = \frac{n_i e^2}{mc} \frac{f_{ij}}{\gamma} . \quad (21)$$

Because of the rapid decrease in f_{ij} and increase in γ with increasing n , the most common situation in laser-produced plasmas is one in which the line center opacity is large for the first few lines of the principal series and less than unity for the highest observable series members.

Holstein has shown that the principal mechanism for photon escape is by frequency redistribution upon multiple scattering from the opaque core into the optically thin wings.⁵⁶ The results of his variational solution of the source free transfer equation show that the relaxation time is reduced from the spontaneous emission rate A_{ji} by an "escape factor" $g(\tau_0)$ which is essentially the probability of frequency redistribution into the wings in any absorption and re-emission. This escape factor is written in terms of the absorption profile $\phi(\nu)$ as follows:

$$g(\tau_0) = \int d\nu \phi(\nu) \exp \left[-\tau_0 \frac{\phi(\nu)}{\phi(0)} \right] \quad (22)$$

A discussion of the validity of the assumption of complete redistribution is given in Holstein's work. He shows the assumption to be generally valid for Lorentz pressure broadening and to introduce only small errors in g for Doppler-broadened profiles. More recently, the emergent lineshape for the constant properties slab has been obtained from an asymptotic analysis for $\tau_0 \gg 1$.³⁷ However, our principal diagnostic will be based on a comparison of spectral intensities, which are determined by the rate equations once $g(\tau_0)$ is known for each line. That is, in the rate equations for the level populations

$$0 \approx \frac{\partial n_j}{\partial t} = n_e \sum_{j' \neq j} c_{j'j} n_{j'} + \sum_{j' > j} A_{j'j} n_{j'} \\ = n_j \left[\sum_{j' < j} A_{jj'} + n_e \sum_{j' \neq j} c_{jj'} \right]. \quad (23)$$

Make the replacement

$$A_{jj'} \rightarrow g(\tau_0) A_{jj'} \quad (24)$$

everywhere to account for radiation trapping.

Application to Data

We illustrate the techniques described above by applying them to data recently obtained in laser target experiments at Livermore. The total spectrum observed by the crystal spectrometer is shown in Fig. 6-23. The Silicon He-like lines $1s^2-1s2p$, $1s^2-1s5p$ and the H-like line $1s-5p$ are shown in Figures 6-24 a, b, and c, respectively.

Fig. 6-23. Experimentally observed total x-ray energy emitted in J/sr/keV vs photon energy in keV.

The electron temperature is readily obtained from the slope of the He and H free-bound continua. Both measurements yield a value of 650 eV. Another temperature measurement can be made from the ratio of the $1s^2-1s5p$ and $1s-5p$ intensities. As indicated in Part 2, this ratio is related to the ground state population densities of H-Si (n_{H^+}) and of H⁻-Si (n_{H^-}) through the formula

$$\frac{I_{He}^{5,1}}{I_H^{5,1}} = \frac{n_{He}^5}{n_H^5} \frac{A_{He}^{(5,1)}}{A_H^{(5,1)}} \\ = \frac{g_{5, He}}{g_{1, He}} \frac{g_{1, H^+}}{g_{5, H}} \frac{n_H}{n_{H^+}} \frac{A_{He}^{(5,1)}}{A_H^{(5,1)}} \quad (25) \\ = \frac{1}{2} \left(\frac{13}{14} \right)^4 \frac{n_H}{n_{H^+}} = 0.37 \frac{n_H}{n_{H^+}}$$

Using the observed intensity ratio of 0.59 and Fig. 6-22c for $n_{H^+}/n_H = 0.63$, we find $T_e = 750$ eV, a result in reasonable agreement with that obtained from the continuum slope. The ratio n_{H^-}/n_H is also obtainable from the height of the free-bound continuum edge. This measurement again yields a temperature of 750 eV.

An estimate of the ion pressure can be obtained from the observed 5-eV half-width of the $1s-5p$ and $1s^2-1s5p$ lines. Combining Eqs. (15b) and (16), and solving for $n_i T_i$, we obtain

$$n_i T_i = 2.8 \times 10^{21} \text{ keV/cm}^3 \quad (26)$$

The combination $(n_{He}^I)^2 V$ is obtained from the total energy in the He free-bound continuum. An integral from the 2.44-keV continuum edge upward yields 1.1×10^{-2} J/sr after subtraction of the H-like Si and O continua. Using this result along with an emission time $\tau \approx 100$ ps and $\bar{Z} = 10$, we obtain $(n_{He}^I)^2 V = 2.5 \times 10^{36} \text{ cm}^3$.

The thickness of the emitting layer is obtained from the ratio of the He resonance line intensity to that of the free-bound continuum. Because of radiation trapping, the effective spontaneous emission rate is reduced as indicated by the mapping [Eq. (24)].

The escape factor is determined by the behavior of the wings of the line profile. In general, the electron and ion broadening must be convoluted with the Doppler profile

$$\phi_D(\omega) = \frac{1}{(2\pi\Delta)^{1/2}} \exp(-\omega^2/2\Delta^2) \quad (27a)$$

whose width Δ is related to the Si ion temperature T_i as follows:

$$\hbar\Delta(\text{eV}) = 0.195 T_i^{1/2} (\text{keV}) \hbar\omega (\text{keV}). \quad (27b)$$

Only the asymptotic behavior of the Voigt profile

$$\phi \sim \frac{1}{\pi} \left[\frac{x}{\omega^2} + \left(\frac{\pi}{2} \right)^{1/2} \exp(-\omega^2/2) \right] \quad (28)$$

is needed for an evaluation of g for $\tau_0 \gg 1$. In Eq. (28) the frequency has been normalized to Δ and $x \equiv \gamma_i/\Delta$ is the ratio of the Lorentz to Doppler width. In deriving Eq. (28), it has been assumed that $|\omega| > \max(x, 1)$. For the parameters of interest, $x \sim 0.1$ - 0.2 and

$$\begin{aligned} \tau_0 &= k_l(\omega_{ij})L = \frac{2\pi^2 e^2 n_l f_{ij}}{mc\Delta^{1/2}} L \\ &= 1.27 \times 10^{-20} \frac{L(\mu)n_l}{T_i^{1/2}(\text{keV})} \end{aligned} \quad (29)$$

is $\approx 10^2$. A numerical evaluation shows that in this parameter range both the Lorentz and Doppler wings play an important role in determining g . That is, $g(x, \tau_0)$ lies between the asymptotic limits

$$g\left(\infty, \frac{\tau_0}{x}\right) \sim 2\left(\frac{x}{\tau_0}\right)^{1/2} \quad (30a)$$

and

$$g(0, \tau_0) \sim \left\{ \frac{\tau_0}{(2\pi)^{1/2}} \left[\pi \ln \frac{\tau_0}{(2\pi)^{1/2}} \right]^{1/2} \right\}^{-1} \quad (30b)$$

corresponding, respectively, to pure Lorentz and pure Doppler lineshapes.

Assuming τ_0 large enough so that $gA_{21} < n_e \sum_j c_{2j}$ (otherwise the optical depth has no effect on the intensity), Saha equilibrium obtains between the He I and 2 levels, and the emission rate per steradian is

$$I_{\text{He}}^{2,1} = \frac{g_{\text{He}}^2}{g_{\text{He}}} n_{\text{He}}^1 \text{Ve}^{\exp(-x_{12}/T_e)} A_{\text{He}}(2,1) \frac{h\nu}{4\pi} g(x, \tau_0) \quad (31)$$

Dividing Eq. (31) by Eq. (7), we find

$$\begin{aligned} R &\equiv \frac{I_{\text{He}}^{2,1}}{I_{\text{He}}^{\text{free-bound}}} \\ &= 6.1 \times 10^{23} \frac{T^{1/2}(\text{keV})}{n_{\text{He}}} g(x, \tau_0) \exp(-x_{12}/T_e) \end{aligned} \quad (32)$$

for the ratio of line/continuum emission. Substituting the observed ratio $R = 2.28 \times 10^{-3} \text{J/sr}/1.1 \times 10^{-2} \text{J/sr} = 0.207$, and $T_e = 0.75 \text{ keV}$, we obtain

$$n_{\text{He}} = 2.16 \times 10^{23} g(x, \tau_0). \quad (33)$$

Since both x and τ_0 depend on n_{He} , this is an implicit equation for $n_{\text{He}}(L)$. For a given value of R , and T_e , the thickness L decreases with increasing n_{He} . The solution of Eq. (33), with $T_i = T_e = 750 \text{ eV}$, yields $L = 300 \mu\text{m}$ for $n_{\text{He}} = 1 \times 10^{21} \text{ cm}^{-3}$, and $L = 3 \mu\text{m}$ for $n_{\text{He}} = 5 \times 10^{21} \times \text{cm}^{-3}$. A tabulation of $L(n_{\text{He}}, T_e, T_i)$ is contained in Ref. 54. A set of values for $L = V^{1/3}$ and n_{He} which yields the correct R and 0.6 of the continuum energy is $L = 10 \mu\text{m}$ and $n_{\text{He}} = 3 \times 10^{21} \text{ cm}^{-3}$.

The ion pressure determination, Eq. (26), suggests the value $n_{\text{He}} \sim 3.7 \times 10^{21}$ if indeed $T_i = 0.75 \text{ keV}$, a value which is in good agreement with that obtained above, given the simplicity of the microfield strength estimate.

Another indicator of the microfield strength is the ratio of the 2's forbidden to 2'p allowed intensity. After combining Eqs. (13) and (15) and multiplying by $1/g$ to correct the intensity of the line for opacity, the equation

$$I^f = \frac{7.6 \times 10^{-20}}{Z^2 [h\omega_{01}(\text{eV})]^2} \frac{n_i T_i(\text{keV})}{g}$$

is obtained. The observed value (see Fig. 6-24a) of I^f is 0.22. The calculated value of $h\omega_{01}$ is 10 eV. Again choosing $T_i = 0.75 \text{ keV}$, we obtain the estimate $n_i \approx 1.3 \times 10^{21}$.

Conclusions

This work suggests that valuable information about the parameters of laser-produced plasmas is obtainable from the analysis of line spectral data using a relatively simple model.

Logical extensions of the analysis include a more detailed treatment of radiation transfer which could be coupled to a hydrodynamic simulation in order to realistically include time and space variation. A fundamental statistical mechanics problem is the calculation of the ion microfield distribution including the effects of strong ion-ion correlation. Work on these problems is currently underway.

E. Valeo
H. Griem
J. Thomson
D. Bailey

Fig. 6-24. Expanded scale plots of three of the lines appearing in Fig. 6-23.

- a) He-like Si resonance transition $1s^2-1s2p$.
- b) He-like Si $1s^2-1s5p$ transition.
- c) H-like Si $1s-5p$ transition.

6.8 Suprathermal Electrons

6.8.1 MEASUREMENT OF SUPRATHERMAL ELECTRON PRODUCTION DUE TO PARAMETRIC INSTABILITIES NEAR THE CRITICAL SURFACE

Our experiment is designed to model anomalous absorption of laser light normally incident on the plasma.^{58,59} Absorptive parametric instabilities are excited near the critical surface where the microwave frequency ($\omega_0/2\pi = 1.2$ GHz) equals the plasma frequency, ω_{pe} . The parametrically-excited high frequency wave grows exponentially with time and then saturates. (Fig. 6-25a). After the instabilities saturate, both strong anomalous absorption and suprathermal electron heating are observed. (Fig. 6-25c).

For powers corresponding to laser fusion conditions ($\zeta_0 = E_0 \sqrt{4\pi n k T_e}^{1/2} \approx 0.2$), the suprathermal electrons are formed shortly after the instabilities saturate. Also, for these high powers, the suprathermal distribution is

exponential in velocity shortly after the microwaves are pulsed on; later, the distribution is Maxwellian (Fig. 6-26 a). These results agree with simulations performed at LLL. The heated electrons extend out to very large energies ($E_e > 130$ KT_{eo}). The temperature of the suprathermal electrons increases with power as the square root of power, i.e., $T_h \propto P_0^{1/2}$ (Fig. 6-26 b). The suprathermal electron density is almost constant at 10% of the plasma density in the high power regime, while the absorbed microwave power is about 20%. A rough calculation of power flow indicates that the absorbed power is fed into energetic electrons. The thermal electrons are also heated; the hot-to-cold temperature ratio varies from about 4 to 10. The heated

Fig. 6-25. Wave energy and hot-electron current (all electrons with energy above 40 eV are collected) vs. time. Curves 1, 1', 2, 2', and 3' correspond to the pump powers of 14 W, 57 W, and 360 W. Insert shows the time history of both the reflected pump power (solid curve) and the hot-electron current (broken curve) at a pump power of 0.5 kW. The horizontal scale is 2 $\mu\text{s}/\text{div}$.

thermal electrons tend to be confined near the critical surface due to a dc potential while ions are accelerated outward from the critical surface.

We have also studied the effects of finite-source band width on the parametric instabilities. When the pump power P_0 is near the coherent threshold value, P_{th} , i.e., $P_0 < 4 P_{th}$, both the growth rates and the saturation levels decrease with increasing source band width, $\Delta\omega$, while for larger pump power, the saturation level of the instabilities is almost constant as $\Delta\omega$ is increased although the growth rate decreases. Therefore, at high powers, the suprathermal electron production is essentially unaffected up to the maximum band width presently available, $\Delta\omega \sim \omega_{pl}$.

K. Mizuno
J. S. DeGroot

6.8.2 MEASUREMENT OF SUPRATHERMAL ELECTRON PRODUCTION IN A PLASMA-FILLED CAPACITOR

Using a plasma-filled capacitor, we have measured the distribution function of electrons that are accelerated during resonant absorption.^{60,61} We observe a suprathermal component of the electron distribution function, as predicted by simulations.⁶² Over the range of absorbed power that we have studied, the suprather-

Fig. 6-27. Schematic of the apparatus.

($N^{-1}dn/dx \approx 0.16 \text{ cm}^{-1}$) is created by a hot cathode discharge at one end of the vacuum chamber. A 470-MHz signal is applied to the capacitor comprised of 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. This field resonantly excites an enhanced field where the

electron plasma frequency approximately equals the applied frequency.

The electrons accelerated parallel to the density gradient by this enhanced, localized field are sampled using an energy analyzer located far enough from the resonant region that the field is not perturbed. A sensitive measure of the energy distribution of accelerated electrons is the difference (Δf) between the time-averaged steady state distribution functions measured with and without an applied electric field. The points in Fig. 6-28 are measurements of Δf as a function of electron energy, presented for four values of the total absorbed power P_A .

Also shown in Fig. 6-28 (solid lines) are calculated values of Δf that have been fitted to the data. The calculation models the localized field by a Gaussian distribution of width 2-D and field strength $[\eta = E_0/(4\pi nkT_e)^{1/2}]$. The parameters η and 2-D used to fit to the data are shown in the inset of Fig. 6-28. They may be regarded as an indirect measure of the size and amplitude of the actual field in the experiment.

C.P. DeNeef

6.9 Code Development

6.9.1 AN 880-ns 1-D ELECTROSTATIC PARTICLE MOVER FOR THE CDC 7600

We describe a very fast computational method of moving particles for 1-D electrostatic plasma simulations using integer arithmetic.⁶³ The "cloud-in-cell" method forms the basis of this technique. The paper is a compass-compliant subroutine with comments and examples describing methods of using an entirely integer representation to gain up to an order-of-magnitude increase in speed over equivalent floating point Fortran coding.

Integer arithmetic has several advantages over floating-point arithmetic for 1-D particle movers. The adds are much faster, and the binary numerical description allows the implementation of very simple boundary conditions if the simulation region extends from zero to a power of two. Furthermore, integer arithmetic makes very efficient use of each memory bit since there

is no floating-point exponent. Consequently, it becomes feasible and fast in long-word-length machines to pack the velocity and position of a particular particle into the same word, thus saving a factor of two in computer storage and/or IO. These advantages are combined with the fact that integer adds and logicals complete in only two computer cycles, allowing nearly complete optimization of register and instruction interleaving. The measured timings on a CDC 7600 are 880 ns and 935 ns per particle for the periodic and general boundary condition sections, respectively. Methods for adapting the technique to other computers are discussed in Ref. 63.

K. Estabrook
J. E. Tull

Fig. 6-28. Measured (points) and calculated (solid lines) changes of distribution function vs electron energy is shown for several values of total absorbed power P_A .

References

1. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Fluids* **18**, 1151 (1975).
2. A. B. Langdon and B. F. Lasinski, in *Methods in Computational Physics*, **16**, J. Killeen et al. Eds. (Academic Press, N.Y., in press).
3. H. G. Ahlstrom, *Laser Fusion Experiments at the Lawrence Livermore Laboratory*, Lawrence Livermore Laboratory, Rept. UCRL-77094 (1975).
4. R. A. Hass, D. W. Phillion, M. J. Boyle, and H. N. Kornblum, *Laser Irradiation of Parylene Disks with a 1.06 μ m Laser*, Lawrence Livermore Laboratory, Rept. UCRL-77073 (1975).
5. B. H. Ripin et al., *Phys. Rev. Letters* **34**, 1313 (1975).
6. G. H. Dahlbacka, W. C. Mead, C. E. Max, and J. J. Thomson, *Calculation of Self-Generated Magnetic Fields in Parylene Disk Experiments*, Lawrence Livermore Laboratory, Rept. UCRL-77150 (1975).
7. R. C. Malone, R. L. McCrory, and R. L. Morse, *Phys. Rev. Letters* **34**, 721 (1975).
8. W. M. Manheimer, *Energy Flux Limitation By Tame Turbulence*, Lawrence Livermore Laboratory, Rept. UCRL-77149 (1975).
9. W. L. Kruer, E. J. Valeo and K. G. Estabrook, *Phys. Rev. Letters* **35**, 1076 (1975).
10. *Laser Program Annual Report - 1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74, (1975) p. 407.
11. C. S. Liu, M. N. Rosenbluth, and R. B. White, *Phys. Fluids* **17**, 1211 (1974).
12. D. Forslund, J. Kindel, and E. Lindman, *Phys. Rev. Letters* **30**, 739 (1973).
13. W. L. Kruer, K. G. Estabrook, and K. H. Sinz, *Nuclear Fusion* **13**, 952 (1973).
14. H. H. Klein, W. M. Manheimer, and E. Ott, *Phys. Rev. Letters* **31**, 1187 (1973).
15. A. T. Lin and J. M. Dawson, *Phys. Fluids* **18**, 201 (1975).
16. M. Lubin, E. Goldman, J. Sources, L. Goldman, W. Friedman, S. Letzring, J. Albritton, P. Koch, and B. Yaakobi, in *Plasma Physics and Controlled Nuclear Fusion* (International Atomic Energy Agency, Vienna, Austria, 1974), Paper F4-2.
17. B. H. Ripin, J. M. McMahon, E. A. McLean, W. M. Manheimer, and J. A. Stamper, *Phys. Rev. Letters* **33**, 634 (1974).
18. P. Lee, D. V. Giovanielli, R. P. Godwin, and G. H. McCall, *Appl. Phys. Letters* **24**, 406 (1974).
19. A back reflection of as high as 83% has been observed in recent laser plasma experiments at Livermore. (Private communication, E. Storm.)
20. A discussion of many laser plasma experiments can be found in *Laser Interaction and Related Plasma Phenomena 3*, H. Schwarz and H. Hora, Eds. (Plenum, New York, 1975).
21. J. G. Meadors, *J. of Applied Physics* **40**, 2510 (1969).
22. G. L. Tang, *Ibid.* **37**, 2945 (1965).
23. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, *Phys. Letters* **49A**, 109 (1974); also *Phys. Fluids* **18**, 115, (1975); J. Kindel, K. Lee, E. Lindman, and R. Morse, *Phys. Rev.* **11A**, 679 (1975).
24. R. L. Dewar and E. J. Valeo, presented at the 6th Conference on Numerical Simulations of Plasmas (Berkeley, 1973); K. G. Estabrook, *Phys. Fluids* **15**, 2026 (1972).
25. A. B. Langdon and B. F. Lasinski, *Phys. Rev. Letters* **34**, (1975).
26. E. J. Valeo and K. G. Estabrook, *Phys. Rev. Letters* **34**, 1008 (1975).
27. J. J. Thomson, C. E. Max, and K. G. Estabrook, *Phys. Rev. Letters* **35**, 663 (1975).
28. S. Jackel, J. Albritton, and E. Goldman, *Phys. Rev. Letters* **35**, 514 (1975). K. Eidmann and R. Sigel, *Phys. Rev. Letters* **34**, 799 (1975).
29. K. G. Estabrook and E. Valeo, *Bubbles and Their Implications to Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-77146 (1975); to be published in *Phys. Fluids*.
30. A. L. Wong, private communication.
31. R. Haas, private communication.
32. W. Woo and J. S. DeGroot, Abstract in *B.A.P.S.* **20**, 1377 (1975).
33. J. M. Dawson and C. Oberman, *Phys. Fluids* **5**, 517 (1962) and **6**, 394 (1963).
34. R. J. Bickerton, *Nuclear Fusion* **13**, 457 (1973).
35. D. W. Forslund, *J. Geophys. Res.* **75**, 17 (1970); R. C. Malone, R. L. McCrory, and R. L. Morse, *Phys. Rev. Letters* **34**, 721 (1975).
36. D. Biskamp and R. Chodura, *Phys. Rev. Letters* **27**, 1553 (1971).

37. M. Lampe, W. M. Manheimer, J. McBride, J. Orens, K. Papadopoulos, R. Shanny, and R. Sudan, *Phys. Fluids* **15**, 652 (1972).
38. J. H. Erkkila, *Laser Light Scattering and Absorption in Dense Spherically Symmetric Plasmas*, Ph.D. thesis, Lawrence Livermore Laboratory, Rept. UCRL-51914 (1975).
39. V. L. Ginzburg, *The Propagation of Electromagnetic Waves in Plasmas* (Pergamon, New York, 1964).
40. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975).
41. S. I. Braginskii, in *Review of Plasma Physics 1*, M. A. Leontovich, Ed. (Consultants Bureau, New York, 1965).
42. G. B. Zimmerman, *Numerical Simulation of the High Density Approach to Laser Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-74811, (1973).
43. 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. Bleach, J. A. Stamper, and E. A. McLean, *Phys. Rev. Letters* **34**, 1313 (1975).
44. R. Kulsrud and W. P. Pearce, *Astrophys. J.* **156**, 445 (1969).
45. A. E. Walstead, J. S. DeGroot, and C. Barnes, *B.A.P.S.* **20**, 1383 (1975).
46. T. Stringer, *J. Nuc. En. Part C* **6**, 267, (1964).
47. Ref. 10, p. 440.
48. F. Seward, J. Dent, M. Boyle, L. Koppel, T. Harper, P. Stoering, and A. Toor, *Rev. Sci. Inst.* (to be published April, 1976).
49. B. Yaakobi has presented some spatially resolved line measurements; *Bull Am. Phys. Soc.* **20**, 1302 (1975).
50. A. Burgess, *Mem. Soc. Roy. Sci. Liège* **4**, 299 (1961).
51. M. J. Seaton, *Mon. Not. Roy. Astron. Soc.* **119**, 81 (1959); see also the review article by R. W. P. McWhirter in *Plasma Diagnostic Techniques*, R. H. Huddleston and S. L. Leonard, Eds. (Academic Press, New York 1965) pg. 201.
52. I. M. Podgorny, *Topics in Plasma Diagnostics*, (Plenum Press, New York, 1971), p. 116.
53. D. Attwood, private communication.
54. E. J. Valeo, H. R. Griem, J. J. Thomson, and D. S. Bailey, *Interpretation of X-ray Line Spectra*, Lawrence Livermore Laboratory, Rept. UCRL-77771, (1975); H. R. Griem, *Spectral Line Broadening by Plasmas* (Academic Press, New York, 1974).
55. D. Mihalas, *Stellar Atmospheres*, (W. H. Freeman and Co., San Francisco, 1970) p. 286.
56. T. Holstein, *Phys. Rev.* **72**, 1212 (1947); **83**, 1159 (1951).
57. V. V. Ivanov, *Transfer of Radiation in Spectral Lines*, Chapter 8 (NBS Special Publication 385, U. S. Government Printing Office, 1973).
58. K. Mizuno and J. S. DeGroot, *Phys. Rev. Letters* **35**, 219 (1975).
59. K. Mizuno and J. S. DeGroot, *B.A.P.S.* **20**, 1375 (1975).
60. C. P. DeNeef, *Electron Acceleration during Resonance Absorption*, University of California at Davis Plasma Physics Research Group Report R-9 (1975).
61. J. S. DeGroot and J. E. Tull, *Phys. Fluids* **18**, 672 (1975).
62. K. G. Estabrook and J. E. Tull, *An 880 N-Sec 1-D Electrostatic Particle Mover for the CDC 7600*, Lawrence Livermore Laboratory, Rept. UCID-30129 (1976).

7. TARGET FABRICATION

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7. TARGET FABRICATION

Important advances were made in target fabrication in 1975:

- Routine measurement of the wall thickness and uniformity of hollow glass microspheres to an accuracy of $0.05\text{ }\mu\text{m}$.
- Laser cutting and lapping of tiny glass parts.
- Assembly of complex, multicomponent laser fusion targets.
- Production of uniform glass spheres by droplet generation techniques.
- Production of liquid droplets at cryogenic temperatures.
- Fabrication of prototype high-gain laser fusion targets.
- First measurements of electrical resistivity of solid DT.

7. TARGET FABRICATION

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7. TARGET FABRICATION

7.1 Overview

The major task of the Target Fabrication Group is the production of laser fusion targets designed to achieve the goals of the laser fusion program. These targets range from simple glass, plastic, and metal disks to very complex glass, metal, and plastic assemblies.

During the past year we have established facilities for the lapping and laser cutting of tiny glass parts, for the experimental production of hollow glass spheres, and for the production of liquid droplets at cryogenic temperatures. We have developed interferometric techniques to permit measurement of the thickness and uniformity of glass microspheres to within $0.05\text{ }\mu\text{m}$. These measurement techniques are now routinely used by most of the laser fusion community for target characterization. Our techniques for assembling targets have been refined to the point that we are able to construct targets consisting of several separate parts, most of which are smaller than one or two hundred micrometers.

Prototypes of a number of high-gain targets have been constructed, and several types of complex, multicomponent targets have been fabricated on a routine basis.

We have initiated research to determine the electrical and other physical properties of liquid and solid deuterium and tritium and their mixtures. Some of these properties, such as electrical conductivity, have been measured for the first time.

The target fabrication process can be divided into a number of separate but overlapping tasks. These are: (1) selection of target materials composition; (2) parts manufacture; (3) fuel ball selection; (4) DT-filling of fuel balls; (5) characterization of all target parts including the fuel balls; and (6) target assembly.

Target components are either selected from commercially available supplies or manufactured in the laboratory. The glass compositions used include soda-lime, borosilicate, lead-phosphate, tungsten-phosphate, tantalum-borosilicate, lithium-borate, lead borosilicate, and several other less common formulations. Several plastics are used, including polyethylene, polymerized xylene, methacrylates, styrenes, various epoxy formulations and a number of deuterated hydrocarbon materials (commonly known as CD_2). A number of metals are also used in target

fabrication, including gold, tungsten, stainless steel, nickel, platinum, copper, aluminum, brass, molybdenum, indium, and beryllium. Target parts are fabricated by such diverse methods as sputtering, evaporative deposition, electro- and electroless plating, lapping, laser cutting, and photoetching.

Some target types which have been developed are described in Table 7-1. More than 1000 targets of various types are constructed each year for laser, e-beam, CTR, dense plasma focus, and other experiments.

Characterization of targets includes measuring all appropriate target dimensions to state-of-the-art accuracy, measuring the mass of the target parts and the total mass of the completed device, measuring to a high degree of accuracy the DT fill in the fuel ball, and determining the chemical composition, density, and other characteristics of the target components. At LLL, target dimensions have been measured almost exclusively by optical techniques. Thickness and uniformity of glass parts are measured by optical interferometric techniques which provide measurements of thickness to a routine production accuracy of $\pm 0.05\text{ }\mu\text{m}$; linear dimensions are determined by split image microscopy which allows measurements to $\pm 1.0\text{ }\mu\text{m}$ accuracy. Electronic methods described in detail in Sec. 7-2 provide mass measurements to a possible accuracy of $\pm 1\text{ ng}$ while quartz fiber balance techniques are usable in many cases to an accuracy of 25 ng.

Targets are assembled from well characterized parts under the optics of high quality microscopes. Target parts are primarily handled with micromanipulators, though skilled personnel are able to do a significant amount of assembly by hand. The parts are manipulated by using vacuum microchucks made by members of the Target Fabrication Group.

Fuel balls are filled with an appropriate DT mixture by diffusion techniques at high temperatures and pressures ranging from an atmosphere or less to several hundred atmospheres. By counting the tritium decay products and their interactions with the target materials, we can determine the tritium content of the targets to an accuracy of about $\pm 20\%$.

The following sections describe in more detail the processes and methods of laser fusion target fabrication.

Table 7-1. Kinds of targets

Target type	Shapes	Materials	Sizes	DT-filled
Alignment targets	Spheres	Glass	20-200 μm	No
		Glass	20-200 μm	Yes
		Tungsten	100-500 μm	No
		Copper	20-2000 μm	No
		Steel	100-3000 μm	No
	Circular disks	Plastic	50-10000 μm diam 0.5-50 μm thick	No
		Metal	50-500 μm diam 500Å-50 μm thick	No
Diagnostic targets	Circular disks	Composite metal, glass, plastic	50-2000 μm diam 500Å-50 μm thick	No
	Spheres	Glass	40-250 μm diam	Yes
		Plastic	20-1000 μm diam	No
Implosion, thermonuclear	Spheres	Glass	40-100 μm	Yes
		CD ₂ Plastic	50-100 μm	Yes
	Complex	Glass	40-220 μm	Yes

7.2 Glass Targets

The basic component of the glass laser fusion targets which we are currently using is a tiny hollow glass sphere with a very thin, uniform wall. These microspheres are filled with a mixture of deuterium and tritium gas. More complicated targets are also fabricated in order to improve the efficiency of the implosion over that obtained with a simple ball.

The glass microspheres presently used for fuel capsules are manufactured in large quantities for use as lightweight fillers in plastics and epoxies. Only a small fraction of the microspheres is of high enough quality to be used as laser fusion targets. We describe the methods used to select and characterize the usable microspheres below.

7.2.1 SIEVING

The first step in sorting the microspheres is to sieve for the proper diameter. Because of the small size of the microspheres, electrostatic forces on them are much stronger than gravitational forces. Ordinary downward sieving is therefore impossible.

Our sieving is done upwards in an ultrasonically agitated alcohol bath. The alcohol bath minimizes the effect of static charges on the shells, and the large buoyant forces make the sieving quite efficient. An additional advantage is that glass fragments and broken

microspheres sink to the bottom of the bath and can be easily rejected. The ultrasonic agitation helps to break up agglomerates. Large-scale circulation of the material is maintained by directing a small, hand-held alcohol jet onto the surface of the sieving screen.

Presently, microspheres used for fuel capsules are usually from 60 to 100 μm in diameter. The sieves used are 8-in. Buckbee-Mears screens, rated to $\pm 2 \mu\text{m}$. The sieved microspheres have roughly a Gaussian distribution of diameters. The finest sieve cuts yield approximately a 5 μm FWHM.

7.2.2 DT-FILL AND MEASUREMENT

In order to fill the hollow glass spheres with DT gas, we take advantage of the fact that gas diffuses through glass much faster when the temperature is raised. Accordingly, the microspheres are loaded into a beryllium tube which is then attached to a tritium pressure system. A heater is placed around the sample and the entire assembly is surrounded with a secondary container. After checking for leaks, the sample is pressurized with DT gas and heated to 420°C. Temperature and pressure are generally maintained for 24 hours. Finally, the system is cooled while maintaining pressure. At room temperature the gas is effectively trapped inside the microspheres. Then the system is depressurized and the new batch of fuel balls can be removed from the line.

Once filled, the balls are routinely selected, physically characterized as described below, and counted individually on the gas-flow proportional counter. This detects the secondary radiation caused by tritium inside the balls.

The gas-flow proportional counter is calibrated using an ionization chamber. To accomplish this, a few balls are picked out one at a time (under a microscope) and measured to determine their volume. They are then placed on a planchet and counted in the gas flow counter. Then they are crushed one at a time in the ionization chamber. The radioactive tritium ionizes the argon gas which is pumped into the chamber. The ionized particles are seen as an electric current by an electrometer. Since this current is a direct function of the amount of radioactivity present, we can determine the absolute amount of tritium present inside the balls. Knowing this, we can now calculate a ratio between the count rate from a particular ball and the absolute amount of tritium inside it. We do this for several balls in order to get a statistically valid number. This procedure enables us to get accurate fill numbers on every fuel ball in a non-destructive manner by utilizing the calibrated proportional counter.

7.2.3 PHYSICAL CHARACTERIZATION

Wall Thickness and Uniformity

Both the wall thickness and its uniformity are measured with the aid of an interference microscope.¹ The short coherence length of white light can be exploited in order to measure the absolute optical path through any small, transparent object. If the index of refraction of the material is known, this provides a direct measurement of the physical thickness.

Figure 7-1 shows the optical design of the Twyman-Green type of interferometer which we use for these measurements. Under white light illumination, interference fringes can be seen only when the two paths through the interferometer are within a few micrometers of being exactly equal. The white light fringe pattern as seen on a very slightly tilted mirror is shown in Figure 7-2a. It consists of only a few fringes with rapidly increasing color dispersion and decreasing intensity away from the center of the pattern.

The white light interference pattern seen in a flat object being measured will appear displaced from the pattern seen on the background. This displacement is directly proportional to the optical path through the object. Once white light has been used to determine where the center of the interference pattern is, the displacement can be measured very accurately by using monochromatic illumination. Under monochromatic light, many very distinct fringes are visible, and one

simply counts the number of fringes which appear between the center of the pattern on the object and the center of the pattern on the background.

When a microsphere is viewed through the interference microscope, the rapidly varying optical path through different parts of the ball distorts the interference pattern into a series of concentric rings. The principle for measuring optical thickness remains the same, however. Figure 7-2b shows a microsphere on the same mirror surface shown in Fig. 7-2a with the center of the interference pattern appearing on the center of the ball. Figure 7-2c shows the same field of view under monochromatic illumination; Fig. 7-2d shows a cutaway of the field of view of Fig. 7-2c and illustrates the relationship of the fringe displacement and the wall thickness.

The optical path through the ball is equal to the optical path to the point on the mirror where the reference fringe appears. The difference in the physical length of these two paths is given by

$$\Delta P = \frac{1}{2} x \lambda \quad (1)$$

where x is the number of fringes (integer plus fraction) appearing between the reference fringe and the center of the ball, and λ is the wavelength of the monochromatic

Fig. 7-1. Optical design of interference microscope.

tic source. This path difference ΔP is also equal to the change in optical path caused by the passage of the light through the microsphere walls.

$$\Delta P = 2t(n' - 1) \quad (2)$$

where t is the wall thickness and n' the index of refraction of the glass. From these two equations we can solve for the wall thickness as

$$t = x\lambda / 4(n' - 1). \quad (3)$$

Since the refractive index of glass is approximately 1.5, a displacement of one fringe corresponds to a difference in wall thickness of about $\lambda/2$, which for

visible light will be about $0.25 \mu\text{m}$. It is quite easy to determine the number of fringes to within $1/10$ of a fringe with the eye alone. After determining the number of complete fringes between the reference fringe and the ball, the final fraction of a fringe can be determined very accurately by leveling the mirror on which the ball rests so that the fringe pattern spreads out to the point that only two fringes, one on either side of the ball, remain in the field of view. In this configuration the final fraction of a fringe shift can be measured to within $1/10$ of a shift. This means that one can measure the wall thickness to within $0.03 \mu\text{m}$ using only the eye.

If the microspheres are filled with a gas with index of refraction significantly different from that of air, Eq.

Fig. 7-2. Interferometric wall-thickness measurement of glass microspheres. (a) The white light interference pattern on a slightly tilted mirror; (b) a glass microsphere with the reference fringe appearing in the center of the sphere; (c) the microsphere and mirror under monochromatic illumination; (d) cutaway of the field of view shown in (c) illustrating the geometry of the thickness measurement.

(2) can be modified to include this effect. Equation (3) then becomes

$$t = \frac{1}{n' - 1} \left[\frac{x\lambda}{4} - r_i (n'' - 1) \right] \quad (4)$$

where r_i is the inner radius of the sphere and n'' is the index of refraction of the gas inside the sphere. For

reference, with 10 atm of DT gas in an 80- μm -diam microsphere, the correction to the wall thickness necessitated by the presence of the gas is about 0.1 μm .

The uniformity of the wall thickness is determined by observing the uniformity of the interference pattern on the microspheres. For a perfect microsphere lying

on a flat background surface, the interference pattern appears as one or more concentric rings, perfectly centered on the ball. Any deviation from this pattern indicates a non-uniformity in the wall thickness.

The magnitude of the non-uniformity can be determined by measuring the optical path through the defect and comparing it with the optical path through equivalent defect-free points on the ball.

Fuel Capsule Selection

After the DT filling, all sorting of the fuel capsules is done by hand under the interference microscope. A few hundred DT-filled microspheres are spread on a mirror which is then placed under the interference

microscope. The spheres are scanned to find those on which the interference pattern appears symmetric and centered on the microsphere. When one of these spheres is found, it is then rotated by 90° to look for defects not visible in the first orientation. If the sphere is sufficiently uniform, its wall thickness is measured and it is transferred with a vacuum chuck to a numbered metal planchet. The outside diameter of the ball is measured to $\pm 1 \mu\text{m}$ using a microscope equipped with a split image eyepiece and electronic readout. The planchet is then placed in the proportional counter to determine the gas fill as described above.

At this point the ball is ready for mounting. The details of the mounting procedure are presented in the section on target assembly.

7.2.4 OTHER PARTS

Many of the targets which are required for laser fusion are more complicated than simply a glass ball on a stalk. We have developed two methods of fabricating small, intricate pieces of glass: laser drilling and lapping.

Laser Drilling

The overall layout of the laser drilling system is diagrammed in Fig. 7-3. A normally pulsed ruby laser is focused through a microscope objective onto the part to be cut. The part is viewed with the aid of a movable prism and a rifle telescope. The viewing system is thereby focused in the same plane as the laser. The telescope crosshairs are aligned to coincide with the focal point of the laser. Positioning the holes is therefore very straightforward and can be accomplished within $\pm 2 \mu\text{m}$. By controlling the laser power and

using microscope objectives with different focal lengths, we can vary the hole size from $2 \mu\text{m}$ to more than $250 \mu\text{m}$.

This procedure is effective for drilling holes in metals, plastics, and glass. For some glass samples a thin layer of carbon (50-100 Å) is evaporated onto the surface before cutting, enhancing the light absorption and facilitating drilling.

By cutting a series of small holes, almost any shape can be cut from a flat piece of material. Some examples of the parts which have been fabricated by this method are shown in the target assembly section.

Besides the fabrication of target parts, the laser drilling system has proved useful in several other respects. It has been used to drill a hole in the side of a fuel ball to remove the DT fill, to disassemble defective or damaged targets to salvage useful parts by drilling the glue joints apart, and to make pinholes in gold, tungsten glass, and lead glass for x-ray pinhole cameras. (See Section 8.3.9).

Fig. 7-3. Diagram of the laser drilling apparatus.

Lapping

Another method of shaping tiny parts is by grinding on a very smooth, accurate lap. A small piece of glass is potted in lucite to support it during the lapping process. It is attached to the end of a thin glass fiber and positioned against the lap with a micromanipulator. By changing the orientation of the potted part during the lapping, various shapes such as circular, elliptical, and rectangular disks can be cut. When the grinding is finished, the lucite is dissolved away, leaving the lapped glass part. This method has an advantage over laser drilling in that one can cut much thicker samples.

It has become necessary to develop a means of measuring the mass of microspheres and assembled targets. Simple calculations indicate the mass of these targets ranges from a few tens of nanograms to several micrograms. Various schemes were studied, but only the quartz crystal oscillator microbalance and the quartz spring balance were actively pursued. Handling problems and insufficient resolution led to the rejection of the other methods.

Quartz Crystal Oscillator Microbalance

This microbalance technique relies upon a shift in the resonant frequency of a quartz crystal with a change in the mass of the crystal. Theoretically, crystal microbalances are capable of measuring masses to at least ± 1 ng accuracy; actually, several major problems must be solved to realize this accuracy.

First, the oscillator frequency must be designed to be stable within one part in 10^8 . Careful thermal stability compensation in the transistor circuits of the crystal-controlled oscillator and the use of precision, temperature-stable components in the oscillator are required.

Second, the crystal should be loosely coupled and lightly driven to reduce self-heating effects and improve phase stability. Also, the oscillator circuit itself should be lightly loaded by measurement devices as loading effects generate random-phase shifting of the oscillator, leading to short-term frequency instability.

Third, the crystal should be well mounted to reduce mechanical vibration to the crystal. It should also be well shielded to reduce unwanted random capacitive loading effects.

Fourth, the temperature of the crystal must be well controlled. Crystal cuts are available with temperature coefficients of ± 0.5 ppm per $^{\circ}\text{C}$. However, to achieve the stabilities of 0.01 ppm required to measure ± 1 ng, temperature control of $\pm 0.02^{\circ}\text{C}$ is required. This fine control can be avoided somewhat by building two identical oscillators and measuring the difference in their frequencies to determine the frequency change due to the target mass applied to one of the crystals. In this way, if both crystals are subjected to the same minute temperature variations, the frequency effect will be greatly reduced due to the differential measurement of the frequency. This has the added advantage of allowing the use of standard frequency measurement devices to measure the relatively low-frequency differential signal accurately.

The final and most difficult problem is finding an effective means of coupling the target mass to the measurement crystal. The crystals will not respond to simply placing the targets on the crystal, for the mass coupling is much too weak. For thin films deposited on the crystal surface, well-defined theory exists relating the film mass to the frequency change. Films, however, offer a large surface area for strong molecular adhesion to the crystal face, thus coupling the film mass very effectively to the crystal mass. To effectively couple the target mass to the crystal mass, we sought a mechanism which would provide greater crystal-surface coupling to the target surface.

Various thin glass cup-shaped holders were constructed and glued to the crystal surface with the hope of offering greater contact area when the targets were placed in the cups, but the coupling was still too loose. To increase coupling, the holders were coated with materials with various adhesive qualities. We found that materials with relatively low viscosity such as vacuum grease caused severe viscous damping of the crystal oscillations, thus reducing the crystal Q and resulting in the loss of crystal control of the oscillator. The more viscous materials often had surface tensions too high for the targets to penetrate or were too heavy, causing severe mass damping of the crystal.

Much experimentation ensued to find a suitable mass coupling mechanism. We sought a material which could be easily changed from a very low viscosity for target injection, to a solid for mass weighing, and then back again to a low-viscosity material for target removal from the coupling material. Also the material had to be easily removed from targets if the target became contaminated during the weighing process. Rosin was found to be almost ideal as a mass coupling agent; it will melt at 120°C and attains a viscosity low enough to inject targets for weighing. When the heat is removed the rosin quickly freezes, thus holding the targets firmly while maintaining effective coupling to the crystal surface. Rosin is also soluble in alcohol which allows a simple and thorough cleaning of any contaminated targets. The targets can be easily removed from the molten rosin by suction applied through a small hollow glass pipette.

At present, we are studying two crystal types currently: a 10-MHz-AT-cut series resonant crystal and a 10-kHz-series resonant tuning-fork type of quartz crystal. Each type has certain advantages and disadvantages. The 10-MHz crystal is more responsive to mass changes, but the crystal Q is also more susceptible to disastrous damping effects. The 10-kHz crystal is less responsive to mass changes, but the Q is not so easily

damped, thus allowing greater experimentation with the rosin to gain a more effective mass coupling.

We are studying these two microbalances for linearity, repeatability, and practicality. Preliminary tests look promising. Microspheres have been weighed with a repeatable accuracy of 5%. Absolute measurements have yet to be established as more data is required to establish a baseline for calibration.

Quartz Spring Microbalance

The quartz spring microbalance technique relies upon Hooke's law for spring extension as a function of

applied force. A thin quartz spring was constructed with a spring constant of $180 \mu\text{N}/\mu\text{g}$. The spring was mounted vertically in an evacuated glass column bolted firmly to a granite table to reduce vibration. The spring had a hook at each end to support the spring at one end and to attach a thin glass weighing pan at the other. An optical microscope was used to measure the weighing pan deflection. At present, resolution of 0.05 mg has been attained, with immediate improvements expected with a refinement in vibration damping of the weighing pan. Also, by using an interference microscope with a resolution of 500 Å, a mass measurement accuracy of a few nanograms appears realistic.

7.2.6 TARGET CLEANING

As the knowledge of laser/target interaction grows, target requirements become more demanding. One such requirement is target cleanliness. At present, smaller microspheres under 100 μm used for DT-filled fuel balls have been successfully cleaned of surface contamination, but future target requirements demand the use of larger microspheres that are unfortunately severely contaminated by surface debris and must be more carefully cleaned.

Scanning electron microscope studies have shown that some of the larger glass microspheres used in the construction of laser targets which are apparently optically clean are actually covered by a variety of glass fragments and other inorganic debris. Other microspheres have optically observable contamination in the form of glass shards, small circular opaque areas, large irregular-shaped opaque patches, and relatively large miniballs attached to the microsphere surfaces. The smaller microspheres presently used for DT-filled fuel balls are relatively clean viewed under both the optic and electron microscopes. Debris ranges from tens of micrometers to submicrometer sizes. The type of contamination varies greatly with the type of glass used to make the microspheres and also with the amount of exposure to moisture which the microspheres have had. The craters are usually small, on the order of 1 μm or less, and the miniballs range from submicrometer to tens of micrometers in diameter. Careful examination showed bubbles trapped inside the balloon walls which were obviously as yet unformed miniballs. These are also discernible with the optical microscope. The smaller miniballs and craters appear as small, circular opaque spots under the optical microscope.

Figure 7-4 shows a microsphere which has several of the commonly observed defects. The microsphere is shown both as it appears under an optical microscope and also as seen in the electron microscope.

Microspheres with discernible miniballs have always been rejected as have all gross deformities, but as target requirements grow more stringent, greater knowledge of marginal deformities is required to determine the feasibility and the advisability of cleaning certain kinds of contamination.

The remaining debris—glass shards and inorganic surface contamination—are of greater interest because at least partial solutions exist for removal of such debris from microsphere surfaces. Glass shards are an almost universal contaminant of the unprocessed glass balls, but they are easily removed by an ultrasonic agitated rinse in warm distilled water followed by a gravity-induced separation of the shards from the balls in a separatory funnel.

A more difficult problem is the removal of inorganic surface dirt having a morphology ranging from amorphous to crystalline in structure as viewed under the electron microscope. This inorganic contamination appears regularly to varying degrees on glass balloons composed of borosilicate glass; thus it would seem possible that it may be a sodium tetraborate salt. X-ray analysis shows a strong sodium peak in contamination of this type, thus supporting this conjecture. Due to the leaching of borosilicate glass when exposed to moisture, this formation is common. These debris range in size from submicrometers to several micrometers across, with a similar range in thickness. Under the light microscope these debris appear as dark, jagged, irregularly shaped patches when thick, and as irregular, hazy patches when thinner or smaller. When the contamination is very thin, it is optically transparent. Limited success in removing this third type of contamination has been achieved using warm water and strong ultrasonic agitation. The balls appear to be about 80% cleaned when viewed under the optical microscope, but

(a)

Fig. 7-4. (a) Borosilicate glass microsphere (160x magnification) viewed under light microscope. Notice attached miniball on upper portion of the ball and crystalline structure of the contamination around the periphery of the ball. (b) The same microsphere (375x magnification) viewed through an electron microscope. Notice the sharply defined crystalline contamination littering the surface as well as the miniball protrusions.

closer examination under the electron microscope reveals many small patches of debris. The water/agitation combination appeared to loosen and remove much of the debris, but did not totally remove the more severely contaminated areas. Other solvents were tried with little success. It has been recommended that severely contaminated balls with the type of surface debris just mentioned be rejected, and that relatively fresh, new

balls with less severe contamination be cleaned using water and strong agitation. It should be noted that severe agitation can have a degrading effect on the clean ball surfaces in the form of pitting and cracking of the glass due to collisions of the microspheres. Upgraded cleaning procedures are being incorporated into the target fabrication process and should result in a significant reduction in target contamination.

7.2.7 TARGET ASSEMBLY

To handle the microscopic parts of the target, microminiature vacuum chucks are made. These are pulled glass capillaries whose tips are cut and carefully ground to remove irregularities which would otherwise impair handling the target parts or even puncture the thin glass fuel balls. The chucks are hand-held or mounted in a micromanipulator and attached to a vacuum system with a set of controlled air bleed valves by which the vacuum (pressure) in the lines can be adjusted. Thus, the tiny parts can be picked up, manipulated, and released without destruction or loss.

Most of the target is assembled above the stage of a high power microscope. Using an instrument which has movable optics for focusing is advantageous since the targets are attached to manipulators which cannot move with a movable stage. Figure 7-5 shows one of the target fabrication laboratories at LLL and Fig. 7-6 is a view of one of the target assembly stations.

One of the simplest targets is a ball-on-stalk, shown in Fig. 7-7. As a mounting stalk for the target, we draw a standard glass capillary from a few millimeters diameter to a tapered hollow fiber with a tip 2 to 3 μm in diameter. The base of the fiber is left its original size to provide a means of mounting the target easily. Epoxy resin is injected into the hollow stem with a syringe. The fuel ball is held by a miniature vacuum chuck on the micromanipulator. The small end of the capillary is allowed to touch the ball, and adhesive is forced out the end to contact the glass fuel ball. The whole piece is allowed to set for about 30 min. The mounting stalk is then glued on to an appropriate base and is ready for mounting in the laser target chamber.

The steps for building a more complicated ball-in-plate target are shown in Fig. 7-8. Techniques for cutting the disk and drilling the hole are discussed in Sec. 7.2.3. First, a hole is drilled in the

glass sheet (Fig. 7-8a). Then a guide pattern is cut around the hole (Fig. 7-8b), and finally the bridges between the holes are cut (Fig. 7-8c). The glass piece is held by a thin capillary inserted through the hole just before the last few bridges are cut. A completed disk held on a capillary is shown in Fig. 7-8d. After the glass piece is removed from the capillary with the micromanipulator, the disk is mounted on a glass stalk and the fuel ball is glued in place. Figure 7-9 shows a

glass disk mounted on a support stem ready for the fuel ball which is held on a vacuum chuck. The finished target is seen in Fig. 7-10.

The techniques for gluing and handling have been sufficiently developed that simple targets such as a ball-on-stalk are readily produced. The more complicated targets remain difficult, and their construction requires a great deal of skill, patience, and time.

Fig. 7-5. Target fabrication laboratory.

Fig. 7-6. Typical gluing station with microscope and micromanipulators.

7.3 Microsphere Production

7.3.1 INTRODUCTION

The hollow glass bubbles which are used for manufacturing targets are currently supplied by outside vendors. These glass balloons are produced in large quantities for commercial purposes such as low-mass epoxy fillers. Because the demand for the hollow microspheres is principally for commercial applica-

tions, the manufacturers have tailored their production processes for that market and not for the low volume uses such as target fabrication.

The glass microspheres, as received from the manufacturers, are usually irregularly shaped with walls of varying thickness. The spheres are not uniform in

weight or diameter. To obtain one microsphere with desired wall thickness, diameter, and specified sphericity, and wall uniformity, we must sort through approximately 10^3 of the microspheres which are delivered from the manufacturer.

Because of the expense of sorting the commercial spheres, it is desirable to develop our own method of microsphere production, optimized for the needs of target fabrication rather than high volume commercial uses. By concentrating on producing microspheres of a specified mass and wall thickness, we should be able to improve the yield to at least one good microsphere out

of 10, thus producing dollar savings by reducing the sorting expense. A second advantage of developing a microsphere manufacturing facility is the possibility of producing spheres whose composition can be adjusted to aid the implosion studies; we can get microspheres of only a few compositions from our present suppliers. A third advantage of manufacturing our own spheres is that the contaminations can be controlled. Since the present manufacturers are catering to a high-volume commercial market, they are not particularly careful with packaging and storing. In-house manufacturing will allow the microspheres' environment to be controlled from the time of production to the time of use.

7.3.2 APPARATUS AND OPERATION

The present apparatus for producing the microspheres is shown in Fig. 7-11, and a schematic diagram of the apparatus is shown in Fig. 7-12. The equipment consists of a droplet generator which is mounted on top of the drying oven. The droplet generator forms uniformly sized drops of an aqueous solution of the glass constituents and a blowing agent. These drops then fall into the oven where the water is removed, leaving a solid particle of the glass constituents. This solid particle then falls into a higher temperature zone of the oven where it is melted into a glass, and the blowing agent decomposes. The gas from the decomposition then blows the molten glass bubble into a microsphere.

The operation of the droplet generator can be seen in Fig. 7-12. The jet of glass solution is formed by the orifice plate at the top of the figure. This jet is modulated by piezoelectric crystals which are coupled to the reservoir. This modulation causes the jet to undergo "Rayleigh breakup" and to form a stream of drops of uniform size. The electrical charge on the drops is determined by the voltage on the charge electrode or "charge ring." This electrode charges the forming drops by induction; if the charge ring has a positive voltage, a negative charge will be induced on the drops and vice versa. By switching the charge-ring voltage to either a positive voltage or ground, the drops can be either charged negatively or left neutral. The drops then pass between the deflection electrodes where the charged and uncharged drops are separated. The negatively-charged drops are repelled by the negative-deflection electrode and strike the grounded electrode, where they are collected for recycling. The uncharged drops pass through the deflection region unaffected and then pass into the oven.

Fig. 7-7. Fuel ball glued on mounting stalk.

Fig. 7-8. Steps in building ball-on-plate target. (a) Initial large hole. (b) Guide pattern of holes. (c) Disk just prior to removal, held onto glass sheet by one fiber on the "handle." (d) Completed disk, held on a glass fiber.

During normal operation, one out of every 32 drops is uncharged while the remainder are charged. This causes most of the drops to be caught while only the few uncharged ones go into the oven. Since most of the drops are caught, the space between the drops which go into the oven is made large. By spacing the drying drops far apart, the chance of a coalescing collision between drops is minimized, and the resulting particle size is kept uniform.

The oven has three zones and the temperature can be individually controlled in each zone. The normal mode

of operation is to set the top zone to approximately 200°C, the middle zone to 750°C, and the bottom zone to 1300°C. The drops are dried in the top section, and the particles are then fired into glass in the lower sections. The glass particles are then collected as they fall out of the oven.

A picture of several of the solid spheres is shown in Fig. 7-13. These spheres are 40 μm in diam and they contain the mass necessary to produce a 100- μm diam hollow microsphere with a wall 1 μm thick.

7.4 Miscellaneous Targets

7.4.1 PLASTIC DISKS

In addition to glass targets using fuel balls in some configuration, we have built a number of thin flat plate targets ("lollipops") used primarily for diagnostics. One type is made from sheets of Parylene. The others

are made of various glasses.

The Parylene is produced in sheets and the targets are simply punched out of the sheet and mounted on a stalk. Fig. 7-14 shows a typical Parylene disk.

Fig. 7-9. Glass disk mounted on support stem; fuel ball held on vacuum chuck.

Fig. 7-10. Front view (a) and side view (b) of finished ball-in-plate target.

7.4.2 GLASS DISKS

Figure 7-15 shows a W-glass target whose glass composition is 75% WO_3 and 25% P_2O_5 . A thin sheet of the glass was obtained by blowing a bubble of the glass. The disks were cut out using laser drilling techniques (see above). The disk shown in Fig. 7-15 is

671 μm across and has an average thickness of 6.8 μm .

Pb-glass targets are similar to the W-glass in appearance and are cut the same way. We also made similar targets from ordinary glass.

7.4.3 ALIGNMENT TARGETS

Several types of targets are used for laser alignment. These are usually metal or metal-coated glass balls.

Figure 7-16 shows a stainless steel ball bearing which has been welded onto a stalk. These alignment targets are from 250 μm to several mm in diameter.

Tungsten alignment targets from 100 to 300 μm are made by creating an arc from the end of a tungsten wire which has been tapered to a sharp point by electroetch-

ing. The current pulse melts the tip of the wire and causes a small ball to form at the end. Figure 7-17 is an example of one of these.

Very small alignment targets are made by coating gold onto a glass microsphere by electro- or electroless plating or by sputtering gold onto an already mounted microsphere. Figure 7-18 shows a microsphere with an electroless gold plating.

Fig. 7-11. Glass microsphere production apparatus.

Fig. 7-12. Schematic diagram of microsphere production apparatus.

7.5 Cryogenic Targets

Cryogenic materials will be very important in a number of target designs for use in future targets. For lasers in the MJ energy class, targets of layered cryogenic materials such as deuterium-tritium, neon, xenon, etc. may be used and ballistically injected into the laser focal region. Means of generating solid hydrogen and other cryogenic materials have been developed and are currently being used. A system for generating and controlling liquid cryogenic particles is shown in Fig. 7-19. A schematic diagram of a

cryogenic particle-generation system designed several years ago by Hendricks and since improved upon by Foster and others is shown in Fig. 7-20.² It has also been experimentally demonstrated that frozen hollow shells of hydrogen can be produced in a system very similar to that shown in these figures. Basically the method of cryogenic particle production employed in these systems is that of controlled jet disintegration. A periodic disturbance of suitable wavelength is launched on a jet of the liquid cryogen. Surface tension forces

Fig. 7-13. Solid glass spheres produced by the microsphere generator.

cause the amplitude of the impressed wave to grow — thereby leading to the production of uniform drops by “cutting” off equal masses of liquid at each internal

antinode of the wave on the jet. Thus, a series of uniform liquid masses are formed which quickly relax to form spheres. When spheres of high vapor-pressure materials, such as most cryogenic liquids, are injected into a vacuum, they will freeze because of evaporative heat loss. Solid spheres may be formed very conveniently in this manner.

Simpler targets consisting of shells of DT mixtures frozen on the inside of glass or metal shells are also of considerable importance. Experimental systems to produce shells of DT have been constructed and are being tested. We anticipate that layered targets in which solid DT is an important part will be irradiated in high power laser systems in the near future.

Because of the importance of solid and liquid deuterium and tritium and their mixtures, we have initiated research to determine the physical properties of DT systems in the solid and liquid phases. The properties of interest include surface tension, phase separation upon freezing (if any), electrical and thermal conductivities, permittivity, permeability, and optical properties. Variations of these parameters with temperature are also of considerable interest in the target fabrication field. A number of papers have been prepared and published by LLL staff members in which

(b)

Fig. 7-14. Front (a) and side (b) views of a Parylene disk target.

Fig. 7-15. A tungsten-glass disk laser target.

Fig. 7-16. A stainless steel ball-bearing alignment target, 250 μm in diam.

many of the properties of deuterium, tritium, and their mixtures are presented and discussed.³⁻⁶ This work is a continuing effort and is being carried out primarily by members of the Chemistry Department at LLL.

C. D. Hendricks
J. L. Dressler
I. M. Moen
B. W. Weinstein
D. L. Willenborg

Fig. 7-17. A tungsten alignment target.

Fig. 7-18. A gold-coated glass microsphere alignment ball.

Fig. 7-19. System for generating and controlling liquid droplets at cryogenic temperatures.

Fig. 7-20. Particle-generation and control system.

References

1. Berthold W. Weinstein, *J.A.P.* **46**, 5305 (1975).
2. C. Foster, R. J. Turnbull, and C. D. Hendricks, *Appl. Phys. Lett.*, **26**, 580 (1975).
3. C. K. Briggs, R. G. Hickman, R. T. Tsugawa, and P. C. Souers, *Estimated Values of Some Cryogenic Properties of Hydrogen Isotopes*, Lawrence Livermore Laboratory, Rept. UCRL-76708 (1975).
4. C. K. Briggs, R. G. Hickman, R. T. Tsugawa, and P. C. Souers, *Estimated Viscosity, Surface Tension, and Density of Liquid DT from the Triple Point to 25 K*, Lawrence Livermore Laboratory, Rept. UCRL-51827 (1975).
5. P. C. Souers, R. G. Hickman, and R. T. Tsugawa, *Estimated D_2 -DT- T_2 Phase Diagram in the Three Phase Region*, Lawrence Livermore Laboratory, Rept. UCRL-76706 (1975).
6. C. K. Briggs, R. T. Tsugawa, C. D. Hendricks, and P. C. Souers, *Estimated Refractive Index and Solid Density of DT, with Application to Hollow-Microsphere Laser Targets*, Lawrence Livermore Laboratory, Rept. UCRL-51921 (1975).

8. LASER FUSION EXPERIMENTS AND DIAGNOSTICS

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8. LASER FUSION EXPERIMENTS

- Laser fusion yields in excess of 10 million neutrons from 0.7 ng of DT fuel were achieved. Using both two-beam irradiation at 450 GW (May 1975) and a single-beam irradiation at 600 GW (August 1975), laser fusion targets were imploded, resulting in thermonuclear burn with yields of 11 and 12 million neutrons, respectively.
- Proof of true thermonuclear burn was obtained. Measurements of the energy spread of the alpha particles resulting from the DT reaction confirmed that true thermonuclear conditions had been achieved (May 1975).
- Time-resolved x-ray spectra from exploding pusher targets show a peak corresponding to the compressed core. X-ray spectra of laser-imploded targets were obtained with a 15-ps resolution. Emissions from the exploding shell and the compressed core were clearly resolved.
- Beam filamentation was observed in target irradiation experiments at 10.6 μm . Structures smaller than the diffraction limit of the 10.6- μm laser beam were evident on x-ray pinhole pictures of the targets. Their size agrees with predicted filament widths. Irradiation uniformity at 10.6 μm can be severely limited by such phenomena.
- Frequency-quadrupled laser light was used to probe the plasma atmosphere. Holographic interferometry, shadowgraphs, and measurements of the polarization rotation provide information on electron density, critical density contour, and proton and magnetic fields.
- A strong polarization dependence of the scattered radiation was observed. Measured spatial distributions of the scattered radiation showed that polarization-dependent scattering and absorption processes were dominant at high power densities.
- Unique calorimeters were developed to obtain a reliable energy balance and determine the energy distribution. Scattered radiation in better than 93% of 4π was measured providing absorption values for various classes of targets. Spatially-resolved but time-integrated measurements of the particle and x-ray energies showed some evidence of polarization-dependent plasma heating.
- An active readout provided real time x-ray spectral distributions in the 2-keV range. A diffraction crystal spectrometer (using a KAP crystal) was modified to replace the film by an active readout system. With insignificant loss of sensitivity, the spectrometer data are immediately available.

8. LASER FUSION EXPERIMENTS AND DIAGNOSTICS

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8. LASER FUSION EXPERIMENTS AND DIAGNOSTICS

8.1 Overview

The basic responsibility of this part of the LLL laser program is to perform and analyze well-diagnosed experiments on the physics of high-intensity laser interaction with plasmas and to apply this knowledge to achieving laser-driven, high-yield thermonuclear events. The laser fusion program is using high-intensity laser radiation as a heat source to drive a thermal conduction wave into the target medium which implodes and compresses the fuel to conditions necessary for efficient thermonuclear burn.

Successful laser implosions require very carefully tailored deposition of the laser energy, and thus the detailed understanding of the physics involved in the laser/plasma interaction is of paramount importance. Thus experiments are designed to elucidate and test the fundamental physics of the laser/plasma interaction and also to study the implosion and burn phenomena. The diagnostics of multi-keV plasmas have seen more than 20 years of development. However, laser fusion adds three aspects which significantly complicate the plasma diagnostics. High-yield events require plasma densities of 10^8 - $10^9 \times$ liquid density for hydrogen, i.e., many orders of magnitude greater than densities normally encountered in plasma physics. Laser fusion targets are microscopic, and consequently their lifetime is correspondingly short. This leads to a requirement of better than $1\text{-}\mu\text{m}$ spatial resolution and temporal resolution of the order of 1 ps. We therefore must spend considerable effort in the development of new diagnostics.

In 1975 a large number of experiments enabled us to make significant progress in the understanding of the physics of laser-driven inertial confinement thermonuclear fusion. Approximately 200 single-beam implosion targets were irradiated on Janus and Cyclops with peak power levels of 0.2 and 0.7 TW, respectively. The largest fusion yield obtained was 1.2×10^7 neutrons from the DT fuel.

Approximately 300 DT-filled implosion targets (Fig. 8-1) were irradiated on Janus and Cyclops with peak power levels of 0.5 and 0.7 TW, respectively. Time-of-flight measurements of the 3.5 MeV alpha

particles produced in the D + T reaction were used to prove that the reactions were thermonuclear and that we had achieved ion temperatures of 2 keV.

In addition to the large number of plasma diagnostic instruments that we have implemented on the experiments, we have carefully diagnosed the laser output and laser intensity at the target plane. The laser diagnostics have been crucial in defining the power limits, and the target plane information was essential to the analysis of the experiments.

In 1976 we will use 4π illumination systems on Janus and Argus for both low- and high-density implosions. Argus will also be used with f/4 and f/2.5 lenses.

In the diagnostics development area we have continued developing streak cameras, particle diagnostics, x-ray diagnostics, and microscopic imaging systems. We have started development of ultra-fast framing cameras and a computer data acquisition and analysis program.

We have used our x-ray streak camera on the implosion experiments on Janus with six K-edge channels of data. The data shows a temporal peak emission at the time of implosion which agrees with the LAS-NEX calculations. This camera has been coupled to a pinhole camera which will be used in 1976 to make the first time-resolved x-ray pictures of the imploding targets. New high-resolution ($1\text{-}\mu\text{m}$), high-throughput, f/50 x-ray microscopes have been designed and fabricated using single-point diamond machining. We have also developed the capability of optical probing using the fourth harmonic of the Nd:glass laser frequency. Thus in 1976 we will be able to make measurements in the plasma corona up to densities of 10^{21} cm^{-3} .

We have begun to make significant use of minicomputers in our data acquisition and analysis program. On Janus and Cyclops we use PDP 11/10 computers to gather and scale 1-D data. The system for Argus will have a PDP 11/40 and will gather and reduce both 1-D and 2-D data.

H. G. Ahlstrom

8.2 Laser Systems and Optical Diagnostics

Laser-induced thermonuclear fusion requires well-diagnosed high-quality lasers. Indeed, successful implosion of a target is critically dependent on the temporal and spatial distribution of the laser pulse. Without

a detailed knowledge of these features, meaningful interpretation of plasma diagnostics is difficult if not impossible.

The following sections describe the target oriented

Simultaneous beams

West beam delayed 42 ps

West beam delayed 84 ps

West beam delayed infinitely
(one-sided shot)

Fig. 8-1. Mismatch in beam simultaneity is dramatically displayed by x-ray micrographs of $80\text{-}\mu\text{m}$ microspheres with $2\text{-mg}/\text{cm}^2$ DT fill. All targets are seen in the 2.5-keV x-ray emission window. Note: colors are normalized in each photograph separately.

aspects of progressively higher power Nd:glass laser systems which have been or will soon be used at LLL. The causes of beam distortion, the diagnostics used to monitor the variation in beam profile along the laser chain during irradiations, and the steps which were taken to maximize the beam quality on target are discussed. The methods which have been devised to minimize target damage prior to the arrival of the main laser pulse are presented. These features are also described for the CO₂ laser facility which was used to irradiate targets in early 1975.

In addition to a detailed knowledge of the laser beam, it is imperative to properly position the target within the beam. Considerable improvements in our

target illumination and positioning capabilities have been achieved.

Irradiation symmetry has been improved with new focusing systems which result in almost 4 π target coverage at normal incidence. These are being implemented for the Janus and Argus irradiation facilities.

Two of the most useful laser diagnostics, 10-ps resolution streak cameras and laser calorimeters, have been refined. They provide reliable information on pulse shape and energy amplification along the laser chain as well as data on back or forward scattered radiation.

L. W. Coleman

8.2.1 CRITICAL CONSIDERATIONS IN THE USE OF HIGH-POWER Nd:GLASS LASER SYSTEMS FOR LASER FUSION EXPERIMENTS

Laser fusion experiments require the illumination of small targets with well-characterized laser pulses of very high power.¹ The laser energy must be distributed uniformly over the surface of the target to generate a uniform implosion necessary to produce high compression. The laser light must intercept the target at near normal incidence to minimize refraction losses and maximize the absorption by the target. The temporal properties of the beam at the target must be controllable and predictable to tailor the implosion history of the target. These requirements dictate the use of fast focusing systems, multisided illumination, and the reduction of beam aberrations in the laser to acceptable levels (for most aberrations $\leq \lambda/2$).

Current laser fusion targets are difficult and time consuming to fabricate because of their small size and strict tolerance requirements.² The alignment of the beams on the target and of the target diagnostics are also time consuming; hence the laser irradiation system should have good reliability and predictable output. The Nd:glass laser is the most reliable type of high-power pulsed laser in operation today, but it still falls short of the requirements for repeatable experiments. Our experience is that about 75% of target irradiation attempts are successful and that the laser output and pulse duration are predictable to about $\pm 20\%$. These factors combine to make complete monitoring of the laser output necessary for successful target irradiation experiments. The laser parameters which are of interest to the target experimenters are the beam energy incident on the target, the temporal and spatial shape of the beam at the target, and the prepulse energy which can prematurely change the target configuration.

Beam aberrations which occur in the laser amplifier produce distorted illumination patterns and intensity irregularities at the target.³ Passive aberrations occur due to manufacturing inaccuracies and in addition

phase distortions result from the intensity dependent index of refraction of the media in the laser chains. Sources of passive aberrations are those present in the laser which are measurable with a low-intensity beam and include surface and material irregularities, alignment errors, beam propagation aberrations, and thermal irregularities and air turbulence in the beam path.

Glass laser amplifier systems contain a large number of components; for instance, each Janus beam passes through 130 optical surfaces between the oscillator and the target focusing lens. A small deviation from ideal figure of the surfaces will accumulate and cause large aberrations. The total length of glass in the beam path of a glass laser amplifier is large (in Janus, approximately 1.6 m). Occlusions, bubbles, and refractive index inhomogeneities in the glass can accumulate to a significant degree. These effects must be minimized by strict tolerancing and a careful selection of all optical elements.

Tilt and centering errors of the beam expander and spatial filter lenses will produce aberrations and must be carefully minimized. The propagation of the beam through the many tilted and wedged elements in the amplifier train can also produce aberrations; for instance, a diverging beam passing through an array of tilted disks will produce astigmatism. Nonuniform temperature distribution in the amplifier disks are another source of aberrations. The disks are nearly uniformly heated during the flashlamp pumping cycle, but the cooldown can not be made uniform and each of the disks becomes a weak tilted lens. Significant aberrations are present from immediately after firing until the disks cool to ambient temperature (a time period of from 1 to 2 hr). This cooling time restricts the laser firing rate.

Air density variations in the beam path are a cause of significant aberrations. We have minimized this effect

by enclosing the beam in a sealed pipe which excludes room air currents and provides a near stationary medium for the beam propagation. Tests performed with a cw laser propagating through sealed pipes in the amplifier chain show a significant reduction in energy distribution variation at the target.

The other important class of aberrations is active aberrations caused by the beam in propagating through the laser chain. The active aberrations are caused by the refractive index nonlinearity which produces whole-beam self-focusing and beam filamentation. Whole-beam self-focusing occurs from the self-induced phase retardation which is proportional to the integral of the intensity times length along the propagation path.⁴ The phase retardation takes the shape of the beam intensity contour, and thus the focal spot distortion is dependent on time and on the beam shape. In Janus at 400-GW output, the maximum phase retardation is about 0.65λ . For the super Gaussian beam currently used in Janus and Cyclops this results in a time-dependent distortion at the focus which resembles spherical aberration.

A more serious effect of the nonlinear index is to produce beam filamentation.^{5,6} High-power beams propagating through the glass elements in the laser are unstable to the growth of small variations in amplitude. The growth rate is approximately exponential and dependent on the spatial frequency of the perturbation and on the local beam intensity. The maximum growth rate

of the instability is described approximately by the beam breakup integral

$$B = \int g_{\max} dz = k \int \gamma I dz.$$

Figure 8-2 shows the effect of filamentation on the Janus near field beam intensity. The beam photograph on the left was taken at low power where the system $B < 1.0$. The beam photograph on the right was taken at a single arm output of 240 GW at a location in the chain where $B = 4.3$. An even more serious effect is evident in the beam far field, as shown in Fig. 8-3. This figure shows film density scans of streak camera records of the beam focus of the Janus system using $f/1$ focusing lenses. In all cases the temporal pulse input to the amplifier train was monitored by a second streak camera and was a smooth bell-shaped pulse with the FWHM shown in the figure. The total B to the output streak camera is given for each record. At low B values very little distortion is evident. As B increases a temporal distortion of the pulse becomes obvious. The photographs taken at $B = 4.0$ and $B = 7.5$ indicate a double maximum with a dip in the pulse center where maximum intensity occurs on the input pulse. This intensity dip is caused by beam defocusing from filamentation. In Janus it is necessary to limit B to less than 4.5 to minimize temporal defocusing from filamentation.

Fig. 8-2. Janus near field beam photographs illustrate beam breakup into filaments at high power.

Fig. 8-3. Density profiles of streak camera photographs of the Janus beam focus taken at various output powers illustrate the effect of the system B . x is the spatial dimension along the streak camera slit, t is the time dimension, and D is film density. The FWHM of the pulses input into the amplifier train as measured with a streak camera at the oscillator output are shown at the bottom of each figure.

Another critical consideration in using high-power lasers is the damage threshold of the targets. A small amount of energy that arrives before the heating pulse² may damage or even destroy a target. The source of this prepulse energy has been discussed previously.² The measured damage threshold for glass shell targets is about 0.1 mJ with 100-ps-duration pulses in the Janus $f/1$ focusing configuration. Output of our target irradiation

systems is routinely monitored for prepulses of energy greater than 50 μJ caused by oscillator noise and leakage through the optical gate by fast photodiodes, as shown in Fig. 8-4.²

When using Nd:glass lasers for target irradiation experiments, it is most convenient to insert gates or isolators in the chain to protect the target from damage by prepulses. The single, bleachable dye cell used in

Fig. 8-4. A schematic of the prepulse detector at the output of the Janus laser. This arrangement can detect prepulses which contain less than 10^{-6} times the energy of the laser output pulse. Time resolution is about 0.5 ns.

1974 was not sufficient for the present operation, and we now use two dye cells¹⁰ placed at strategic locations in the amplifier train to suppress prepulses to acceptable levels at the target. We find that a critical alignment of the oscillator switchout components and insertion of bleachable dye cells with a small signal transmission of less than 0.1% are necessary to reliably suppress oscillator noise pulses and switchout leakage pulses.

Laser fusion experiments require uniform illumination of microscopic size targets. To achieve this condition requires that all beam aberrations, both active and passive, in the laser and focusing system be minimized. Passive distortion may be controlled by tight tolerancing and inspection of all optical components and by

proper design of the beam propagation path. Active distortions are controlled by optimized staging of the laser to minimize the growth of beam instabilities and by operating at beam power levels below those at which catastrophic beam breakup occurs. Targets must be protected from premature damage from ASE, oscillator noise pulses, and oscillator leakage pulses.

D. R. Speck
E. K. Storm
D. R. MacQuigg
J. E. Swain
J. F. Holzrichter

8.2.2 THE JANUS IRRADIATION FACILITY

In 1975 Janus, previously operated as a single-beam irradiation facility, was upgraded to two-beam operation. A schematic of the system is shown in Fig. 8-5. Several other changes discussed in the previous section have been made to the system to improve the beam quality. An additional dye cell was added after the spatial filter to lower prepulse and ASE levels. The final polarizers (after B4 and B6) were removed to decrease the value of the B integral¹¹ and thus increase

focusable power. A new electronic pulse switchout (Sec. 4.2.2) has been added to provide more reliable operation than was obtained with the previous sparkgap switch.

Changing from single-beam to two-beam operation necessitated an increase in both the laser beam and target optical diagnostics. A schematic of the "west" laser beam diagnostics is shown in Fig. 8-6 and the "east" beam diagnostics are shown in Fig. 8-7. By

using beams reflected from the Faraday rotator glass, we measure the beam energy and its distribution. In addition, the beam prepulses are measured on the west side, and the beam temporal behavior is monitored with a streak camera on the east side.

The streak camera was also used to determine simultaneity of arrival of the two beams on target (Fig. 3-7). By adjusting the length of the laser "arms," the east and west beams were made simultaneous to ± 3 ps. To provide fixed delays between the beams (Sec. 3.2.1), calibrated thicknesses of antireflection (AR)

coated glass were placed before the west turning mirror.

Two alignment improvements were added to the Janus system in 1975. A cw YAG alignment laser was introduced at the "T" (see Fig. 8-5) to provide increased illumination for beam and target diagnostics. Also, streak camera alignment difficulties were overcome by placing a prism behind the streak camera slit and directing the slit plus beam image onto an ir TV.

Figure 8-8 is a schematic of the Janus target chamber and the optical diagnostics which are used to

Fig. 8-5. Schematic layout of Janus laser system.

Fig. 8-6. The Janus west beam diagnostics include a photodiode for prepulse monitoring.

Fig. 8-7. The Janus east beam diagnostics include a streak camera which records both the incident and backscattered radiation (see Fig. 8-8).

Fig. 8-8. Janus target and beam imaging optics.

position the target, align the beams, and observe the "target plane" laser intensity distribution. The heavy line indicates the path of the main pulses, which are typically 60 to 80 ps in duration and up to 0.25 TW in each beam.

The focusing system consisted of two 90-mm-focal-length, $f/1$ lenses. These are single-element aspheric lenses with a 6-mm hole on-axis to prevent damage from internal reflections within the lens. Comparison of the observed focal spot diameter with that expected from a perfect lens shows these lenses to be nearly diffraction limited.

Four-percent beamsplitters direct a portion of the light from the focus to the optical diagnostic systems. A 4-m auxiliary lens focuses the collimated light onto the various instruments. The beam focusing lens and the 4-m lens together form an imaging system with a lateral magnification of 45. The imaging system is identical on each side.

Multiple-image cameras¹² provide a photographic record of the light reflected from, and transmitted by, a target. The array camera provides images of the beam at several planes stepping through the focus. These cameras provide a reliable indication of how accurately the target was hit on each shot. They are also used to obtain quantitative information on the beam energy distributions (Sec. 8.2.4).

Television cameras are used to view the target and beam alignment. Special ir-enhanced silicon-target vidicons are used to minimize the light energy incident on a fusion target during the alignment procedure. Reticles burned into the silicon target provide a mechanically fixed reference point and a precise calibration of the magnification, independent of distortion and drift in the camera and monitor electronics. Figure 8-9 shows an image of a typical target. The burn spots are spaced precisely 1 mm on the vidicon, which corresponds to 22.4 μm in the target plane.

A side-viewing telemicroscope is used in initial alignment of the target and in photographing the target during a shot. The distribution of green second-harmonic light in the color polaroid pictures taken with this camera also provides an indication of how accurately the target was irradiated.

Moving diffusers are used to provide back-illumination of the targets with 1.06- μm laser light during alignment. The cw alignment laser provides the necessary source of bright, monochromatic light, and the diffusers provide a smooth, speckle-free distribution of this light over the target area. The optical requirements of a target illumination system are discussed more fully in Sec. 8.2.3.

The basic method which has evolved¹³ for aligning targets in our laser systems uses the opposite focusing lens to re-image the beam and target onto a TV viewing system. The side-viewing optics provide a reference position for the target along the line of sight of the TV viewing system. Successive adjustments of the lenses (auxiliary and focusing) and the mirrors are used to obtain a sharp image of the target on which a beam image of desired size is centered.

Alignment is facilitated by a unit which remotely controls lenses and mirrors in the focusing and diagnostics optical chains. The experimenter thus has a central control over all components necessary for accurate target positioning.

Use of this method in a multibeam laser fusion system is possible if the beams are arranged in diametrically opposed pairs.

J. E. Swain
D. MacQuigg
E. K. Storm
D. R. Speck
J. F. Holzrichter

Fig. 8-9. 80- μm target ball backlit with 1.06- μm laser light, and moving diffusers. Fringes are due to multiple reflections in the vidicon.

Target viewing during the alignment procedure requires backlighting the laser targets and viewing both targets and beam through the opposite focusing lens. In this first year of operation with two-beam systems, we have addressed the difficult problem of finding a suitable source of illumination. This article summarizes the optical requirements, discusses some of the methods which have been proposed or tried, and presents what appears to be an optimal solution of the illumination problem.

The optical requirements for an illumination system may be summarized as follows:

- Wavelength 1.06 μm
- Bandwidth less than 1 nm
- Power sufficient to provide clean image on TV system
- Spatial distribution uniform over target and surrounding area

Since the laser beam is monochromatic but the focusing lenses are not achromats, viewing of the target at the laser wavelength is desirable. Use of another wavelength requires careful cross-calibration at the two wavelengths and a more complicated optical system to image the same plane at the same magnification.

The bandwidth restriction is necessary to avoid chromatic aberration, a problem which is especially severe with larger diameter lenses. The diameter of the blur circle may be calculated using a thin lens approximation for the focal length.¹¹

$$d_B \approx D \left(\frac{dn}{d\lambda} \right) \Delta\lambda,$$

where D is the lens diameter, $dn/d\lambda$ is the glass dispersion, and $\Delta\lambda$ is the illumination bandwidth. For example, Janus with $f/1$, 90-mm lenses, dispersion $1.3 \times 10^{-5} \text{ nm}^{-1}$,^{12,13} and illumination bandwidth 10 nm (standard interference filter) gives a blur circle diameter $d_B \approx 12 \mu\text{m}$. The effect of this blurring can be seen in an image of a broken target stalk taken with the 820-nm illumination from xenon arc light (see Fig. 8-10).

The power requirement may be stated as a radiant intensity needed at the input to the illumination lens. For the Janus system, assuming the bandwidth is restricted to 1 nm, the input to the lens must be 2 W/sr·nm. This exceeds the radiant intensity at 1.06 μm of all but the most powerful xenon arc lamps. Spatial

distribution is not a problem with an incoherent source; however use of a laser source introduces problems of speckle and hot spots which could damage the target.

The methods we considered for laser illumination of the target fall into the following categories:

- Expanded beam from the cw alignment laser
- Sweeping the beam rapidly over the target area to obtain a smooth distribution
- Diffused 1.06- μm laser light

Use of a stationary expanded beam engenders all of the problems inherent in coherent optical imaging systems—extreme sensitivity to dust, scratches, and localized aberrations. The highly collimated character of the coherent light causes small defects on any of the elements to have visible effects at the image plane.

Sweeping the beam rapidly over the target plane allows for some redundancy in the light-ray paths from target to vidicon, and thus reduces the influence of localized defects. A lens vibrator with plastic Fresnel lenses was used for several months in the Janus laser system. The optical quality of commercially available plastic Fresnel lenses is so poor, however, that even with very large vibrations, streaks in the distribution are still visible.

The use of diffused 1.06- μm laser light provides illumination with an extremely narrow bandwidth and eliminates the chromatic aberration problem. The diffusers are inserted in the beam and the target is viewed as shown in Fig. 8-11. The optical requirements for good diffusers are:

- High efficiency to conserve available power
- Low specular transmission to avoid the possibility of burning a target during alignment

Fig. 8-10. Sharpest image of a target stalk showing blurring due to chromatic aberration. The photo was taken with the Janus system using an 820-nm xenon arc source; $\Delta\lambda = 10 \text{ nm}$.

¹¹This value for the dispersion is calculated using the Schott glass dispersion formula¹² with coefficients for BK7.

Fig. 8-11. Illumination of the target with diffuse laser light.

- Rapid motion of the speckle pattern to provide a uniform average illumination over 1/30-s TV frame time

The efficiency is primarily determined by the solid angle over which the light is scattered. Energy must be scattered forward into a very narrow cone (1- to 100-mrad angular diameter for the range of focusing systems presently planned). Ground glass is very inefficient in this respect.

Most diffusers have a distinct specular component of the transmission function which results in a portion of the beam passing through undiffused. Figure 8-12 shows light distributions at the focus using diffusers with high and low specular transmission. The specular transmission in a random phase diffuser is dependent on the amplitude of the phase modulation, with several waves required to reduce the specular component to a negligible level.

Several media were tested for use as diffusers, including various brands of shower glass, nonglare picture framing glass, matte-surface drafting mylar, and miscellaneous samples of plastic sheet. The shower glass showed very irregular light distributions. The nonglare glass and mylar and plastic samples, in general, had very high specular transmission at 1.06 μm . None of the above media allowed variation of the scattering cone angle for various focusing systems.

The method finally selected for target illumination in the Janus and Argus laser systems uses a pair of random phase diffusers—one spinning, the other stationary—placed in the beam ahead of the target chamber. These diffusers provide a uniform, monochromatic, but spatially incoherent illumination of the target, ideal for high-resolution imaging. Parameters of the diffusers may be adjusted in fabrication to set the cone angle of diffusion for the particular focusing system in use.

Figure 8-9 is an image of an 80- μm target ball taken with moving diffusers on the Janus laser with $f/1$

(a)

(b)

Fig. 8-12. 1.06- μm light distributions from: (a) bad and (b) good diffusers. The hot spot in (a) results from specular transmission.

lenses. The fringes seen in this image are due to multiple reflections of the $1.06\text{-}\mu\text{m}$ laser light within the vidicon—a problem which should be eliminated by application of AR coatings on the faceplate and silicon target.

The diffusers presently in use consist of bleached holographic plates on which have been recorded speckle patterns generated with an argon laser beam and a ground glass diffuser. Upon bleaching in gaseous bromine,¹⁶ the density variations are converted to phase variations, mostly due to surface profile,¹⁷ but partly also a bulk index effect. These diffusers perform well optically, but have a limited life in the laboratory

environment. The bromine processing causes the emulsion to become brittle and flake off the glass on dry days. Also, due to the limited thickness of the emulsion, the lowest specular transmission seems to be about 1%, even with careful optimization of the exposure and development to achieve the maximum phase modulation. We are currently working on a method to record speckle patterns as surface relief profiles in a clear plastic or glass material, which should provide more durable and highly efficient diffusers.

D. R. MacQuigg
L. G. Wiley

8.2.4 LASER ENERGY DISTRIBUTIONS AT THE TARGET

Experiments were conducted on the Janus laser with $f/1$ lenses to characterize the laser energy distributions incident on a target. Images of the east beam focus have been obtained with an array camera for power levels with nonlinear distortion ranging from 0 to 0.9 waves. The following effects have been observed in the high power focus:

- Inward shift of the focus at the peak of the pulse and formation of a ring due to whole beam self-focusing
- Scattering of energy out of the focal spot due to small-scale beam breakup

Computer simulations¹⁸ of the focus confirm the focal shift and ring formation and provide a reasonable model of the time-resolved focal characteristics.

Following a shot in which the disk amplifiers have been pumped, thermal effects in the amplifiers result in slow drift of the focus away from the lens for a period of at least 2 hr. There is also significant distortion of the focus for about 1 hr after a shot.

Data were obtained in these experiments by firing the laser with no target in place and re-imaging the focal distribution onto the diagnostics shown in Fig. 8-8. A unique feature of these experiments is the use of a multiple image camera with an additional mirror pair to provide images at several planes stepping through the focus. The first mirror pair is closely spaced and generates a vertical column of identical images with known intensity ratios. The second mirror pair produces several columns, each of which images a different plane near the focus. The spacing between planes at the focus is determined by the spacing, Δ , of the beam splitters and the longitudinal magnification of the imaging system.

Figure 8-13 shows a typical set of images obtained with the array camera. These images cover a region from $135\text{ }\mu\text{m}$ ahead of focus to $15\text{ }\mu\text{m}$ beyond best focus. The second column shows the energy distribution at a plane where an $80\text{-}\mu\text{m}$ -diam target ball would

be placed. The images in each column are identical except for intensity level. Analysis of these images allows determination of the photographic-density to energy-density conversion curve without a separate calibration exposure for each plate. The use of this camera allows us to observe correlations between the different planes which would be impossible to obtain on separate shots due to thermal drift and variations in the laser power from shot to shot.

Array camera images have been obtained for the Janus beam at several power levels. Images from the target plane for two of these shots are shown in Fig. 8-14. The high-power energy distribution shows the buildup of a ring due to whole-beam self-focusing and the presence of scattered light due to the beam breakup resulting from small-scale self-focusing.

The features observed in these distributions may be explained with a simple model (see Fig. 8-15). An initially spherical wave becomes distorted at high power due to the nonlinearity in the refractive index of the glass. The center, being more intense, is retarded more than the edges. The first-order effect of this whole-beam self-focusing is an inward zoom of the focus at the peak of the pulse. In addition, if the intensity profile is not spherical, the marginal rays at peak power will focus at a different position than the paraxial rays. Optimization of energy extraction in the final amplifiers requires an intensity profile which is nearly flat in the middle and falling off rapidly at the edges. Such a profile will induce positive spherical aberration in the high-power wavefront and cause a ring buildup at the target plane ahead of focus. A parabolic profile results in a nonlinear distortion with very little spherical aberration. The proper choice of beam profile at the apodized aperture will require a compromise between fill factor in the amplifiers and uniformity of the energy distribution on the target surface. A small amount of predistortion at low power may be desirable.

Fig. 8-13. Array camera images showing the energy distributions at several planes near the focus of the Janus $f/1$ lenses. This is the east beam with peak power of 208 GW and peak nonlinear distortion of 0.7 wave.

Several of the array camera images have been microdensitometered and analyzed. Density vs log (exposure) curves were generated by plotting the density levels of identical features in a column of images. Density traces taken through the center of the images were converted to energy density using the calibration curve generated for the same column of images. Figure 8-16 shows plots of the average energy density vs radius for the two images in Fig. 8-14. These are hand averages in which fine structure in the central part of the beam was ignored and the features of the ring (height, width, etc.) were determined by averaging of both sides of the beam. These idealized radial profiles

were used as input to the 2-D LASNEX target design code.

We have two methods of experimentally determining the focal shift at high power: (1) measurement of the inward curvature of features on a streak camera record of the target plane intensity distribution, and (2) comparison of the apparent focal position in an array camera record of a high-power shot with the measured focal position of the low power cw beam. The streak camera in Janus was configured to record the incident east beam and the transmitted west beam. Both beams show features with a definite inward curvature which is consistent with a 10- μm inward focal shift, but because

Fig. 8-14. Images of target-plane energy distributions for Janus $f/1$ lenses. (a) Low power, $108\text{-}\mu\text{m}$ inside focus, east beam, rod shot, $B = 0.1$ wave. (b) High power, $80\text{-}\mu\text{m}$ inside focus, east beam, 235 GW, $B = 0.9$ wave. High-power image shows ring buildup due to whole-beam self-focusing and beam breakup due to small-scale self-focusing.

Fig. 8-15. Modes of the focal behavior at high power. Focal zoom and the formation of a ring at high power are explained by considering the effects of nonlinear distortion of the wavefront.

Fig. 8-16. Averaged radial energy profiles for the distributions in Fig. 8-14. (a) Low power, $108\text{-}\mu\text{m}$ inside focus, rod shot, $B = 0.1$ wave. (b) High power, $80\text{-}\mu\text{m}$ inside focus, 11.1-J/47-ps 235 GW, $B = 0.9$ wave.

Fig. 8-17. Plot of the Janus f/1 lens focal position vs time showing drift due to cooling of the amplifiers.

Fig. 8-18. Computer simulations of the Janus energy distributions confirm the origin of the ring structure and focal zoom and provide a time-resolved model of the focal behavior. This figure shows the computed energy profile 80-μm inside focus of f/1 lens; input beam intensity profile, $\exp[-(r/r_0)^2]$

the records are noisy and irregular, it is difficult to make this a precise measurement. The second method can provide fairly good accuracy in determining the time-integrated focal shift, but this method requires great care in determining the position of the planes in the array camera relative to the cw focus.

An array of images from a 160-GW (0.5 waves) shot was analyzed to determine the focal shift. The position of the planes at the time of the shot was computed, taking account of the thermal drift of the focus due to cooling of the disks (see Fig. 8-17). The FWHM beam diameters were determined for the first four planes by measurements from density traces. The marginal rays for these FWHM points were projected to the focus. The location of this time-integrated, high-power focus relative to the low-power focus was found to be $-8 \pm 4 \mu\text{m}$.

The general features observed in the high-power focus—formation of a ring and inward shift of the focus—are confirmed by computer simulations of the focal behavior.¹⁸

Figure 8-18 shows computer-generated radial profiles for low- and high-power cases. The exact shape of

the high-power ring depends on the input intensity profile, which in this case is assumed to be a twelfth power super-Gaussian. Focal shifts, inferred from measurements of the beam diameter in these computer simulations, show that the shift scales linearly with power and has a peak instantaneous value of $19\text{ }\mu\text{m}$ at $B = 1.0$ wave. The time-integrated focal shift was about 0.4 times the peak focal shift. These simulations,

when properly normalized to experimental data, can provide time-resolved, idealized radial intensity profiles suitable for input to LASNEX.

D. R. MacQuigg
J. Hunt
D. R. Speck
J. F. Holzrichter

8.2.5 4 π STERADIAN IRRADIATION SYSTEM

Over the past year the Janus laser facility, in the configuration described in the preceding sections, has been dedicated to feasibility studies for laser-driven fusion. One of the requirements for such studies is maximum uniformity and normality of the optical radiation incident on the target. To that end the focusing system was changed from two f/1 lenses to a refraction-reflection configuration which gives near 4 π target illumination.

Using refracting optics only, the maximum solid angle covered by a single aperture is restricted to values of about 0.6π , for normal incidence on target corresponding to an NA 0.7 lens. This f number is limited both by the acceptable total glass thickness and manufacturing difficulties associated with strongly aspheric surfaces. The high luminous intensities required for laser fusion induces nonlinear variations in the index of refraction of optical materials. This intensity-induced nonlinearity causes spatial ripples on the phase or amplitude of the beam to grow and produces filamentation or localized beam breakup which also imposes severe limitation on the maximum focusable power of a given laser system. Since filamentation scales exponentially¹⁹ with the total glass path, focusing systems for laser fusion experiments must be designed to minimize this effect.

A refraction-reflection system with near 4 π illumination coverage for two beams was first designed by C.E. Thomas and implemented at KMSF.²⁰ The LLL 4 π sr irradiation system is an improved version of the original KMS design, and is shown in Fig. 8-19. This system uses two NA 0.7 doublet lenses of 85-mm aperture designed to take a fifth-order super-Gaussian beam input profile

$$I = I_0 \exp - \left(\frac{r}{r_0} \right)^5$$

and provides near uniform illumination of laser fusion targets. Each mirror is part of an ellipsoid of revolution

around the beam axis with an eccentricity of 1/3 and an aperture of 304 mm. The nominal position of the two mirrors is confocal, with their common foci coincident with the target center. The other focus of each mirror is on the surface of the opposite one and coincides with the focal point of the corresponding lens. This geometry is shown in Fig. 8-19. In this way, each lens fully illuminates the opposite mirror which in turn concentrates the light on the common focus centered on the target. This arrangement provides an illumination system with an effective f/0.077, covering a solid angle of approximately 1.7π for each beam. The maximum theoretical 2π coverage value is not achieved because the two mirrors are separated by 40 mm along the vertical equator. This circular space is necessary for diagnostics, target loading, and target alignment optics. Full illumination of the target is accomplished by defocusing each mirror lens combination such that there is a 20- to 40- μm overlap between the focal points of opposing beams. By this means the equatorial zone is illuminated with only a slight deterioration of the ray normality condition.

This situation is illustrated in Fig. 8-20.²¹ Also shown is the shadow cone produced by the hole in the center of the lenses. These holes are necessary to prevent internal damage due to the formation of on-axis ghost foci by internal reflections.²² Figure 8-20 shows the calculated relative intensity distribution as function of the polar angle.²¹

From the structural and mechanical point of view, the lens-mirror system is mounted on a ring elastically suspended by torsion bars from the target chamber interior. Within this "mounting ring" each mirror is in turn elastically supported by a finger-ring-like structure through a system of Ω -shaped tension springs. The torsion bar suspension prevents the target chamber distortions from reaching the mounting ring which thus performs the functions of an optical bench for the target holder, the target alignment optics, the "x-ray microscope," and other diagnostics which are alignment-sensitive.

Fig. 8-19. Janus spherical illumination system.

Fig. 8-20. Ellipsoidal mirrors provide near uniform 4π illumination. (a) Overlap focusing configuration. (b) Corresponding relative intensity distribution.

The finger-ring structure provides a way of supporting the mirrors without introducing thermal or mechanical distortions of their optical figure. The Ω -shaped tension springs provide an elastic coupling which allows centering, focusing, and tilting the mirrors. Centering is accomplished by the hand-actuated differential screws. Tilting and translation along the axis are done with three stepping-motor differential screw combinations. The lenses and their translation stages are rigidly bolted to the mounting ring through four arm "spiders," which are the platform for the lens positioner. Each focusing lens is mounted on a five-axis lens positioner, such that translation along three axes and tilting about two axes can be electronically controlled by a combination of stepping motors, gear boxes, and differential screws. The tilting and translation of the mirrors, as well as the five motions of the lenses, are

monitored by digital readouts connected to properly placed linear transducers. The system provides a resolution of $1\text{ }\mu\text{m}$.

Two sets of mirrors have been manufactured; one, by Perkin-Elmer, with a Cervit substrate and a high reflectance multilayer coating, and another, at ILL, with a beryllium substrate, silver-plated and single-point diamond-turned. This last manufacturing process has been shown to provide greater damage threshold (about $35 \times 10^9\text{ W/cm}^2$)²³ and improved resistance to tarnishing than similar hand-polished surfaces, with fully satisfactory optical properties. These mirrors are the ones being used at the present time in the Janus experiments.

J. A. Monjes
E. K. Storm

8.2.6 CYCLOPS, A 20-cm-APERTURE IRRADIATION FACILITY

The second laser irradiation facility operated in 1975 is the Cyclops chain which is described in Sec. 3.2.2. As in the Janus system, the Cyclops beam must be carefully focused and precisely aligned with respect to the target. Figure 8-21 shows the configuration of the

target viewing system which allows these tasks to be accomplished.

Two major differences can be seen between its layout and the Janus layout shown in Sec. 8.2.2. Here no amplifiers are located beyond the main beam splitter

Fig. 8-21. Target alignment and beam focusing optics for the Cyclops radiation facility.

Fig. 8-22. Target and beam display (Cyclops).

complex (or "T"), and all target and beam alignment diagnostics rely on the fraction of radiation transmitted through the final turning mirrors (see Fig. 8-21). This latter arrangement minimizes the B (Sec. 8.2.1) of the system since no additional beam splitters are introduced between turning mirrors and focusing lenses.

Alignment is accomplished as in Janus using a cw YAG alignment laser which propagates through the entire chain with the same radial profile and divergence as a pulse.

The beam is directed to the target chamber along one or two paths by three turning mirrors. Using the angular adjustment capability of the last two mirrors, the laser is centered on the focusing lens with its central ray passing through the target. A rotating diffuser is then placed in the beam ahead of the focusing lens so that the whole target area is illuminated by scattered light. Under these conditions the vidicon viewing system on the other side of the target chamber can be adjusted to obtain optimum imaging of the target. Magnification is provided by a positive-negative lens combination (Galilean telescope). This configuration allows large magnification in a short system with no internal focal spot which could cause air breakdown. The depth of field of the imaging optics is several times smaller than the dimensions of typical targets; so careful adjustment of this viewing system establishes the position of the target along the beam axis as well as

transverse to it. With the diffuser removed and the target translated out of the beam, the viewing system provides an image of the beam in the target plane, and the focusing lens can be moved along the z axis to obtain the desired match between beam and target dimensions.

To avoid overheating the target with the alignment beam, the cw source is shuttered on and off with as low a duty cycle as necessary. Between shutter openings one frame from the vidicon is replayed continuously by a disk recorder and monitor.

Figure 8-22 shows examples of the information obtained during the alignment and focusing process. Figure 8-22a is a conventional microscope photograph of a Parylene disk target. Figure 8-22b is a photograph of the TV image obtained on the target-chamber viewing system when this target is mounted in the chamber. Figure 8-22c is an image of the focused beam in the same plane with the target position referenced by ink marks on the glass face of the TV monitor. Any scan line from the disk recording of this image can also be displayed to obtain qualitative information about the radial beam profile. The alignment and focusing arrived at by this procedure can be verified by observing a low-power pulse on the same monitors, and the cw and pulsed results have always been found to be in agreement.

An additional feature of the target monitoring capa-

Fig. 8-23. The Cyclops target chamber. In the foreground on the left is the east lens manipulator assembly. Inside the chamber numerous diagnostics can be seen, many of them mounted on specially designed semicircular arches. The target manipulator is in the chamber with the target holder partially retracted in its protective sleeve. Other port-mounted diagnostics inside on the photograph are an x-ray microscope, low-energy x-ray spectrometer, and neutron detector.

bility at Cyclops is a low-power He-Ne laser beam which is located behind Beam 1 turning mirror and can image the target on an additional vidicon located behind Beam 2 turning mirror. Thus, the target can be viewed continuously from the end of the $1.06\text{-}\mu\text{m}$ alignment phase through the actual shot.

As in the Janus system, part of the beam used for imaging (Fig. 8-21) is also used to obtain multiple image photographs of the target during the shot and a streak camera picture of the incident and backscattered beam. Back and forward scatter calorimeters use the energy transmitted through mirrors A and B (Fig. 8-21).

On an actual target shot, a large number of additional diagnostics are employed. A few of these can be seen in Fig. 8-23. This figure also shows two of the semicircular arches which have been used extensively both on Cyclops and on Janus for mounting the numerous instruments used for scattered light and particle diagnostics.

Basically the Cyclops and Janus target chambers are similar except that the 20-cm-aperture $f/2.5$ spheric focusing lenses are outside of the vacuum region. Their design was therefore modified to cancel the spherical aberration introduced by the converging beam passing through the vacuum window. The lenses are remotely adjustable in five axes to an accuracy of $2\text{ }\mu\text{m}$ by means of stepping motors.

Since the lenses are outside the vacuum region, more room is available inside the chamber for diagnostics. In particular, two circular holding rings are placed around and close to the beam to probe the azimuthal distribution of the scattered light.

Another difference between the two operating facilities was the design of the target holder. Targets are suspended at the focal point by a manipulator, which is remotely adjustable to an accuracy of $0.4\text{ }\mu\text{m}$ per step. Rotation about the vertical axis is manual, over 360° .

The target holder assembly is removed from the

chamber for installation of the target. The target is prealigned in a bench fixture and then retracted into a protective sheath. The assembly is inserted into the target manipulator and clamped into place to effect a vacuum seal. The target is then extended downward about 15 cm to the exposure position. Rough positioning (to about 25 μm) is accomplished by means of a prealigned telemicroscope, and final positioning is

done by superimposing the target onto the focal spot as discussed above. Positions of the x and y translation stages are displayed by dial indicators having 10 μm per division but readable to about 2 μm .

K. R. Manes
R. Rienecker

8.2.7 THE 10.6- μm IRRADIATION SYSTEM

The Valkyrie 10.6- μm laser facility was operated at the beginning of 1975 to irradiate Parylene disks and polyethylene foils. The design and construction of the system has been described in previous reports,²¹ and a comprehensive review of its operating principles is available in the literature.²²

Figure 8-24 shows the Valkyrie system with most of the target diagnostics installed on the vacuum chamber. In the background the actively mode-locked oscillator

and preamplifiers which use Lumonics TEA discharge gam media may be seen. The switched-out nanosecond pulse is amplified by two cold-cathode electron-beam-sustained amplifiers. After passing through the beam diagnostics tables, the beam is finally focused on the target in the chamber.

Valkyrie is shown schematically in Fig. 8-25. Its unique features are its two-stage electrooptic switch-out system, high beam quality afforded by large aperture

Fig. 8-24. Here the Valkyrie CO₂ laser system is seen from the south with its oscillator-amplifier chain in the background and beam diagnostics tables, and target chamber in the foreground. All cables and plumbing are routed through trenches to a remote control room.

Fig. 8-25. Schematic diagram of Valkyrie showing its oscillator, switchout system, beam delays for streak camera triggering, beam expander, and amplifier chain.

uniform gain amplifiers, and low electrical noise due to careful shielding. Reliable 10- to 30-J pulses with durations of 1.5 to 3 ns with no detectable parasitic oscillations, and prepulses ≤ 33 dB down were provided for target experiments.

Figure 8-25 contains a schematic of the pulse selection system used for target experiments. Low-level pulses separated by 20 ns eventually produced enough ionization in the laser-triggered spark gap to cause it to close, launching a 10-kV square wave of 20-ns duration. When this voltage appeared across the CdTe electrooptic crystal, it caused the next mode-locked pulse's polarization to be rotated by $\pi/2$, and consequently that pulse was eventually reflected off the output Brewster plate. Figure 8-26 includes a diagram of the experimental arrangements used to determine the efficacy of this pulse selection technique by measuring the ratio of the amplitude of the switched-out pulse to that of the immediately preceding pulse, i.e., the prepulse extinction ratio. A photograph obtained with this apparatus is shown in Fig. 8-27. This switchout system had a measured extinction ratio of 2×10^6 at the oscillator, which was degraded by amplifier saturation to 2×10^5 at the target. Tests of a single-stage

switchout system had previously shown an extinction ratio of 2 to 5×10^4 at the oscillator, which was reduced to only 20 to 50 at the target. Separate target damage studies established that 10- μ m CH₂ foils could often survive irradiation by pulses with energies of ≤ 100 mJ and showed negligible damage after exposure to ≤ 40 -mJ pulses. Consequently, the single-stage system was found to be inadequate, but the two-stage system guaranteed that the target would not be prematurely disassembled.

Figure 8-28 demonstrates the quality of the 10.6- μ m laser beam. Pyroelectric arrays were used to monitor the near field and focal energy distribution. The focal intensity distribution observed in this way shows most of the energy in a diffraction-limited peak with approximately 80 μ m FWHM. However, the smooth output beam profile shown in Fig. 8-28 was found to be sensitive to the pumping of the preamplifiers. Thermal lensing in the early stages of the amplifier chain distorted the beam. This problem was avoided by a reduction in preamplifier pumping and/or by launching the 1-ns pulse ~ 0.5 μ s before the time of peak gain.

With a target at the focus of the sodium chloride

Fig. 8-26. Schematic diagram of Valkyrie laser beam diagnostics designed to measure beam energy, temporal pulse shape, prepulse extinction ratio, and near and far field beam profile.

lens, about 50% of the pulses were accompanied by unacceptably large parasitic oscillations. The e-beam-sustained amplifier gains were reduced by using a 1:1:1 He:N₂:CO₂ gas mix rather than the 3:1:2 mix used previously. Configured in this way, Valkyrie produced ~ 25-J pulses with no detectable parasitic oscillations. With targets in place, back reflections of 1 to 6% were observed. The 25- μ m mylar foil located in the focal plane of the Keplerian beam expander was broken down by the amplified returning pulse and protected the switchout and oscillator optics.

As shown in Fig. 8-26, incident, forward scattered, backscattered, and sidescattered energy; pulse duration; prepulse extinction ratio, near field energy distribution, and focal spot energy distribution were monitored on each shot. The targets used in our experiment were located within 100 μ m of the true focus, well within the

Fig. 8-27. Oscillograph of extinction ratio measurement. Typical prepulse extinction ratios: at the oscillator, about 2×10^4 ; at the target chamber, about 2×10^5 .

8.2.8 COMPOUND ELLIPSOIDAL FOCUSING SYSTEM FOR FUSION LASERS

Isentropic compression of laser fusion targets requires highly uniform illumination over the entire target surface, and near normal incidence. For a two-beam laser, this is best achieved using a fast catadioptric system. In designing such a system, the total thickness of refracting material must be minimized to avoid loss of optical quality through small-scale self-focusing. Such a system has been designed for use with the Argus laser. It consists of a pair of nested ellipsoidal reflectors coupled with an aspheric doublet refracting element

~ 1.4-mm Rayleigh range of the focused beam. The beam was therefore co-located at the target and normally incident.

In summary, Valkyrie provided a high-quality 10.6- μ m source capable of reaching intensities of about 10^{14} W/cm² on fragile laser fusion targets.

K. R. Manes
H. E. Eddleman

Fig. 8-28. Laser beam energy distributions in the Valkyrie CO₂ laser. Near and far-field beam patterns are displayed with pyroelectric arrays. (a) Near field, $\omega_1 \sim 1.7$ cm. (b) Imaged focal spot, $\omega_0 \sim 68$ μ m.

of 200-mm-aperture diameter, has been designed for use with the Argus laser. The power which can be transmitted through such a system is limited, however, by the advent of small-scale self-focusing in the lens itself, leading to severe phase distortion and filament formation in the beam. This effect can be relieved by increasing the lens diameter, since the integrated optical intensity through the lens is inversely proportional to the diameter for fixed focusing power. But to achieve a significant reduction in beam breakup would require a prohibitively large lens, if power levels of the order of those projected for the Argus system (3.0 TW per beam) are to be transmitted. To

circumvent this difficulty, angle-amplifying reflecting optics²⁷ (patent applied for) were incorporated into the illumination optics design. In this way, the required focusing power of the lens was reduced by a factor of 2, with a corresponding reduction in the lens thickness and the nonlinear phase distortion. The compound clamshell system is shown in Fig. 8-29. It consists of an interior pair of ellipsoidal mirrors into which light is focused by angle-amplifying, ellipsoid-plane mirror pairs.²¹

We have designed an optical fuse into the system in order to protect the relatively expensive ellipsoidal mirrors. The optical fuse is evident in the optical path

Fig. 8-29. Argus spherical illumination system.

presented in Fig. 8-29 as the flat mirror in back of the inner ellipsoidal mirror. This flat, diamond-turned, copper-plated beryllium mirror will damage at power densities over 35 GW/cm². Even though the flat is only loaded at 4 GW/cm², short pulses and filamentation formation may increase the flux. If damaged, this flat is easily replaceable.

Decentering the foci of the inner clamshells for better target uniformity is not practical due to the complex optical coupling; thus the lenses were designed to provide the necessary overlap initially with a conic corrector as shown in Fig. 8-29, just in front of the window. This conic corrector bends the paraxial rays in to eliminate the shadow cone projected from the large hole in the mirrors. A spherical corrector must replace the conic corrector in order to form a point focus required for alignment and necessary for the fabrication of the doublet.

The f/1.25 doublet was designed to provide perfect illumination while minimizing internal reflection foci which may be intense enough to cause damage.

The vacuum window is also a weak f/128 lens necessary to recollimate the beam which was expanded from the 200-mm laser aperture to the 280-mm aperture of the chamber optics.

With the conic corrector in position this system provides perfectly uniform illumination on the target.

The mirror substrate material choices were BK-7, Cervit, and beryllium. There are four primary properties which determine the final choice since each of the four affects the substrate design at different times during processing and final use. A detailed discussion of the chosen process is presented in Ref. 21. The pertinent parameters guiding this choice are presented in Table 8-1.

As can be seen, beryllium substrates are 7 times stronger than those of BK-7 or Cervit, thus giving superior rigidity for the same geometric dimensions. Moreover, beryllium is 4 times stiffer than BK-7 and 3

times stiffer than Cervit. Due to the required high aspect ratio required in the geometry of the reflecting portion, both strength and stiffness necessitate thicker peripheral sections for BK-7 and Cervit than for beryllium substrates.

As far as long-term dimensional stability, beryllium and Cervit substrates are both better than 5 times more stable than BK-7 substrates.

Finally, thermal distortion needs to be considered in the final step of mirror processing, the dielectric overcoating. This overcoating subjects the substrate to temperatures of 200-300°C. Although beryllium has twice the distortion of Cervit the amount of distortion seen by beryllium substrates can be reduced by coating both sides. The substrates can be stabilized by subjecting it to numerous temperature cycles, such that all creep has been accelerated prior to final lapping.

The logical choice is therefore beryllium, but even this material is subject to further choices. The desired high strength and low creep with relatively low cost and delivery time were met using ultrapure beryllium particles further shattered by impact with a beryllium target in an inert gas atmosphere. This material is subjected to a number of proprietary elevated temperature-pressing and sintering operations to give the highest density with a maximum isotropy. The amount of beryllium oxide in the chosen material directly determines the strength and indirectly the amount of long-term creep, hence long-term dimensional stability.

The actual processing of the mirrors is detailed in Ref. 21 with particular attention paid to the solutions necessary to insure maximum adhesion. To insure that this processing would yield the required diffraction-limited, high damage threshold mirrors, a test program was instituted to investigate variable parameters.²¹ As an example, Fig. 8-30 shows the movement of the substrate during the sequential processes which lead to the decision to have the 900°C anneal cycle.

The optical mounting and positioning system is

Table 8-1. Mirror substrate design parameters

Material	ρ (g/cm ³)	E modulus of elasticities (10 ⁹ N/cm ²)	MYS, micro yield strength (psi)	UTS, ultimate tensile strength (psi)	K therm. conduct. (cal/g·°C)	C specific heat (cal/cm ³ ·s·°C)	Coef. of therm., expans. (10 ⁻⁶ /°C)	Dimen- sional change K/αp (x 10 ⁻³)	αpC/K (x 10 ⁶)	T trans (°C)
BK-7	2.200	7.00	1,500	—	0.0033	0.188	0.55	2.7	69.0	1,500
Cervit	2.500	9.23	1,500	—	0.0040	0.217	0.10	16.0	14.0	800
Beryllium										
(KBI HP-20)	1.852	28.00	3,000-10,000	55,200	0.3800	0.450	12.40	16.5	27.0	1,300

Fig. 8-30. Substrate stability for HP-20 Be 2-in. disks.

designed to provide stability with adjustment to properly illuminate the envisioned target sizes in their range of positional errors. The corrector lens mounts into a precision-lapped clamp ring which can be quickly and accurately inserted into an indexed mount outside the chamber window. The chamber window generously overlaps the chamber and has a unique clamped edge design which lowers the vacuum deflection by a factor of 5 over ordinary edge clamping. The lens and mirror positioners are described in Sec. 8.2.9.

The flat mirror mount is specially designed to offer the same adjustments available with the ellipsoidal mirrors and also provide an indexed mount for accurate insertion of the clamping fixture retaining the mirror.

The 10-mm-thick, 360-mm-diam mirror presents problems in fabrication which may be resolved by

resorting to a precision-lapped clamp ring which offers 5 times lower deflection over a freely mounted configuration. The clamp ring may also be used to freely mount the mirror again as a subassembly.

The Argus illumination system presented an excellent solution to the problem of focusing power on targets with a minimum of glass to prevent loss of focusable power up to a maximum of 6 TW. Above this power, it becomes more economical to add more beams, and additional beams require some alternate type of illumination such as in LLL's Shiva laser system which has 20 beams and can only accommodate a refractive illumination system.

S. S. Glaros
A. J. Glass

8.2.9 ARGUS TARGET CHAMBER DESIGN

The target chamber used in the Argus laser system was designed so that the target and all focusing elements can be positioned under vacuum with a resolution of $1\text{ }\mu\text{m}$. This required support of all the beam optics, target positioner, and target alignment optics in a stress-free space frame isolated from vibration, temperature changes, and vacuum load. The chamber had to be able to implement any of four projected focusing systems:

- Two-beam irradiation with $f/1$ or $f/2.5$ lenses
- Two-beam irradiation with lenses and Janus simple ellipsoidal mirrors
- Two-beam irradiation (or four beams folded into two) with lenses and compound ellipsoidal mirrors
- Four beams in a plane or tetrahedral irradiation with lenses^{2b}

In addition, minimum vacuum of 10^{-5} Torr with all internal motors running and diagnostics installed was required. A secondary design objective was to be able to introduce the targets into the chamber without destroying the high vacuum. To satisfy the alignment requirement, all optical components, target manipulator, and target alignment optics are supported on a rigid framework which is freely supported within the vacuum chamber. The floor pad is a 3-ft-thick concrete slab which is carefully isolated from vibrations due to vacuum pumps, air conditioning machinery, vehicular traffic, and microseisms.

The optical system can be installed in the space frame and aligned in an optical laboratory before being placed in the target chamber. Different space frames allow a variety of optical configurations to be installed in the basic vacuum chamber with minimum interruption of the experimental program.

The target manipulator is similar to the one used at Cyclops. The unit was designed for maximum rigidity at the target, precise alignment to within $0.5\text{ }\mu\text{m}$, and the capability of target replacement without breaking the vacuum. To insert a target into the chamber, the vacuum interlock is closed at the bottom of the target entry tube. A target is installed on the target rod of the translation stage and retracted into the shield tube. The vacuum interlock is opened and the motorized z axis extends the target rod and target into the chamber for positioning.

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 5X magnification. The image on the reticle is then viewed through a 20X microscope for alignment or with a camera for record-

Fig. 8-31. Five-axis microlens positioner for Argus with $f/1$ buses.

Fig. 8-32. Argus target chamber baseline configuration.

Beam turning mirrors

Fig. 8-33. Argus target chamber layout for (a) two to four co-linear beam configuration and (b) for four-beam tetragonal configurations.

ing. The TAO is mounted directly to the space frame (optics support tube) and is decoupled from the chamber with a bellows. Two TAO's are normally used on the chamber, mounted 90° apart, to aid in the positioning of the target.

The lens micropositioner (Fig. 8-31) is a device for positioning lenses precisely within a vacuum chamber with five degrees of freedom (three translations and two angular rotations). The axis motions are actuated by stepping motors and gear reducers which drive precision screws. Single steps of the motors translate into $0.25\text{-}\mu\text{m}$ incremental movements at the output of the actuators. The positioner has a clear aperture of 250 mm, and each axis motion is spring loaded and free of backlash. Additional details are available in Ref. 29.

The mirrors²¹ are supported around their periphery by segmented finger rings, elastically preloaded to provide uniform support and eliminate distortion due to mounting. These finger rings are suspended in a stiff support ring which, in turn, is mounted to the space frame in completely adjustable mounts.

The ellipsoids can be positioned manually in five dimensions, as follows:

Motion	Range
Translation in x, y, and z	$\pm 5\text{ mm}$
Angular rotation Θ_x and Θ_y	$\pm 1^\circ$

In addition, a motorized drive is provided for fine adjustment of the axial drive screws. This will allow fine tuning of focus and tilt while under vacuum over a range of $\pm 55\text{ }\mu\text{m}$, with a resolution of better than $0.1\text{ }\mu\text{m}$.

The vacuum system uses turbomolecular pumps

which will withstand occasional accidental excursions to atmospheric pressure without damage and without contaminating the system. A dual pump arrangement provides fast pumpdown and gives a backup in case of breakdown. Cryogenic pumps remove condensable vapors and greatly increase pumping speed. This is necessary because of the large amount of plastic insulation on motors, wires, and detectors. The cryogenic pumps and all cold traps are automatically filled with liquid nitrogen as required.

Control of all vacuum pumps and valves is remote, and functions are interlocked to prevent errors.

Vibration and noise from the roughing pumps are isolated by placing the pumps on a mezzanine in the basement of the building (Fig. 8-32). Vibration from the turbomolecular pumps is small and is minimized by flexible bellows which are arranged in opposition so that no net lateral air pressure loads are placed on the support pedestal.

The basic target chamber and optic support tube can accommodate a variety of two-beam focusing systems as discussed earlier. In the future, we expect to increase the total power by adding two more amplifier lines. The new beams will be polarized orthogonally to the existing beams and will be combined in the polarizer as shown in Fig. 8-33a.

Four beams in a plane can be accommodated by adding new vacuum chamber heads equipped with focusing lenses as fast as $f/1.2$ (Fig. 8-33b).

S. S. Glaros
F. Rienecker
M. Kobierecki

An integrated laser calorimeter package has been designed and 12 units built for use on the Argus laser system. This assembly combines the LC-13 calorimeter core, described in previous reports,³⁰ with a special new electronic module.

The LC-13 calorimeter was designed to replace earlier, more complicated, and more expensive models. It uses commercial semiconductor thermoelectric modules rather than thermopiles made of soldered chromel-constantan wire. These thermoelectric modules give a higher output and have a lower electrical resistance than the thermopiles. This reduces the requirements on the amplifier in the readout system. The calorimeter assembly is neatly housed in a cylinder. All parts are made from readily available aluminum tubing and plate in order to minimize the fabrication costs.

The amplifier section of the Argus calorimeter package was designed to provide a great deal of flexibility to accommodate both current and future needs. This was achieved by using plug-in circuit cards for the amplifier, power supply, and jumper sections of the electronics. This enables various amplifier configura-

tions to be used without changes in the chassis wiring. It also enables the power supply, which normally operates from the 120-V, 60-Hz line, to be replaced by a regulator card taking ± 18 V dc. A servo-card may also be substituted for the jumper card. It is designed to provide automatic zeroing of the amplifier. A similar card could allow for remote (control room) zeroing. Evaluation of these options on Argus will determine the form of future models intended for advanced laser systems such as Shiva.

The LC-13 calorimeter as configured for Argus (Fig. 8-34) is available in three receiver diameters: 25, 38, and 51 mm. The amplifier section has a variable gain control with settings of 10^3 , 10^4 , and 10^5 controlled by a switch on the rear control panel. The noise level, long-term drift, and linearity of the system have been measured and found to be sufficient to insure reliable, accurate laser-pulse energy measurements.

J. W. Houghton
S. R. Gunn
S. W. Thomas

Fig. 8-34. LC-13 laser calorimeter with integrated amplifier.

Seven more compact cameras were completed (six of which are now in operation). Replacement of the avalanche transistors in the sweep circuits by the 2N3700's made by National Semiconductor resulted in much more stable and noticeably quieter operation. Since then mechanical and electrical reliability seems to have been excellent.

A bid package is being prepared for procurement of more of the LLL compact streak cameras from a commercial source. All of the electronic and mechanical drawings have been updated to this end and are now complete.

We discovered that stray magnetic fields from the low-voltage power supplies used in the new cameras were modulating the electron beam inside the streak tube, as evidenced by direct observation on the output phosphor screen. This had no effect on operation in the streak mode as the nanosecond sweep times are much faster than the magnetic field period. However, it did cause a problem during setup on the dc mode when electrical and mechanical focusing are being done. The effect was to blur the output presentation slightly, preventing optimizing the focus. The best resolution obtainable in the past was about 7 lp/mm. The supplies were relocated, orienting for minimum effect, and several layers of magnetic shielding were added between the supplies and tube. The magnetic effect was completely eliminated and the static focusing of the camera can be optimized now to produce better than 14 lp/mm at the streak tube output and 10 to 12 lp/mm at the output of the intensifier.

We continue to have problems in procuring 40-mm microchannel plate intensifiers for the compact streak cameras. To meet program needs, we used four-stage, magnetically focused intensifiers on four cameras. An inexpensive electrostatically focused tube was used on one camera and a relay lens coupled 18-mm microchannel plate tube on another. We also procured an available, subspecification, 40-mm microchannel plate tube which has a very high background noise level but is usable with the Reticon array readout system discussed below.

S-1 cathode slump in the image converter (streak) tube remains a problem. The sensitivity at 1.06 μm decays with time, as reported previously. Measuring sensitivity of the tubes mounted in cameras required downtime for removal of the tube in order to have the measurements made at a laboratory in a distant building. A small portable test set was built to solve this problem. The tube leads are unplugged from the high voltage multiplier and connected to the tester. An ir LED source behind a 1.06- μm bandpass filter is used to illuminate the cathode, and the cathode current is

Fig. 8-35. Width of static streak camera image vs slit width.

measured with a built-in picoamp meter. The output is calibrated to read directly in microamps per watt. The unit was used to measure the tubes in seven new cameras, and the results show a drop in cathode sensitivity of from 2.5 to 10 times over values measured 1 year earlier. However, all still are well above our 5- $\mu\text{A/W}$ sensitivity limit.

We are investigating the use of new design streak tubes which may offer enhanced performance in resolution and linearity in our streak cameras.

Investigation of the contact slit reported on last year continued at a low priority. Since it was then shown that static and dynamic testing gave similar results, a series of slit sizes was statically tested to find the optimum slit size for minimum image width. The work was done at 1.06 μm since diffraction would be most severe here. The results are shown in Fig. 8-35. The image size is nearly independent of slit size from 10 to 200 μm . The image width jitter shown in the figure represents less than 1 ps time jitter. A slit size of 100 μm was selected as producing a minimum image size but also allowing more photons to hit the cathode than the previously used 25- and 50- μm slits, thereby improving the apparent camera sensitivity another factor of 2 to 4. The design of the RCA streak tube currently

used in our streak camera lends itself to the application of this technique because the photocathode is on the tube input window and the multiwire grid structure and electron optics provide image resolution and masking that makes the use of this technique possible for some applications.

An electronic readout system has been devised for the ultrafast streak camera, allowing the hard-copy film and microdensitometer processing to be bypassed for pulse width measurements. This yields the required information in a matter of seconds instead of days. The first system consists of a linear, self-scanned, 512-element diode array proximity coupled to the streak camera output with a fiber optics minifier.

The success of the 512-element array, as reported upon last year²⁸ and in use now for almost 2 years, has

led to further development in this field. A 1000-element array is now being used, and a systematic procedure for attaching a fiber optic extender (straight section) or minifier to the diode array was developed. A micromanipulator in the laser target assembly area was used to position the fiber optics surface to within less than 5 μm of the array surface and hold it there while epoxy glue was applied. Subsequently, it has been discovered that a much less elaborate method can be used. The fiber optics was coated with index matching fluid and then set down on top of the array using tweezers. An eye loop was used to check positioning, and the fiber optics were pressed down by hand until no bubbles were visible through the fiber optics (Fig. 8-36 shows the unit at this stage.) Then a heavy coating of optical coupling compound was laid down over the

Fig. 8-36. Fiber optics extender positioned for gluing onto the Reticon array chip.

Fig. 8-37. Camera with Reticon readout system bolted on rear.

array and connecting leads. Next, 5-min epoxy was applied with a syringe to fill the header and contact the fiber optics while alignment was being monitored. Finally, all but the fiber optics entrance window was sprayed with black paint to block stray light from the sensitive area of the array. Inspection and testing of damaged "reject" arrays (purchased at a considerable discount for assembly technique development) has demonstrated a remarkable ruggedness of the chip. Also, accidental mishandling of the assembled system involving a sizable jolt on the fiber optics input window resulted in no damage to the chip. The line spread function of the completed assembly with the fiber optic

extender input illuminated through a 10- μm contacted slit was less than 26 μm . The amplitude in each adjacent channel was only about 25%, which is comparable to that obtained by a source focused directly on one element. Figure 8-37 shows a streak camera with the system attached.

S. W. Thomas
J. W. Houghton
G. E. Phillips
W. R. McLerran

8.3 Diagnostics Hardware Development

The demands of laser fusion experiments to be able to make quantitative high-resolution measurements over a wide range of physical observables have strengthened our commitment to the applications of the highest possible quality diagnostics capability to our experimental program. These development and application efforts are pursued both "on-line" and "off-line" for maximum effectiveness and flexibility. In addition to the requirement to obtain complete data on each shot our efforts are aimed toward the goals of utilization of diagnostics with spatial and temporal resolution capabilities of $1\text{ }\mu\text{m}$ and 1 ps , respectively. Measurement techniques must be developed and applied to study a density range of 10^{16} to 10^{26} cm^{-3} and a temperature range from 50 eV to 500 keV . In addition to measurements of electromagnetic radiation from the x-ray through ir regions of the spectrum, diagnostics of the charged and neutral particle emissions from laser heated targets are essential to obtain a physical understanding of the interaction processes.

The extension of our ultrafast streak camera technique to the x-ray regime has been refined by new understanding of system performance capability, by time-resolved spectral and x-ray imaging applications to laser-target experiments, and by the engineering design of an improved x-ray streak camera system. Continued applications of x-ray imaging via grazing incidence microscopes and pinhole cameras and the use of new x-ray diagnostics systems including a low

energy x-ray spectrometer with real-time hard copy spectrum presentation have contributed to target diagnostics capabilities. New techniques and applications for time-resolved x-ray diagnostics via fast scintillators as well as x-ray applications of "optical" techniques are being addressed.

New applications of calorimetry and photodiode arrays to studies of the energy balance in laser target experiments were employed this year. In addition to our neutron yield diagnostics a new time-of-flight system for neutron energy spectrum measurements has been designed and is being constructed for use at the Argus facility. Time-of-flight α -particle spectrometers have been implemented and are yielding important ion temperature data on current fusion experiments.

The "Monojoule" laboratory continues to be used as a reliable, valuable off-line diagnostics development facility. Some of the new x-ray diagnostics development is being done using radiation from laser irradiated targets at that facility. Our development of optical probing diagnostics for laser produced plasmas has been pursued at the Monojoule laboratory. Details of accomplishments in each of these diagnostics development areas are presented in the following sections.

L. W. Coleman

8.3.1 SILICON PHOTODIODES FOR SPATIALLY RESOLVED SCATTERED LIGHT MEASUREMENTS

The scattered light distribution from a laser-irradiated target is important for determining the amount of energy absorbed in the plasma and the processes by which it is absorbed. A system to measure the time-integrated angular dependence of the $1.064\text{-}\mu\text{m}$ light scattered from targets irradiated by pulsed Nd lasers has been built and tested. It consists of an array of the small detector packages shown in Fig. 8-38. Each contains a light-sensitive silicon photodiode; a $1.064\text{-}\mu\text{m}$, $100\text{-}\text{\AA}$ bandpass filter; and an ND filter. Light incident on each photodiode forms a number of electron-hole pairs which is proportional to the total light energy absorbed in the diode. The charge is separated by an electric field applied across the detector and then electronically integrated.

Each detector package is calibrated as a unit under

conditions that approximate the experimental mode of operation. A 12-mm-diam , 150-ps , Nd:YAG laser pulse is expanded, recollimated, and apertured to produce a 1.0-cm-diam beam with a uniform energy density. It is split into two parts by a pellicle. The reflected beam, which is totally collected within the 1-cm^2 active area of a silicon photodiode, is used to monitor the relative beam energy from shot to shot. The transmitted beam overfills the 0.11-cm^2 active area of the diode package under calibration. Beam uniformity and diameter measurements are made with a Reticon linear diode array mounted in place of the detector package. Absolute energy calibration of the transmitted beam is done by replacing the diode package with a calorimeter that collects the entire beam.

Because the photon energy of $1.06\text{-}\mu\text{m}$ light is less

Fig. 8-38. Si photodiode detector package. The parts of the package from left to right are the housing, photodiode, spacer, bandpass filter, spacer, ND filter, spacer, and cap.

than 0.1 eV greater than the bandgap of Si, the photodiode response to this radiation has been carefully examined. The absorption coefficient is 0.1 cm^{-1} and rapidly varying with wavelength. In our detectors, which are $300 \mu\text{m}$ thick, the energy is deposited quite uniformly throughout the active volume, whereas visible light is deposited within the first $10 \mu\text{m}$ of the front surface. A measurement has been made to show that the detectors are operated with sufficient reverse bias voltage to insure complete charge collection. Calibration stability over a 6-month-use period was found to be excellent. However, calculations indicate that the calibration is strongly temperature dependent ($\sim 0.5\%/^{\circ}\text{C}$ at 300°C for $1.06\text{-}\mu\text{m}$ light). Measurements show that the diodes are linear to power densities over 10^9 W/cm^2 for 150-ps pulses. The detector package with an appropriate ND filter may be used to measure pulsed power densities in the range between 1 and 10^9 W/cm^2 .

Arrays containing 20 to 40 detector packages are used to map the angular distribution of the $1.06\text{-}\mu\text{m}$

light scattered from targets at our irradiation facilities. Inside the plasma chamber, the diodes are mounted on sets of semicircular rings which contain diode mounting holes spaced every $7\frac{1}{2}^{\circ}$. No diodes can be placed in the cone subtended by the focusing lens system because they would block the incident laser energy. The scattered energy in this cone is measured with diodes placed outside the target chamber. Energy scattered back through the lens is collimated and directed towards the diodes by a set of beam splitters. Two computer codes have been written for use with the diode arrays. One handles the preshot preparation, and the other does the data analysis which includes generation of the energy distribution curve and an estimate of the total scattered energy for each target shot. Data taken with diode arrays at our target irradiation facilities are illustrated and discussed in Sec. 8.5.7.

R. A. Lerche
D. W. Phillion

8.3.2 SCATTERED LIGHT CALORIMETER

The photodiodes used to probe the scattered light usually show a highly structured, three-dimensional distribution. The number of these instruments required to obtain an accurate value of the total scattered radiation thus becomes quite large.

Hence, a calorimeter in the shape of a hollow cube has been built and used to integrate most of the $1.06\text{-}\mu\text{m}$ photon flux emanating from laser-imploded targets in the Janus facility; a cross section is shown in Fig. 8-39 and a photograph in Fig. 8-40.

The absorbers are BG-18 glass, which is also used for $1.06\text{-}\mu\text{m}$ beam calorimeters.^{31,32} $1.0 \times 50.8 \times 50.8$ mm. These are cemented to copper plates which serve to give nearly uniform lateral distribution of the heat in each of the six absorbers. Each copper plate bears a wire heater for electrical heating calibration, and the temperature rise of the copper, relative to an aluminum heat sink, is measured by two semiconductor thermoelectric modules.³³

The end panels have large holes to admit the beams, the top has a hole for the target holder, and the sides and

bottom have smaller holes to permit target viewing and simultaneous use of other diagnostic instruments (usually an x-ray microscope and x-ray K-edge filter detectors). The absorbers subtend 79.5% of 4π sr about the target point. A small amount of radiation is lost through the holes after surface reflections from the shield. In addition, a calculated 0.4% of isotropically distributed radiation from the target would be lost through the holes after one first-surface reflection from the BG-18. Multiple reflections occur within the cube and, hence, except for a small absorption loss in the particle shield, all the radiation scattered towards the BG-18 is absorbed. The effective absorption is $97 \pm 1\%$.

The cubical shield, of Pyrex 0.9 mm thick and 38.1 mm on an edge, prevents particles and x rays below 10 keV from reaching the absorbers. It is fitted with six fine-wire thermocouples, in various locations, to permit estimation of the local particle and x-ray flux density. Its transmission to $1.06\text{-}\mu\text{m}$ radiation is $92 \pm 1\%$.

In the Janus system the focusing lenses have a

Fig. 8-39. In the box calorimeter the scattered $1.06\text{-}\mu\text{m}$ radiation heats a BG-18 absorber. Particles and low-energy x rays are stopped by the "ion shield."

Fig. 8-40. The LC-16A box calorimeter viewed from one of the beam holes. On the top right-hand corner of the ion shield one of the thermocouples used to monitor particle and x-ray energy is seen.

collecting angle equal to 13.6% of 4π , and the energy scattered towards these lenses is measured by laser calorimeters.^{23,33} Using these calorimeters with the box calorimeter, it is therefore possible to measure the scattered energy over 93.1% of 4π .

The energy absorbed by various classes of targets can then be obtained from the known incident and scattered 1.06- μm radiation. Results are discussed in Sec. 8.5.7.

The six sections were calibrated independently, before assembly, by electrical heating. The output reproducibility was $\approx 1\%$. The half-time for cooling is about 2.2 min in air and is greater in vacuum (as shown in Fig. 8-41).

An effort was made to make the six panels of equal sensitivity, and the average sensitivity of the six sides is 415 $\mu\text{V/J}$. After the calorimeter was assembled, with six heaters connected in series, it was calibrated by electrical heating in the same manner used for the individual sides; the result was 413 $\mu\text{V/J}$. An average of 414 $\mu\text{V/J}$ has been used.

S. R. Gunn
V. C. Rupert

Fig. 8-41. Typical cooling curves in vacuum for the LC-16A box calorimeter. Targets were 80- μm glass microspheres with 2 mg/cm^3 DT fill.

Another way of determining the fraction of laser energy absorbed by the target is to determine directly the energy of the interaction products. A series of calorimeters have been built to measure energy absorbed in laser-imploded targets and re-emitted as x rays, ions, and electrons.

The *double-ended LC-15* is shown in Fig. 8-42. This first version is of twin construction to partially nullify environmental effects. The evacuated target chamber has been found to provide an adequately stable thermal environment for these and the other calorimeters; an additional jacket around the calorimeter is not necessary.

Because of the low sputtering coefficient of aluminum^{31,33} under ion bombardment, the absorber is a disk of aluminum sheet, 25.4 mm in diameter. This is cemented to a copper disk which bears a wire heater for electrical heating calibration. The temperature rise relative to a more massive heat sink is measured by a semiconductor thermoelectric module.

The reflectivity of the surface for 1.06- μm radiation was determined by measuring the response of the calorimeter to a calibrated 1.06- μm incident energy. During experiments, the LC-15 was used in tandem with a Si photodiode. Assuming the scattered 1.06- μm radiation does not vary significantly between the locations of two instruments, the LC-15 calorimeter readings were corrected for the absorbed fraction of 1.06- μm radiation. This latter assumption and the diode precision were the limiting factors in the accuracy of these measurements.

The *differential ring-and-disk LC-17* is shown in Fig. 8-43. This design uses two receivers, one of them shielded against x rays and particles, to provide automatic compensation for energy deposited by scattered 1.06- μm radiation.

The absorbers are aluminum foil; the disk is 19.0 mm in diameter and the ring has a 22.2 mm i.d. and a 44.1 mm o.d. The absorbers are cemented to a disk and a ring of copper bearing wire heaters for electrical calibration. The temperature rise relative to the heat sink is measured by one thermoelectric module on the disk and four on the ring. The four on the ring are connected in parallel, to average the ring temperature, and then in opposition to the one on the disk; a shunt is used so that the effective sensitivities for the disk and ring, per unit area, are equal.

The transmission of the shield was determined in the range 0.8 to 1.2 μm and found to be 91% at 1.06 μm . The reflection of the aluminum absorber at 1.06 μm was determined as for the LC-15 and found to be 89%, so that only 1% of the incident 1.06- μm radiation is included in the differential reading.

The *glass disk, LC-19*, shown in Fig. 8-44, consists of a glass disk which is suspended on the axis of the laser beam, near the front of one of the focusing lenses to measure the high intensity "plume" of x rays and particles which is directed back along that axis.

Fig. 8-42. The LC-15 calorimeter used an aluminum absorber. Corrections for the amount of 1.06- μm radiation absorbed relied on neighboring photodiodes.

Fig. 8-43. The LC-17 calorimeters are self-compensating. In addition, the aluminum absorber is 89% reflective to $1.06\text{-}\mu\text{m}$ radiation.

The disk is of Pyrex-7740, 12.7 mm in diameter and 1.0 mm thick, which is nearly transparent to $1.06\text{-}\mu\text{m}$ radiation (92% transmission). The temperature rise is measured by two chromel-constantan thermocouples; these are cemented to the disk with a small amount of epoxy cement, which also absorbs very little at $1.06\text{-}\mu\text{m}$.^{*} The thermocouple wires also serve as supports for the disk; the reference junctions are located on a mounting ring. No calibrating heater is provided; the calibration is calculated from the masses and estimated specific heats of the materials and the measured sensitivity of the thermocouples.

Fig. 8-44. The LC-19 button calorimeters, transparent to $1.06\text{-}\mu\text{m}$ radiation, are useful where self-compensation is not practical because of size limitations.

At Janus, this calorimeter covered the central 4.6% of the beam. Since it was not shielded from the instant radiation and some absorption would occur in the thermocouple wires themselves, the background correction was determined in place by firing the laser without a target. It was thus found that a correction equal to 0.23% of the total incident energy has to be made to the calorimeter reading.

S. R. Gunn
V. C. Rupert

8.3.4 NEUTRON DIAGNOSTICS

The primary objective in seeking efficient absorption of laser energy into a target is to produce thermonuclear fusion. Hence, the success of an experiment is measured by the yield of the reaction products: neutrons and alpha particles.

Scintillation detectors are being used on a routine basis to make neutron-yield measurements at the Janus and Cyclops target irradiation facilities.²⁸ Each detector consists of a fast plastic scintillator 17.8 cm in diame-

ter, 10.2 cm thick, optically coupled to a pair of Amperex XP2020 photomultipliers and has a 4-ns FWHM response to a single neutron event when coupled to a 7903 oscilloscope. A minimum of two detectors per facility, placed at distances of 2 to 6 m from the target, provide detection capability for the range between about 10^8 and 10^9 source neutrons per shot. At these distances, the time-of-flight for a 14.1-MeV DT neutron to reach the detector is 30 to 90 ns greater than for an x ray. Thus, the x-ray and neutron signals are well separated in time. A photograph of a typical oscilloscope trace is shown in Fig. 8-45.

At the Argus facility, neutron yield measurements

^{*}A sample of epoxy, several times thicker than that used here, was spread on a glass sample, and the transmission of the assembly was measured using a $1.06\text{-}\mu\text{m}$ laser and a calibrated power meter.

Fig. 8.45. Oscilloscope trace showing x-ray pulse, (n,γ) pulse from chamber wall, and 14.1-MeV neutron pulse. On this shot the detector was located 319 cm from a target that had a yield of 6×10^6 neutrons.

will initially be made using scintillation detectors mounted 4 and 7 m from the irradiated targets. Detector packages are on hand, and mounting hardware is being constructed. When DT yields reach about 10^8 neutrons per shot, the measurement will be made using neutron activation techniques with the $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ reaction which has a relatively large cross section and about a 10.8-MeV threshold which provides excellent discrimination against scattered events. The resulting ^{62}Cu isotope decays predominantly (97.5%) by positron emission with a 10-min half-life. Coincidence counting of the resulting two 0.511-MeV annihilation gamma rays provides reasonable count rates while minimizing background count rates. This technique is particularly amenable to automated operation through interfacing to the Argus data acquisition system described in Sec. 8.4.4 of this report. Electronic equipment for the coincidence counting system is on hand.

One of the immediate goals of laser fusion research is to provide additional confirmation of the origin of the DT neutrons emitted from targets irradiated and compressed by short-duration, high-intensity laser pulses. This can be accomplished directly by measuring the energy distribution of the DT reaction neutrons. The 100- μm size and subnanosecond interaction time of the laser-produced plasma makes possible the use of time-of-flight (TOF) techniques to measure the line shape. Basically, the time of arrival, t_a , of a neutron emitted by a temporal and spatial point source at a detector located a distance D away is determined by its energy. A small spread in neutron source energies about a mean energy E_n results in a time dispersion at the detector of Δt .

A two-beam, 45-m TOF spectrometer to measure the DT neutron energy spectrum on a single laser shot with a resolution better than 150 keV FWHM (which corresponds to a plasma temperature of 1 keV) has been designed.³⁶ Two radiation shields (H_2O tanks) 1 m thick, 4 m wide, by 2 m high and collimators are used to minimize the effect of scattering from the target chamber, air, ground, and any other structures or equipment that might be placed near the experiment. The collimator and shields are located 7, 13, and 43 m from the target. To minimize the signal attenuation, a 43-m evacuated line-of-sight pipe is provided between the target and detector. All air vacuum interfaces are provided with thin Al windows.

The initial system was designed postulating the use of our standard scintillation detector. Its time response folded with Gaussian time distributions was used to obtain representative output signals for evaluating the TOF system. The line width ΔE of a DT neutron source required to broaden the detector response 0.5 ns vs detector-target distance is shown in Fig. 8.46. The number of source neutrons necessary for 100 neutrons (minimum for an acceptable experiment) to be detected by the scintillation detector is also indicated.

A Monte Carlo neutron-gamma-ray transport computer code³⁷ was used to estimate the effect of neutron

Fig. 8.46. Time-of-flight system energy resolution in keV (corresponding to 0.5-ns signal broadening) and required neutron source strength vs target-to-detector distance. Detector is a 17.8-cm-diam, 10.2-cm-thick plastic scintillator with a 4.5-ns FWHM time response.

Fig. 8-47. Effect of shielding and time discrimination on the ratio of signal counts to background counts. Scattered background events originate primarily within shaded areas.

scattering and neutron reactions with structures in the vicinity of the flight path on the ratio of signal events to scattered events (S/N). The results of the study of air scattering, shielding, and time discrimination for a 50-m system are summarized in Fig. 8-47. For a system which contains only a source, a detector, and air a S/N ratio of 3 is expected. The addition of a 1-m-thick, 1-m-radius shield 4 m from the source improves the S/N ratio to 16. Events which arrive significantly after the DT neutrons are of no interest, thus time discrimination may be used to eliminate some scattered events. For the air scattering case, if only events which arrive within 20 ns of the DT neutrons are counted, the S/N ratio is 10. Time discrimination is approximately equivalent to considering scattering centers within an ellipse in which the distance from the target to the ellipse surface to the detector is equal to the detector-target

distance plus the distance a neutron travels in 20 ns. The combination of shielding and time discrimination yields a S/N ratio of 55. Background events are particularly detrimental because they arrive at the detector after the unscattered DT neutrons and contribute directly to signal broadening. A 10 to 20% (0.5 to 1 ns) signal broadening can be totally masked by a 10% background. The experiment hardware has been designed and is expected to be installed and operational at the Argus facility in the spring of 1976.

R. A. Lerche
L. W. Coleman
J. W. Houghton
G. R. Tripp
W. R. McLerran

8.3.5 AN ALPHA-PARTICLE SPECTROMETER

A α spectrometer was designed and built to measure the α particles from the DT reactions in the glass microshell implosions. The purpose of the instrument was to do a time-of-flight measurement of the α

particles to determine their energy distribution. From the energy distribution the ion temperature of the DT plasma can be calculated. The experimental results are detailed in Sec. 8.5.9.

The experimental setup is shown in Fig. 8-48. Note that the detector is far (276.75 cm) from the source of α particles, thus effecting a large energy dispersion. The energy resolution of the system is:

$$\Delta E = 2E \frac{\Delta t}{t}$$

where t is the α particle flight time, E is the α particle energy, and Δt is the detector time resolution (FWHM). Thus, for example, for a 3.3-MeV α particle with $\Delta t = 4$ ns, and $t = 207$ ns,

$$\Delta E = 130 \text{ keV.}$$

The electromagnet is set at 0.56 T and is used to separate the α particles from the more intense light, x-rays, and electron beams. The energy range of the instrument is 2.6 to 3.9 MeV for α particles. The experiment was designed so that α particles in this range that pass through the entrance aperture of the magnet are deflected by the magnetic field onto the scintillator. Thus, the geometry for determining absolutely the total number of α particles emitted from the source is well known. The drift tube has baffles to minimize the background signal from light and x rays. The entire pipe is pumped to 10^{-5} Torr. The scintillator is 10-mm-thick, bare NE 111 fluor coupled to an Amperex 2106 photomultiplier tube. The calibration of the pulse arrival time and the measurement of the time width of the photomultiplier were made with the detector in its shot configuration and with the same Tektronix 7904 oscilloscope and cables used to take the data. These timing calibrations were done with light from the laser operated at low power. The light was frequency doubled and reflected from the center of the chamber to the detector. With these calibrations, the arrival time of the α particles can be determined to ± 1 ns.

The scintillator photomultiplier was calibrated absolutely with 5.8-MeV α particles from a ^{210}Po source. To apply these calibrations at lower energies, a semiempirical relation by Birks³⁵ that relates the light emitted from the scintillator to the range of the α

Fig. 8-48. Experimental setup for alpha-particle detection.

particle in the scintillator material was used. The ranges used were from Nuclear Data Tables.³⁹ (Recently this semiempirical relation was confirmed by experiment by reducing the energy of the 5.8-MeV α particles with a known air path. The calibrations were done in the region of 1.9 to 5.8 MeV.) The time response of the detector for counting individual α particles was measured to be 4 ns FWHM. This was used to correct for instrument response in determining the time-of-flight spreading of the α particles from the plasma.

V. W. Slivinsky
K. G. Tirsell
S. S. Glaros
D. E. Campbell
H. Catron

8.3.6 MULTICHANNEL X-RAY MICROSCOPY OF LASER FUSION TARGETS

The x-ray emission from laser fusion targets provides data from which may be inferred implosion symmetry, energy absorption, volume compression, and various other plasma parameter distributions associated with the implosion event. Our diagnostic capability to spatially, temporally, and spectrally resolve this emission was significantly improved during

the past year. The following section describes our efforts to further refine our x-ray imaging techniques.

During 1975, several multichannel grazing incidence x-ray microscope systems were absolutely calibrated and routinely operated on the Janus and Cyclops laser-target irradiation facilities. These instruments exploit the total reflection properties of x rays at grazing

incidence and use the Baez-Kirkpatrick focusing scheme to image the x-ray emission from laser fusion targets. The Baez-Kirkpatrick x-ray lens, as illustrated in Fig. 8-49, consists of two orthogonal cylindrical mirrors whose effective focal length equals one-half the product of the mirrors' radius of curvature and the sine of the grazing incidence angle. X rays from the source which are reflected from both mirror surfaces form an astigmatic point-to-point image. The high-energy cutoff property of total x-ray reflection and the low-energy absorption characteristics of x-ray filter materials allow one to define discrete "energy windows" for multichannel simultaneous viewing of the target emission. In practice, four-channel sensitivity is realized by superimposing various filter materials on four cylindrical mirrors of different surface composition arranged in a square array. In this configuration, four individual x-ray lenses are defined at each corner of the array.

The properties of these four channel instruments are:

Object distance	229 mm
Grazing incidence angle	1.0
Focal length	19.7 m
Magnification	3
Solid angle	2×10^{-7} sr
Mirror surfaces	SiO ₂ , Ni
Filter materials	Al, Ni, mylar
Energy channels	0.8, 1.5, 2.5, 3.0 keV

The reduction of micrograph images to spatially resolved emissivity data requires an absolute calibration. Our calibration efforts included an evaluation of the spatial resolution and spectral response functions of the instrument. Resolution measurements were made using the standard technique of backlighting wire

Fig. 8-49. Grazing incidence x-ray focusing principles.

meshes with an extended x-ray source. The x-ray micrograph of two superimposed 1000 line/in. electroformed nickel meshes is presented in Fig. 8-50. Densitometer traces across regions where mesh lines intersect imply spatial resolution of approximately 3 to 5 μm in the area of best focus. Better than 10- μm resolution is observed over a several hundred micrometer field of view.

The spectral response functions for each of the four energy channels are the convolution of the x-ray mirror reflectivities and the x-ray filter transmissions. Reflection efficiency measurements for the nickel and glass mirrors were made with fluorescence x rays from a Henke tube source which ranged in energy from 0.7 keV (L line of iron) to 3.2 keV (L line of silver). The emission from this source was collimated and the individual mirrors were oriented at the 1° grazing incidence angle with respect to the incident beam. The reflection efficiency was calculated from the measured incident, reflected, and background counting rates, taking into account the geometry of the slits used to define the incident and reflected beams. These reflectivity data, squared to take into account the double reflection, are combined with the appropriate filter

Fig. 8-50. X-ray micrograph of resolution grid.

Fig. 8-51. Spectral response functions of the four-channel x-ray microscope.

transmission functions to derive the separate channel response functions reproduced in Fig. 8-51.

Using these calibrations in conjunction with previously measured x-ray film sensitivity, spatially resolved emissivity contours and integrated x-ray spectral data may be derived from the experimental micrograph

images of laser-irradiated fusion targets. Figure 8-52 illustrates a typical microsphere target onto which 27 J of 1.06- μm laser light were focused by the f/1.1 optics of the two-beam Janus facility. The color-enhanced image of the target emission seen through the 0.8-keV channel clearly delimits two emission regions: one

0.8 keV micrograph

Iso-emissivity (10^9 erg/cm^2) contours

Fig. 8-52. Typical x-ray microscope data.

associated with the initial laser-plasma interaction at the original diameter of the spherical target, the second emanating from the imploded central core region. The isoemissivity contours corresponding to this exposure and calculated from the MISE code described in Sec. 8.4.7 are also presented.

Equivalent isoemissivity plots for each of the other three microscope energy windows have also been integrated to provide spectral information based on the micrograph exposures. Advantage may be taken of the

spatial resolution provided by the microscope to consider only the emission from specific regions of the target. Spectral data so calculated, including emission only from the imploded core region, are shown in Fig. 8-53. Also included in the figure are spectral results from three other independent x-ray diagnostics. Agreement among all the results is excellent.

M. J. Boyle
T. L. Harper

8.3.7 HIGH-RESOLUTION LARGE-THROUGHPUT X-RAY MICROSCOPES FOR TARGET DIAGNOSTICS

The simple four-channel Baez-Kirkpatrick, x-ray microscopes described in the preceding section function with a magnification of 3 and a spatial resolution of about $5\text{ }\mu\text{m}$ due to their small apertures, large f numbers (f 2000), and the geometrical aberrations inherent in their design. The next generation of high power (> 1

TW), high compression ($\zeta R \sim 0.3\text{ g/cm}^2$) laser fusion experiments will require improved spatial ($\leq 1\text{ }\mu\text{m}$) and temporal ($\sim 1\text{ ps}$) resolution of the x-ray imaging diagnostics to resolve fundamental questions regarding the symmetry and compression characteristics of the implosion phase of spherical laser fusion targets.

Fig. 8-53. X-ray spectral data.

Fig. 8-54. Wolter type I x-ray microscope schematic.

Axissymmetric x-ray microscope designs are theoretically capable of providing such submicrometer resolution over a several hundred micrometer field of view. Furthermore, the increase in collecting solid angle afforded by the axissymmetric design increases the sensitivity of large magnification systems without significant loss of resolution. These high-magnification x-ray imaging systems will enable us to effectively couple the microscope's improved spatial resolution capability with the temporal characteristics of fast x-ray streak and framing cameras. In this manner, 1-D and 2-D time-resolved x-ray emission data of laser fusion target implosion events will become available.

The design of grazing incidence axissymmetric x-ray microscopes is based upon the reflective and focusing properties of coaxial and confocal conic sections. The Wolter Type I x-ray imaging system consists of a hyperboloid-ellipsoid mirror pair. The imaging properties and design principles of this mirror pair are best illustrated in Fig. 8-54. X rays from a point source located at the focus of the hyperboloid's negative branch, F_{1H} , and incident upon the fore hyperboloid surface, form a virtual image at the common focus of the hyperboloid-ellipsoid mirror pair, F_{1H} , F_{1E} . The subsequent reflection from the aft ellipsoid surface re-images these rays in the conjugate focal plane of the ellipsoid, F_{2E} . Appropriate aperturing and baffling are provided to screen radiation not incident upon the microscope mirror pair surfaces.

Design equations, whose input parameters may be expressed in terms of specific experimental requirements, are derived from a straightforward geometrical representation of the hyperboloid-ellipsoid mirror pair and the focusing properties of these conics. The design equations are derived for the case of "balanced angles" in which the grazing incidence angles at each reflecting

surface are approximately equal. This minimizes the total reflection losses and determines the dimensions and figure of the hyperboloid and ellipsoid surfaces when the object distance, D , magnification, M , grazing incidence angle, α , and subtended solid angle, Ω , of the instrument are specified. Only the length of the aft ellipsoid conic section remains undetermined and is subsequently calculated by requiring all the rays from the on-axis object point to experience a second reflection off the ellipsoid surface.

Two specific design calculations have been considered to date. Because of the mechanical constraints imposed by the LLL laser fusion target chambers, microscopes are designed for object distances of 300 mm. The x-ray reflection properties of glass, nickel, and gold surfaces for a grazing incidence angle, α , equal to 1° ensure adequate spectral range coverage between 1 and 10 keV. Collecting solid angles are approximately 7000X greater than our present four-

Fig. 8-55. 6X Wolter microscope resolution vs off-axis object position.

channel microscopes described above and ensure appropriate sensitivity for the larger magnification systems. Magnifications of 9X and 50X were chosen for the prototype models, with the 50X design intended to interface with a fast x-ray streak camera. The calculated designs for these two microscopes are tabulated in Table 8-2.

Figure 8-55 summarizes the results of a design study done under contract by the Perkin-Elmer Corporation investigating the off-axis resolution of this class of microscope. Geometrical aberrations limit the off-axis spatial resolution of the system since the diffraction limit at the x-ray wavelengths of interest is insignificant. The results of Monte Carlo ray tracing code calculations presented in Fig. 8-55 indicate submicrometer spatial resolution over $\pm 200 \mu\text{m}$ field of view. The theoretical resolution at $100 \mu\text{m}$ off-axis is calculated to be $\sim 0.1 \mu\text{m}$. In practice, however, it is well recognized that the ultimate microscope resolution will be determined by manufacturing tolerances and mirror surface quality. The submicrometer resolution requirements demand local slope errors less than $2 \mu\text{rad}$ and figure displacements within $100 \text{ \AA}$. Surface polishing to minimize the effect of x-ray scattering must

produce less than $50\text{-\AA}$ rms axisymmetric surfaces in order to approach the theoretical resolution. The image degradation due to the actual fabrication tolerances must be superimposed on Fig. 8-55.

Several prototype models of the 9X design have been fabricated in-house to evaluate micromachining techniques with respect to the manufacture of these high-precision x-ray optics. The x-ray mirror pairs are fabricated from cylindrical beryllium blanks whose interior surfaces have been electroplated with a copper substrate. The surface figure of the hyperboloid-ellipsoid mirror pair is machined into the substrate using a numerically controlled single-point diamond-turning machine. A several thousand angstrom coating of electroless nickel is plated upon the copper and polished to better than $50\text{-\AA}$ rms. A photograph of one of the first 9X axisymmetric x-ray mirror pairs is seen in Fig. 8-56. Calibration of this mirror pair to evaluate its imaging and scattering properties is presently underway.

M. J. Boyle
H. G. Ahlstrom
T. L. Harper

8.3.8 ACTIVE READOUT KAP X-RAY SPECTROMETERS

Diffraction crystal spectrometers are commonly used to determine the spectral distributions of x rays radiated by laser-induced high-temperature plasmas. We describe here a spectrometer that uses an x-ray-sensitive, spatially resolving solid-state detector known as the self-scanning photodiode array (SSPA) to sense the intensity of radiation dispersed by an analyzing crystal. The region of coverage of the instrument is from 1.8 to 2.2 keV, which includes the resonance and

satellite line radiation of highly ionized silicon emitted by laser-heated glass microsphere targets.

The key components of the spectrometer, shown in Fig. 8-57, are a lighttight beryllium window, a flat potassium acid phthalate (KAP) analyzing crystal, and the SSPA detector. The detector samples the x-ray dose at 512 semidiscrete PN photodiode junctions along a 13-mm active length. The SSPA is a planar silicon device, built with the MOS technology, which incorpo-

Table 8-2. 9X and 50X hyperboloid/ellipsoid x-ray microscope design parameters

Grazing incidence angle = 1.0°
Object distance = 300 mm
Subtended solid angle = 4.2×10^{-4} sr

	9X design		50X design	
	Hyperboloid	Ellipsoid	Hyperboloid	Ellipsoid
Fore radius (mm)	18.09	18.87	19.75	20.56
Aft radius (mm)	18.87	19.06	20.56	20.83
Length, (mm)	17.17	18.11	15.82	16.70
a (major semi-diameter) (mm)	187.76	1690.72	156.32	7824.27
e (eccentricity)	1.000878	0.999903	1.001149	0.999977

Fig. 8-56. X-ray mirror pair for a 9X axisymmetric x-ray microscope.

Fig. 8-57. Schematic of the active-recording crystal spectrometer.

ates a scanning circuit near the array that sequentially biases and reads out the photodiodes. We have found that the SSPA detector had adequate sensitive to low-energy x rays. Figure 8-58 demonstrates the calculated and measured sensitivities of the detector. The low energy sensitivity is comparable to that of Kodak type M x-ray film.

The wavelength discrimination of the spectrometer is obtained by using the KAP diffraction crystal. Divergence of radiation from the laser-lated target causes x rays to be incident on the crystal over a small

Fig. 8-58. X-ray sensitivity of the self-scanning photodiode array.

Fig. 8-59. Typical spectrum recovered by the active-recording spectrometer at the Cyclops laser facility.

range of angles. The Bragg diffraction condition separates out the spectral components that are reflected to the SSPA detector. The range of photon energies dispersed onto one element of the detector has a spectral width of 1 eV.

A digital data system has been built to recover data from the spectrometer. The signal levels from the detector are digitized and loaded into a solid-state memory. A microprocessor controls the distribution of

data from the memory to several output devices.

The spectrometer has been used on a series of laser fusion experiments at the Cyclops laser. Figure 8-59 is a typical spectrogram recovered by the instrument. The data compares favorably with that obtained with photographic film-recording spectrographs.

L. N. Koppel
L. M. Richards

8.3.9 TIME-RESOLVED X-RAY EMISSION

As described elsewhere in this report, a detailed knowledge of x-ray emission from laser-irradiated targets is one requisite for understanding the implosion process. The parameters of present-day implosion studies require us to provide spectrally defined x-ray emission data with space-time resolutions of micrometers and picoseconds. In this section we describe the use of our ultrafast x-ray streak cameras¹⁰⁻¹² to obtain these data. Significant progress with this camera has been made during the past year in defining it as a quantitative instrument, implementing it for time-resolved K-edge filter measurements, and adapting it for time resolved (pinhole) compression measurements.

The x-ray streak camera used for these studies was described in the previous annual report.¹⁰ In addition to that camera, two additional cameras of new design have been constructed which employ a demountable photocathode x-ray streak tube. This feature allows direct replacement of the photocathode assembly in the event of damage to a cathode assembly or to meet changing spectral requirements. Figure 8-60 is a photograph of the new demountable x-ray streak tube.

The new x-ray streak camera design has been completed. Extensive design modifications have reconfigured the camera into a compact, engineered system. The size and weight have been reduced, which in-

creases its portability and usefulness to experimenters. All the electronic circuits, power supplies, and control functions are now contained within the camera body itself. The old cumbersome umbilical cords to external electronic components have been eliminated. The new camera configuration is flexible in that it can be adapted for use with either a multistage electrostatically focused image intensifier or the more efficient, proximity focused microchannel plate image intensifier. Figure 8-61 is a photograph of the new ultrafast x-ray streak camera mounted on the target chamber at the Monojoule laser facility.

The basic streak camera was described in the 1974 Laser Program Annual Report. It is a modified version of the LLL ultrafast optical streak camera, in which the optically sensitive photocathode is replaced by an x-ray-sensitive 100-Å-thick layer of gold evaporatively deposited on an 8- μ m beryllium substrate. This cathode is sensitive to x rays in the 1- to 10-keV range with energy-dependent quantum yields of several percent. The sensitive area of the cathode is defined by a 0.125- $\times$ -10-mm slit. The vacuumtight camera operates

in the transmission mode, allowing it to be quickly and easily moved from one test chamber to another. Measurements with overlaid metal foils indicate a streak tube spatial resolution of 130 μ m at the cathode. The temporal resolution, as determined by direct observation of sharply rising x-ray emission, is 15 ps. This value is essentially independent of x-ray energy in the 1- to 10-keV regime, indicating that photoelectron emission is dominated by a strong secondary group. These observations have been confirmed by recent direct measurements of electron emission spectra from x-ray-irradiated gold cathodes. In experiments at the University of Hawaii,⁴³ the electron energy distribution from our cathode is observed to have a 6.3-eV FWHM for aluminum K α radiation (1487 eV). The observed distribution is shown in Fig. 8-62. Preliminary observations indicate that this distribution is not overly sensitive to primary x-ray energy. A calculation of streak-tube transit-time dispersion, associated with the electron energy distribution of Fig. 8-62, indicates an overall temporal resolution of the x-ray streak camera consistent with the observed value of 15 ps.

Fig. 8-60. Photograph of the new demountable x-ray streak tube.

Fig. 8-61. Photograph of the new ultrafast x-ray streak camera mounted on the Monojoule target chamber.

Temporally and spectrally resolved x-ray emissions from laser-irradiated targets have been obtained by covering the streak camera slit with a series of K-edge filters. Metal foils and polyvinylchloride are used to obtain filtering by Al, Cl, Ti, Co, Zn, and Yt, with the respective K-edges at 1.6, 2.8, 5.0, 7.7, 9.7, and 17 keV. Double foil thicknesses, in the cases of Cl and Ti, provide a degree of exposure latitude and a convenient check on dynamic response. The response of the chlorine filter is shown in Fig. 8-63; the narrow (300 eV) width is due in large measure to the shape of the x-ray emission spectrum of an irradiated glass microsphere. All other channels are significantly wider. Typical contours of film density vs time, obtained with the filter pack, are shown in Fig. 8-64. The target involved was an 87- μm -diam glass microshell, filled with a 5 mg/cm³ mixture of DT, and irradiated from two sides at Janus by a 28-J, 70-ps FWHM Nd laser pulse. Using measured characteristics of the recording film, the density contours of Fig. 8-64 are transformed to relative x-ray intensity via the X-CAL computer code.⁴⁴ Plots of x-ray intensity vs time are shown in Fig. 8-65 for the chlorine, titanium, and cobalt channels. The quoted energies, 2.6, 4.0, and 5.3 keV, indicate mean values for the respective channels. The secondary rise in these x-ray signals is associated with target core compression and burn. This target irradiation produced 4.6×10^6 neutrons. The computer code LASNEX has successfully modeled this shot in that it reproduces the essential features of Fig. 8-64, including the secondary rise, attributed to core compression. Time integration of the six measured temporal profiles, on this particular shot, shows the relative channel responses to be in excellent agreement with the same spectral ratios as determined by the standard-time-

Fig. 8-62. Experimental measurement of the secondary electron emission from a 100-Å layer of gold irradiated by 1487-eV x rays. (From Henke and Smith, Univ. of Hawaii, and Attwood, LLL.)

Fig. 8-63. Response of the chlorine K-edge filter when folded with the emission spectrum of an irradiated microsphere, and with the response of the gold photocathode.

Fig. 8-64. Density-vs-time contours obtained with the x-ray streak and the filter pack described in Fig. 8-62. Royal-X Pan was used as the recording film. Target irradiation parameters are described in the insert and in the text. Numbers 1 to 4 indicate film density.

integrated x-ray spectral measurements made on each shot. These comparisons presently provide the best commentary on our present understanding of the x-ray streak camera's dynamic response. With regard to temporal resolution, it is interesting to observe in Fig. 8-65 that at early times the x-ray intensity in the 2.6-keV channel is increasing by a factor of 3 every 15 ps. As pointed out previously, this is in agreement with resolution estimates based on the measured photoelectron spectra from the gold cathode.

As described in the previous paragraph, efforts have been made to compare measured and computed x-ray temporal profiles. A significant improvement in these efforts would obtain if, in addition, the data were spatially resolved. To this end, an effort is presently underway to obtain time-resolved pinhole photographs by using the x-ray streak camera in conjunction with an appropriate pinhole imaging system. Our immediate goal is to observe the dynamics of target compression

with space-time resolutions of $10\text{ }\mu\text{m}$ and 15 ps. Because the x-ray streak camera has a spatial resolution of $130\text{ }\mu\text{m}$, we require a fairly large magnification imaging system, larger than presently available with x-ray microscopes. An intermediate solution, employing 50X pinhole imaging, is shown schematically in Fig. 8-66. This system will eventually provide spatial resolution in the approximately $6\text{-}\mu\text{m}$ range. Note that the pinhole in Fig. 8-66 produces an image of the target, with its own emission, on the slit of the streak camera. The output image then displays the r.t characteristic of the implosion, i.e., follows target diameter reduction in time.

As compared with the previously described spectral measurements, these spatially resolved experiments impose the additional constraints of reduced photon flux and accurate alignment of the target-imaging system. With the parameters we now employ, x-ray intensities will be reduced on the average by a factor of 100,

a factor we can readily accommodate, even with the use of a chlorine filter. Pinhole alignment, however, is critical in these experiments. It is evident, upon examination of Fig. 8-66, that a target displacement of 1 radius from the optimum position in a direction perpendicular to the axis of the slit is sufficient to render the image unphotographable by the streak camera. In this displaced configuration the image is just tangent to, and therefore not seen by, the slit. We are therefore required to position the target to an accuracy of a fraction of the target radius, perhaps $5\text{ }\mu\text{m}$ for a $100\text{-}\mu\text{m}$ -initial-diam target. The problem of alignment is basically one of simultaneously dealing with diffraction effects in the x-ray and visible regions of the spectrum. The x-ray pinhole camera required for good spatial resolution is in the $3\text{- to }7\text{-}\mu\text{m}$ range, and is essentially diffraction limited for $6\text{-}\text{\AA}$ wavelengths. Simplicity of alignment demands a visible alignment source at $6328\text{ }\text{\AA}$ (He-Ne), which would be severely diffracted by such a small pinhole. Our solution to these apparently conflicting requirements is to use a composite, or dichroic, pinhole as shown in Fig. 8-67. The pinhole assembly is formed by an overlay of concentric holes. The first is a $125\text{-}\mu\text{m}$ -diam hole in a $6\text{-}\mu\text{m}$ -thick gold foil. Over this is laid a $7\text{-}\mu\text{m}$ -thick sheet of 75% WO_3 phosphate glass. The latter is

Fig. 8-65. Temporally and spectrally resolved x-ray emission from a laser-irradiated microsphere. Spectral widths of the respective channels are 0.3 keV at a mean energy of 2.6 keV (C1), 1.6 keV wide at a mean energy of 4.0 keV (T1), and 2.2 keV wide at a mean energy of 5.3 keV (C3).

Fig. 8-66. Schematic diagram of time-resolved x-ray pinhole photography. Dynamic studies of target implosion are expected to have space-time resolutions of $10\text{ }\mu\text{m}$ and 15 ps .

Fig. 8-67. Optical and electron microscope pictures of the composite x-ray pinhole camera. The pinhole appears as a nondiffracting 125- μm -diam aperture to the optical alignment beam, and as a 7- μm -diam imaging pinhole to keV x rays.

transparent to visible light but opaque to x rays in the region of interest. A small (3- to 7- μm) diameter hole is then laser drilled in the tungsten phosphate glass, concentric with the larger hole, as shown in the lower left of Fig. 8-67. A scanning electron microscope photograph of the smaller hole is also shown in Fig. 8-67. The dichroic properties of the glass are then used to obtain target-pinhole alignment, as shown in Fig. 8-68. The object distance is 1.3 cm and the image distance is 65 cm, giving a 50X magnification. A He-Ne laser and appropriate optics provide an alignment beam which appears to emanate from the streak camera slit and is focused to a waist midway between the pinhole and target. By appropriate clipping of the alignment beam, a convenient set of diffraction rings

appear at the waist. These rings are used to accurately align both the pinhole and target. Successive photographs of an 80- μm -diam microsphere being placed in its proper position are shown in Fig. 8-69. Overall alignment accuracy is estimated to be within 5 μm . Implementation of time-resolved pinhole photography, as described here, is planned at our Cyclops laser-target facility for early 1976.

D. T. Attwood
L. W. Coleman
J. W. Houghton

Fig. 8-68. Alignment scheme for space-time resolved x-ray emission studies. The 6328-Å alignment beam appears to originate at the streak camera slit, passes through the dichroic pinhole as an aligned Airy pattern, and finally is used as a background of concentric rings to position the microsphere target.

Fig. 8-69. Target alignment for time-resolved x-ray pinhole photography. Three successive steps show the alignment of a microsphere in the Airy pattern described in Fig. 8-68. Alignment accuracy is estimated to be within 5 μm.

8.3.10 A NEW CONCEPT IN A FRAMING CAMERA TUBE FOR THE SUB-100-ps RANGE

A new type of framing camera tube adaptable for either x-ray or optical events is being developed. It should have capabilities of sub-100-ps framing time. Figure 8-70 illustrates the basic principle of operation of the tube. The depicted concept is based upon line dissection of an electron image through a multiple aperture plate in an image converter tube. Each aperture in the plate contributes to an image frame. By using synchronized deflection in both the dissection and restoration sections of the tube, the sequentially time-developed line images from the apertures are restored to an electron-image frame at the phosphor screen.

In the particular design prototype tested, slit-shaped apertures are used. The slit width is made equal to the 0.1-mm spatial resolution of the dissection section of the tube. The temporal resolution in this section should be the same as in an ultrafast streak camera tube. In the restoration section the deflectors will contribute to a slight increase in the electron transit-time dispersion. The overall temporal resolution for a given line in the restored image frame is estimated to be less than 10 ps. With unity magnification electrooptical system, a 0.1-mm spatial resolution, and 30-ps/mm scan speed, the frame period is estimated as 60 ps for a 2-x-4-mm (2 mm in the scanning dimension) frame size. The

Fig. 8-70. Ultrafast framing camera.

frame is scanned linearly in time, i.e., a 60-ps time delay occurs between the first and last lines of the frame (frame represents an optical event looking obliquely in time); however, the temporal resolution is still maintained at less than 10 ps. If necessary, unfolding techniques could be used to provide single-timed frames rather than obliquely timed frames, or an alternate aperture plate geometry could be employed.

Experimental work to date has been performed on a demountable prototype three-frame tube with a uv-sensitive photocathode. In this model electrons from the outer dissecting slits are statically deflected by compensator plates to a common crossover at the center of the restorer deflectors. Due to the very low intensity photocurrent (Al photocathode irradiated with a Hg light source), only quasi-static (~ 1 s) tests can be performed in this model. Figure 8-71 shows a restored image (through a single slit) for a triangular-shaped shadow mask at the photocathode. These tests clearly demonstrate the principles of line dissection of the electron image and the subsequent image restoration by synchronized rescanning of the image lines.

Dynamic tests require a high-sensitivity photocathode with a high-intensity light source. In the next tube model being fabricated the photocurrent intensity will be increased by using a Cs-Sb photocathode. Framing speed in this tube should be primarily a function of the deflectors, and should have a frame period of 60 ps.

(a)

(b)

Fig. 8-71. Image restoration tests. (a) Triangular shadow mask. (b) Phosphorescent trace.

Plastic scintillators are commonly used as x-ray and neutron detectors in the laser fusion program. The scintillators typically have response times in the nanosecond ranges so that, while they provide valuable time-integrated data, they are inapplicable to time-resolved measurement on the picosecond time scales characteristic of laser fusion experiments. Recently, it has been reported that when a commercially available NE 111 plastic scintillator is doped with either acetophenone or benzophenone, its fluorescence decay time induced by a 50-ps electron excitation pulse decreases substantially.¹⁵ We have begun carrying out measurements of the fluorescence decay time of NE 111 doped with wide ranges of the above quenchers using a lightpipe/S-20 ultrafast streak camera combination to study laser-generated x-ray excitations of the quenched scintillators. Figure 8-72 shows the temporal pulse shape of a highly quenched NE 111 sample along with an unquenched reference scintillator. The x-ray

Fig. 8-72. The fluorescence of a highly quenched NE 111 along with a standard unquenched NE 111 scintillator. The input excitation is a 200 ps FWHM x-ray pulse generated by a 150 ps laser pulse focused onto an iron target. The quenched NE 111's peak amplitude is approximately 6% of the unquenched reference.

Fig. 8-73. A fiber optics image dissector used to encode a two-dimensional picture into a one-dimensional line pattern suitable for streak camera input. The pinhole microscope and ultrafast scintillator are used to magnify and convert the x rays generated by the target.

pulse is produced by focusing a 100-mJ, 150-ps FWHM pulse of 1.06- μm light onto an iron target at our Monojoule facility. The resulting x-ray pulse has an FWHM of approximately 200 ps. We are continuing to study these scintillators in order to better understand their performance in preparation for diagnostics applications to our fusion target experiments.

A novel use of the subnanosecond scintillator is shown in Fig. 8-73. The purpose of the device is to encode, via fiber optics, a two-dimensional picture into a one-dimensional line pattern¹⁶ which is then suitable for streak camera input. The output data from the streak camera can be reduced from photographic film or directly coupled into an SEC vidicon camera (Sec. 8.4.6) for immediate computer decoding of each scan line into a two-dimensional picture. A 7-by-7-element prototype fiber optics framing camera is presently under construction.

J. Cheng

8.3.12 SUBKILOVOLT X-RAY DETECTION USING FAST FLUORS

A silicon surface barrier detector with a 8.4×10^{-4} cm beryllium window is currently being used¹⁷ as a "calorimeter" to measure x rays with energies greater than 1.5 keV from laser-produced plasmas. Such a detector must have a flat response (taken arbitrarily to be $\pm 20\%$) over its useful range so that the charge from

the detector is directly proportional to the total x-ray energy absorbed regardless of the photon energy. Calibrations done by Gaines and Hansen¹⁸ show that this requirement is met by the 500- μm -thick detector from 1.5 to 10 keV. The surface barrier detector can also be used without its beryllium light shield, in which

Fig. 8-74. Subkilovolt x-ray detector.

case its calculated response is flat down to 400 eV. However, precautions against damage of the silicon must be taken in this case. Moreover, the detector is not calibrated below 1.5 keV. A fast fluor-photodiode detector has been built to complement the surface barrier detector for making subkilovolt x-ray measurements.

A relatively slow fluor-photodiode detector was made up for test on the Cyclops laser facility. The detector is made up of an ITT FW128 photodiode (S4 spectral response), optically coupled to a plastic scintillator "sandwich." This sandwich consists of 1.6-mm-thick NE 102 to detect the x rays, with a 4-mm-thick blue glass filter (Corning 7-59) to cut out the frequency-doubled 1.06- μm scattered laser light, plus a thin (< 1 mm) lightpipe to provide spacing for a

vacuum seal at the face of the fluor (Fig. 8-74). Unlike the surface barrier detector, both the plastic scintillator and the photodiode are insensitive to the high 1.06- μm light background.

Measurements have been made using the detector on various targets in the Cyclops target chamber. For these measurements, a thin (50 $\mu\text{g}/\text{cm}^2$) carbon filter was used in front of the fluor to reduce the intensity of the blue light from the plasma impinging upon the photodiode. (Eventually, we hope to operate without this filter.) NE 102 fluor was used for these initial measurements because it is one of the slower available fluors, thus allowing us to distinguish between fluorescence caused by x radiation and plasma light being detected by the much faster photodiode. Figure 8-75 shows the result from one laser shot. Note the long

delay which is typical of the NE 102 fluor response.

This detector's absolute sensitivity for x rays at 280 eV and from 1.5 to 8 keV has been measured at the L-Division very low energy x-ray facility. This response is shown in Fig. 8-76. It is not flat, and thus would hardly qualify as a calorimeter for x rays with energies less than 1 keV. However, new detector units presently being fabricated will have thin fluors, 10 μm thick, which discriminate against the higher energy x rays. If the calibration wave is modified to account for x-ray transmission through the thin fluor, the new response curve is also shown in Fig. 8-76. This calculated response is flat from 0.1 to 1 keV. The new detector units will be composed of ITT 4014 photodiodes and "quenched" NE 111 fluors. Response times for these units will be ≤ 0.5 ns FWHM, a

considerable improvement over the present detector which has a response of 2.5 ns.

V. W. Slivinsky
G. Leipelt

Fig. 8-76. Response curves for subkilovolt x-ray detector.

Fig. 8-75. X-ray signal from laser-produced plasma.

8.3.13 ULTRAVIOLET PROBING OF TARGET ATMOSPHERES

The plasma atmosphere surrounding targets irradiated by subnanosecond Nd laser pulses is of interest because it is here that energy is absorbed and transported to the core region. Optical probing of the target atmosphere, through interferometry and Faraday rotation, is a powerful diagnostic tool that can be used to characterize this important region. These techniques are used to determine electron-density distributions as well as the possible presence of strong magnetic fields. The shape of the electron-density profile $n(x)$ is very important because it determines the efficiency of both inverse bremsstrahlung and resonance absorption.

Interferometric measurements of $n(x)$ can thus provide a crucial check on the accuracy of LASNEX density profile calculations, and on the importance of self-steepening of this profile near the critical region. Strong magnetic fields, which are detectable via Fara-

day rotation, are significant as they inhibit charged-particle motion and thus inhibit energy transfer to the core region. Computer studies show that this transport inhibition can seriously affect target implosion.

In addition to these quantitative techniques, simple shadowgrams of irradiated targets are interesting in that they provide a graphic description of target integrity and blowoff symmetry during irradiation. Figure 8-77 shows an example of our earliest efforts at 2660-Å probing of target atmospheres. In this rather poorly imaged shadowgram we see a 10- μm -thick disk target which has been irradiated from the right and experienced a rupture: the protrusion of matter is shown on the left side. This is not usually observed on these relatively thick targets, and it is certainly of interest in explaining what might otherwise be described as an anomalous irradiation experiment.

Fig. 8-77. Target rupture detected with a 2660-Å shadowgram. This unusual malfunction occurred when a 10- μm -thick, 150- μm -diam Parylene disk was irradiated with a $\frac{1}{2}$ -J, 150-ps Nd laser pulse. Many other shadowgrams, of similar target experiments, showed no such effect.

To quantitatively examine the general requirements of plasma probing in the uv, we consider typical experiments involving 100- μm -diam targets irradiated by 100-ps, 1.064- μm pulses with on-target optical intensities on the order of 10^{13} to 10^{16} W/cm 2 . In simulations of such experiments, axial scale lengths for electron density are in the 1- to 30- μm range, depending on a variety of parameters. Critical density contours move with velocities from zero (at reversal) to more than 10^7 cm/s, depending primarily on target wall thickness, time of observation, and characteristics of the irradiating pulse.

Figure 8-78 shows the basic scheme in which an irradiated target is probed transversely to determine the properties of the surrounding plasma atmosphere. Typical observations include phase velocity, rotation of the polarization vector, and refractive turning. These in turn provide measures of local electron density via interferometry, magnetic field intensity via Faraday rotation, and critical density contour motion via shadowgraphs. The most significant limitation to these probing measurements is due to refractive turning in the steep electron-density gradient. A simple example serves to illustrate the strong wavelength dependence of this effect. We consider the main laser "heating" pulse

to have wavelength λ_h , producing an electron-density distribution which is Gaussian in the transverse direction and exponentially decaying along the irradiation axis, i.e.,

$$n(r) = n_c e^{-8z^2/L^2} e^{-r/\ell}, \quad (1)$$

where L is the $1/e^2$ transverse diameter and ℓ is the on axis "scale length." If this distribution is probed transversely with a probe beam having wavelength λ_p , as described in Fig. 8-78, simple arguments show that in passing through the critical region (for λ_h) the probe pulse is refractively turned through an angle Θ given by¹⁹

$$\tan \Theta = (0.31) \frac{L}{\ell} \left(\frac{\lambda_p}{\lambda_h} \right)^2 \quad (2)$$

The crucial dependence of turning angle on the square of the wavelength ratio is evident in Eq. (2).

For a 1.06- μm heating pulse, it is clearly advan-

Fig. 8-78. Simplified diagram of uv probing of an irradiated target's plasma atmosphere. The main laser "heating" pulse enters from the right. The probe pulse passes transversely, being refracted through an angle Θ as it passes through the critical region. Refractive effects, which limit these studies, are proportional to the wavelength ratio, λ_p/λ_h , squared.

tageous to use a probe wavelength in the middle uv, rather than in the visible. The severity of the refraction problem is evidenced by a numerical example in which we take a transverse dimension $L = 100 \mu\text{m}$, an axial scale length $\ell = 10 \mu\text{m}$, and use a frequency quadrupled probe pulse such that $(\lambda_p/\lambda_h) = 1/4$. In this case Eq. (2) predicts a refractive turning angle of approximately 11° . Collection of this refracted light, which has passed through the critical region, requires viewing optics with at least an effective $f/2.5$ aperture. Fast collection optics such as this clearly require correction for spherical aberration. A further description of the λ^2 refractive behavior is emphasized in Fig. 8-79, where computer ray traces are presented for frequency-doubled and -quadrupled probe pulses. Only those rays collected by $f/2$ viewing optics are shown. Even with this relatively shallow gradient, $\ell = 30 \mu\text{m}$, the $5320\text{-}\text{\AA}$ probe beam cannot convey information describing the critical region; the $2660\text{-}\text{\AA}$ probe is required to probe the critical density for this parameter range.

In response to the above observations we have set out to develop a probing capability in the middle-uv. The method of production is shown schematically in Fig. 8-80, where we employ the successive use of KDP and ADP crystals to double and re-double a split-off sample of a $1.064\text{-}\mu\text{m}$ irradiation pulse from a Nd laser system. The resultant $2660\text{-}\text{\AA}$ pulse has been used to probe transversely at a variety of delay times between -100 and $+800$ ps. For a 150-ps FWHM irradiation pulse, the probe pulse duration is approximately 100 ps. Efficient frequency conversion permits us to obtain probe intensities of 10^{10} W/cm^2 at the target, a value which is required in some applications, but which can readily damage optical surfaces. This uv probe is presently being used on the Monojoule laser system, in a preliminary fashion, for all three of the basic measurement techniques described: interferometry, shadowgraphs, and Faraday rotation. The basic interferometric technique has been described previously.⁴⁹ We discuss in detail here only the latter.

There has existed for some time reasonable theoretical and computational evidence that laser-generated magnetic fields, of megagauss proportion, are produced by irradiation asymmetries in the critical region of a target atmosphere. A discussion of production mechanisms is given in Sec. 6.6.1. If present, such fields can have a dramatic effect upon charged-particle transport and hence implosion symmetry in laser-driven compression experiments. Indeed, recent Faraday rotation experiments performed at NRL with a $5320\text{-}\text{\AA}$ probing pulse and reported by Stamper and Ripin,⁵⁰ indicate the presence of megagauss fields at densities far below critical. We have endeavored to improve and confirm those measurements by measuring polarization rotation at $2660 \text{ \AA}$ on a single-shot basis with a rotation

Fig. 8-79. The advantage of minimizing λ_p/λ_h is shown in these computer simulations, where we observe that rays collected by an $f/2$ lens contain no information about the critical region for a frequency-doubled probe ($5320 \text{ \AA}$), but do for a quadrupled probe ($2660 \text{ \AA}$). Computations were made with $n/n_c = e^{-r/l}$, $n_c = 10^{21} \text{ e/cm}^2$; $l = 30 \text{ cm}$.

Fig. 8-80. An optical probe beam for laser-produced plasmas is obtained by splitting off a small amount of the main laser beam and then frequency doubling it twice to obtain $\lambda_p/\lambda_h = 1/4$. Overall energy conversion from $1.064 \mu\text{m}$ to $2660 \text{ \AA}$ is typically $\sim 5\%$.

angle resolution of 2° . On the basis of a reasonable density-magnetic field model, this resolution allows us to observe fields well below the megagauss level at a density of 10^{21} e/cn^3 . The basic experiment is shown in

Fig. 8-81. Schematic diagram of a Faraday rotation experiment. The $1.06\text{-}\mu\text{m}$ laser heating pulse is focused to a $100\text{-}\mu\text{m}$ -diam spot on a somewhat larger "lollipop" target. Crossed density and temperature gradients produce a toroidal magnetic field which appears to be wrapped about the heating pulse. Spatial pulse shaping greatly influences field asymmetries and their magnetic field amplitudes. The $2660\text{-}\text{\AA}$ probe enters from the right, experiencing polarization rotation, ϕ , only where a propagation vector is aligned with a component of magnetic field.

Fig. 8-81. The magnetic field is presumably toroidal in nature, driven by a $\nabla n \times \nabla T$ source term. It thus appears to wrap itself around the incident $1.06\text{-}\mu\text{m}$ pulse just off the surface of a small Parylene disk, or

Fig. 8-82. Schematic diagram for detecting Faraday rotation of the polarization vector due to strong magnetic fields. This technique works on a single shot basis.

"lollipop" target. The polarization rotation angle, θ , is seen to be a line integral $\int \mathbf{n} \cdot \mathbf{B} \cdot d\mathbf{s}$, so that only the component of $\mathbf{B}$ parallel to the propagation vector contributes to θ . The scheme for observation of this rotation angle is shown in Fig. 8-82. A telescopic system is used to provide a 30X magnified image outside the vacuum chamber. Use of a Wollaston polarization splitter gives two images, one in the unrotated polarization, and one showing any light rotated by more than 2° . Recorded film densities are then transferred to relative intensities by the use of specially prepared film calibrations, as seen, for instance, in Fig. 8-83, for the wide dynamic range plus-x pan film. Note that this calibration curve was constructed using the relevant 100-ps, 2660-Å pulse, again on a single-shot basis. Curves for the somewhat faster type 103-0 film have also been constructed.

A typical result is shown in Fig. 8-84, for irradiation by a 1-J, 150-ps Nd pulse on the Monojoule laser system. Taken 300 ps after the main heating pulse, the probe photograph shows a rounded target blowoff to the right side of the target. No polarization rotation is detected in the right-side image of Fig. 8-84. Further studies indicate that critical surface motion reverses within 500 ps of irradiation in this parameter range. After studying a large number of targets, both lollipops and microspheres, we conclude that we do not observe magnetic fields of near megagauss value, for 1-J,

Fig. 8-83. Film calibration which permits the technique described in Fig. 8-82 to be quantitatively analyzed by converting film densities to relative exposure. This density vs log-exposure curve was constructed with multiple images of a single, 2660-Å light pulse.

150-ps irradiations. These observations are consistent with computations at LLL using LASNEX, as discussed in Sec. 6.6.1. The reference calculations show that for Porylene disk targets, one requires several

Fig. 8-84. Sample result of a Faraday rotation experiment showing the intense reference image on the left, and the weaker cross-polarized image on the right. The 10- μm -thick, 100- μm -diam target was irradiated by a 1-J, 150-ps Nd pulse. The probe pulse at 2660 Å was delayed 300 ps. Photographs at early time show the focal spot to be approximately 80 μm . The blowoff here is seen to be well developed and symmetric. No polarization rotation was detected in this experiment or in any other experiments with 1-J, 150-ps, spatially Gaussian laser irradiation. Target intensities here are on the order of 10^{14} W/cm 2 .

joules in a 100-ps pulse, delivered to a 100- μm focal spot with a super-Gaussian spatial profile, to produce megagauss fields at critical density. Experiments at that level, and particularly with the super-Gaussian spatial profile, are planned for the Janus laser facility. The computations indicate that the sharper spatial distribution will drive significantly stronger fields than examined to date. Efforts with 2660-Å holographic inter-

ferometry will continue at the Monojoule laser facility. Working at a delay time near that corresponding to critical contour reversal, we hope to measure the density distribution near 10^{21} e/cm 3 .

D. T. Attwood
D. W. Sweeney
L. W. Coleman

8.4 Data Acquisition and Processing

One of the newest and most rapidly evolving areas in the Fusion Experiments Program is in the development and implementation of on-line computer-aided data acquisition and analysis systems. The pace of target interaction experiments conducted at multiple facilities coupled with the broad diagnostics applied to each experiment combine to present a formidable data acquisition and analysis problem. For example, a recent tabulation reveals that the data set from a present laser fusion target experiment comprises 89 oscilloscope traces, 7 computer printouts of time-integrated detector signals, 112 photographic images, and 19 chart records. Although an effective computer-based data management system has been established and was in use during the year, the bulk of the data entries are made manually following conventional reading and

initial reduction of raw data. The use of on-line computer-interfaced data systems on our experiments will provide us with easier interaction with experiments for setup and the capability for a "quick look" at results as well as new local detailed analysis and computational ability.

Related diagnostics developments in the areas of real-time image acquisition and analysis techniques and the processing of a variety of transient analog signals are also required in order to provide complete applicability of the computer systems. Our philosophy is to begin the applications at a level where confidence in the techniques and results is high because of demonstrated hardware and software performance and prior knowledge and experience accumulated with data on the physical parameters being measured. A system will

then evolve in capability at a rate consistent with experimental need and adherence with this philosophy.

We have gained considerable experience with the modest data systems (XLASE) being used at Janus and Cyclops. These systems acquire a variety of time-integrated detector signals for hard-copy readout and are also interfaced to send those data to a CDC-6600 at the LLL Computations Center for analysis and archiving. These systems have been effective in their application.

The new data acquisition and analysis system being developed for Argus represents a significant step up in capability. A more powerful computer system and a new diagnostic system architecture form the basis for a

flexible, user-oriented system designed to provide a variety of diagnostic data acquisition, analysis, and display functions.

Target experiment data acquisition and analysis on Shiva will be analogous to the Argus system. The system will be more complete in the sense that it will be a closely integrated part of the overall Shiva data acquisition and control system. Detailed planning and system definition is underway.

The following sections provide elaboration and details on the topics related to our data acquisition and processing effort.

L. W. Coleman

8.4.1 COMPUTERIZED DATA MANAGEMENT

Master Control Program (MCP)^{31,32} is the data base management system that has been written at LLL and is being used for laser-target-interaction data storage. MCP employs an originally undefined basic program, thus allowing the user to define the data base and management system, to store and manipulate the data. The user is allowed to name and define new data arrays for input and specify formats and list options for data output. Being able to define new arrays for input allows us to expand the data base and allow for new instruments to be added on to our experiments without the foresight of the total number of instruments that will be required and provided for in the data base. The ability to specify formats and list options allows the user of

MCP to bring the data out of the data base and display it in any form that is desired. It also allows the user to manipulate the data as it is being brought out of the data base.

MCP is a program that stores, manipulates, and retrieves data, from a data base, through a user-defined interface. The data is thus stored in the data base in a very compact form and can be added to or altered at anytime, since the interface retains information as to location and format of all stored data. MCP also has commands that allow the user to do searches on the data, where the search may be for minimum or maximum numerical values or for specified alpha characters. The user can thus do a search on any selected set

											PAGE	41
1 MASTER CONTROL		OBJ	LASER OUTPUT /					EDIT		U02/10	14.558	
MC-76-3F										COMMAND	PAGE 39	
SHOT	PWIDTH	EL1	EL2	TEL	POWER	TARGET	NFLUX	ERFLU	EOT1	EOT2		
551103101				0.00								
551103102				0.00								
551112991	153			0.00	20	B140						
551112102	102	30.40	23.80	51.20	530	B149			30.40	23.80		
551112103	110	22.30	17.50	39.80	300	B155	1.00E+06	3.00E+03	22.30	17.50		
551112301	110	15.20	11.90	27.10	290	B156	5.00E+04		15.20	11.90		
551112991	104	32.40	23.40	57.10	300	B157	2.50E+06	6.00E+05	29.10	22.06		
551112992	107	25.70	21.10	46.80	400	B158	1.70E+06		25.70	21.10		
551112993		33.00	26.50	59.50	300	B160	1.30E+06		33.00	26.50		
551112994	67	20.00	15.90	35.90	640	B162	3.90E+06	1.00E+06	20.00	15.90		
551112995	99	21.10	17.10	38.20	370	B161	1.70E+06	6.00E+05	21.10	17.10		
551112996		29.30	22.20	51.50	670	B163	1.00E+04		29.30	22.20		
551112102	153	29.10	20.40	49.50	300	B164	1.00E+04		29.10	20.40		
551112103	75	30.70	22.90	53.60	710	B165	1.30E+06	3.00E+05	27.63	23.61		
551112994	87	2.00	2.00	5.10	30	B167			2.00	2.00		
551112991	102	27.60	22.00	49.60	400	B168	1.90E+05	1.00E+05	27.60	22.00		
551112992				0.00		B173						
551112993	173	18.10	14.60	32.70	190	B173	1.40E+05	5.00E+04	18.10	14.60		
551112994	70	29.00	22.00	51.00	730	B170	1.60E+05	4.00E+04	29.00	22.00		
551112995	168	22.00	17.70	40.30	370	B171	2.50E+05	4.00E+05	22.00	17.70		
551112996	109	33.10	26.10	59.20	550	B172	1.40E+05	3.00E+05	33.10	26.10		
551112991	127	33.70	26.50	60.70	440	B176	6.00E+05	3.00E+05	33.70	26.50		
551112992	95	10.20	8.50	18.50	190	B177	1.70E+04	1.70E+04	10.20	8.50		
551112993	110	31.60	26.10	57.10	570	B180	4.00E+05	1.50E+05	31.60	26.10		
551112994	126	22.30	18.00	40.30	370	B182	1.70E+05	4.00E+05	22.30	18.00		
551112995	112	23.60	19.10	42.70	300	B183	2.10E+05	6.00E+05	23.60	19.10		
551112991	118	35.00	25.60	68.20	600	B179	2.20E+06	5.00E+06	35.00	25.60		
551112992	104	15.50	12.30	27.80	270	B184			15.50	12.30		
551112993		18.50	14.00	30.30		B185	1.00E+04		18.50	14.00		
551112994	102	35.40	27.90	63.30	620	B186	3.40E+06	1.00E+06	35.40	27.90		
551112995	87	25.30	19.00	45.10	810	B189	1.50E+06	5.00E+05	25.30	19.00		
551112996		32.30	25.60	57.90	570	B190	2.40E+06	4.00E+05	32.30	25.60		

Fig. 8-85. Typical master control output ordered by target (date).

```
56021804
SHOT RESUME      TARGET BALL      ENERGY BAL      ION CAL      XRAY DATA      BROOKS      XRAY MIC
NELUX---4.30E+05  TARGETH---148  TEST---36.070  YE---52  TA---52  1.5KEV  LENGTH---2.3
EPLU---9.02E+03  BN---1100  ERT1  PE---340  PA---217  2.0KEV  FILTER---D O
EL1---10.140  CIA---90.00  ERT2  EE---000  EA---000  2.0KEV---1.900E+14  FILT---M M
EL2---17.930  WIP---0.60  EMO  TF---50  TO---50  5.0KEV---6.000E+12  IMAG11
TEL---36.070  EIP---0.03  E351  PF---70  PJ---70  7.7KEV---2.900E+11  IMAG12
P-INTH---39  SATCH---30  E312  EF---50  CB---50  9.6KEV---3.000E+11  IMAG13
P-OLR---900  FILL---2.13  EAT  TO---100  TC---52  17.0KEV---2.000E+11  IMAG14
E311---16.140  COUNT---8883  IOM  PO---0  PC---22  20.0KEV---9.200E+10  POINT---D Y
E312---17.930  M3---41.967  DUE  EH---0  ED---704  51.6KEV  57.5KEV---1.900E+10
FSS  MCF---0.778  THRU  PH---0  PD---202  63.0KEV---1.900E+09
                                     115.0KEV
                                     NOTES---RATIOS ONLY
```

Fig. 8-86. Shot summary output from master control.

Fig. 8-37. The SWELL program provides a variety of displays from digitized photographic data.

of shots and then have MCP present that data. For example, Fig. 8-85 shows the data ordered by shot (date). Another example of the way the data may be displayed is shown in Fig. 8-86 where all the data from any specific shot can be presented in a condensed form.

The output from MCP can be selected by the user to be compatible with any input format to other programs. Parametric or nonparametric analysis of the data that has been stored in the data base can hence be easily performed.

Another data management problem which had to be addressed results, for example, from photographs that have been taken with our x-ray microscopes. These photographs are first read with a microdensitometer and the data are then stored in the LLL computer system. Each photograph is stored as a separate file and must be

identified in such a manner that it is easily accessible to all interested people who have access to the computer. These data can now be retrieved from storage and manipulated with a special program, SWELL, that presents the data as shown in Fig. 8-87, where we see in the upper left an isodensity trace of the image, that was stored on the photograph. In the upper right, we see a 3-D display that can be rotated to examine the image from any angle, whereas in the lower left we see a horizontal cut through the image as seen above and in the lower right a vertical cut. Each of these displays can be specified or changed by the user so as to get a better look at any part of the image.

K. J. Pettipiece
H. E. Eddleman

8.4.2 DATA ACQUISITION PHILOSOPHY

The present general instrumentation philosophy used in the Laser Plasma Interaction Group is summarized in Fig. 8-88. The sensors instrumented fall into three basic categories: internal sensors, flange-mounted

sensors, and remote sensors. All sensors are electrically isolated from the target chamber or building grounds. This required the development of a special BNC vacuum feedthrough for the internal sensors.²³ All sensors

Fig. 8-88. The present data acquisition system handles a large number of analog signals.

Fig. 8-89. Future systems will provide for data digitization near the source and incorporate a computer for near real data processing.

receive their single-point ground at the signal conditioning electronics adjacent to the target chamber or at the main racks in the diagnostics room. The instrumentation system is in turn grounded to a single-point ground rod driven adjacent to the racks. All triggering to the system is by means of optically isolated signal paths. The main system trigger is derived just after the laser oscillator and beamed back to a photosensitive trigger diode located near the diagnostics system.

The computer and related peripherals including the CAMAC instrumentation system (Sec. 8.4.3) are also grounded to the main instrument ground. A fiber optics serial highway link is being developed and will be used on Argus (Sec. 8.4.4) to communicate with remote CAMAC crates located throughout the laser facility.

This will eliminate a major source of electrical noise, namely, ground loops. The fiber optics link mentioned will be capable of a 5-megabit data transmission rate, more than adequate for the CAMAC serial bit highway.

As more of the target diagnostics data become digitized adjacent to the sensors, requirements to run analog signals, via cables, to oscilloscopes will be reduced. We will then see a change to a basic instrumentation philosophy similar to Fig. 8-89. Now system noise problems will be isolatable to much smaller configurations and individual (miniature) screen rooms may be used where required.

D. E. Campbell

8.4.3 THE JANUS AND CYCLOPS DIGITAL ACQUISITION SYSTEMS

Although much of the data obtained during the past year are in the form of oscilloscope traces and photographic records which must be preprocessed before manual insertion in the data base, part of the data stored by Master Control are digitized in real time.

The digital data acquisition systems used at the Janus and Cyclops target-irradiation facilities are electrically identical. A block diagram of the system used on Cyclops is shown in Fig. 8-90. The heart of the system consists of a Digital Equipment Corporation PDP 11/10 minicomputer and a single CAMAC³¹ crate which houses various CAMAC modules including the required controller module. Analog signals are sent to the diagnostic room over multiple twisted-pair cables

where they are multiplexed and digitized by a BiRa 5301/5101 Analog Data System. A high-input-level initiator module has been developed to reduce the possibility of false data being recorded due to spurious triggers. Laser areas are potentially noisy electrically, and strict grounding procedures must be maintained to prevent computer malfunction.

The Janus system has been operational since September of 1974 and the Cyclops system since May of 1974. Both systems have proven to be very reliable. A software package named NLASE³² has been developed which permits the system operator to quickly set up the modules required for a target shot. A multiplier is also entered for each data point to be recorded and these are

Fig. 8-90. Cyclops data acquisition system.

listed on the teletype printout adjacent to the multiplied data listing reducing the possibility of entry errors. A typical setup and data printout sheet is shown in Fig. 8-91. A copy of this printout is supplied to each experimenter for each shot he has recorded data. Both the Janus and Cyclops digital data acquisition systems are now linked to LLL's main computer complex, and

data is transferred from the minicomputers to a temporary storage file at this facility immediately after each target shot and transferred to magnetic tape once each week.

D. Campbell

8.4.4 ARGUS DATA ACQUISITION SYSTEM

The past success with the minimal data acquisition systems on Janus and Cyclops (XLASE), has led to a greater commitment of resources for the development and application of a data acquisition and analysis system for Argus. The XLASE systems were designed only to acquire and store one-dimensional (i.e., time-integrated) data, and so did not fulfill the need for immediate real-time acquisition and processing of a variety of target shot data. The Argus data acquisition system (ADAS) is being designed and implemented with this need in mind.

The system is based upon a Digital Equipment Corporation PDP 11/40 minicomputer and CAMAC interfaces. The first phase of development (ADAS-I), to be operational in Spring 1976, consists of the 11/40 processor with 28K of memory, disks, a graphics terminal, and a CAMAC crate (Fig. 8-92). The second phase to be operational in the Summer of 1976 adds the magnetic tape, printer/plotter, remote terminals, and a CAMAC serial highway, which is depicted in Fig. 8-93.

In the ADAS-I concept, all the data is routed directly into the multiplexed A/D converter in a CAMAC crate (Fig. 8-92), as was described for the Janus/Cyclops systems (see Sec. 8.4.3). The system could, if desired, run the XLASE codes since the same hardware configuration is employed.

In the Spring of 1976, the initial tests of the enhanced ADAS system with CAMAC serial highway are planned in the configuration shown in Fig. 8-93. Initially, the highway is bit-serial at 1 megabit/s data rate through fiber optic cable for ground and high-voltage isolation as well as for noise immunity.

Most new diagnostics, including transient digitizers, will be interfaced via the CAMAC serial highway. Initially, the use of two high-speed transient digitizers

are planned, one in the neutron measurements, and the other for alpha-particle diagnostics. Additional interfaces for Reticon arrays, ion calorimeters, Faraday cup, and other diagnostics will be added within the target and neutron room CAMAC crates.

To attain the flexibility and power desired in ADAS, a completely new software system is being implemented with some new features. The first feature is an interactive command language for operator control of the data acquisition environment. This language allows the operator to specify the experimental configuration for the laser event. Data acquisition CAMAC modules can be added, deleted, modified, and calibrated by simple commands to the system.

Secondly, the operator commands are interpreted by a program written in Basic. The operator sees only those functional commands that have meaning in an experimental environment, but the system is easily modified and upgraded since it is written in Basic. The experimental configuration can be specified to the system by the operator and saved on disk. At any time, the operator can modify an existing configuration to meet varying experimental needs, by simple commands. Calibration of instruments can also be done by default options or dynamically by the operators.

During the laser event specialized assembly language routines will acquire the data through the CAMAC interfaces. These routines will allow the reading of time-integrated sample-and-hold data via a multiplexed analog-to-digital converter at 20 μ s per data point. Once all the time-critical response data is acquired with the assembly language routines the system will return to the higher level programs in Basic. The acquired data will be then stored on magnetic tape and disk memory.

After the laser-target interaction the experimenters will have immediate displays and access to the data. Within minutes the important parameters will be avail-

CAMAC SETUP - RE-ENTER, EDIT, OR LIST -

TYPE SHOT ID, THEN 'GO' - CYCLOPS 603 TARGET#236/HAAS 3/22/76 JSS/EJP
- GO

CAMAC SETUP - RE-ENTER, EDIT, OR LIST -
ARE YOU HAPPY WITH INPUT -

READY TO 'ENABLE' THIS CAMAC - YES
WAITING FOR EVENT

STATION 15 CYCLOPS 603 TARGET#236/HAAS 3/22/76 JSS/EJP

1	-31	9.5000E-02	-2.9450E 00
2	-147	5.0500E 00	-7.4235E 00
3	-142	1.0100E 00	-1.4342E 02
4	-87	1.0100E 00	-8.7870E 01
5	-145	1.0400E 00	-1.5080E 02
6	-71	1.0200E 00	-7.2420E 01
7	-53	1.0000E 00	-5.3000E 01
8	417	5.0000E-03	2.0850E 00
9	215	5.0000E-03	1.0750E 00
10	575	5.0000E-03	2.8750E 00
11	617	5.0000E-03	3.0850E 00
12	982	5.0000E-03	4.9100E 00
13	24	5.0000E-03	1.2000E-01
14	961	5.0000E-03	4.8050E 00
15	122	5.0000E-03	6.1000E-01
16	572	5.0000E-03	2.8600E 00
17	-12	5.0000E-03	-6.0000E-02
18	-24	5.0000E-03	-1.2000E-01
19	0	5.0000E-03	0.0000E-01
20	-23	5.0000E-03	-1.1500E-01
21	-8	5.0000E-03	-4.0000E-02
22	-3	5.0000E-03	-1.5000E-02
23	-3	5.0000E-03	-1.5000E-02
24	-3	5.0000E-03	-1.5000E-02
25	1497	5.0000E-03	7.4850E 00
26	674	5.0000E-03	3.3700E 00
27	1815	5.0000E-03	9.0750E 00
28	148	5.0000E-03	7.4000E-01
29	1235	5.0000E-03	6.1750E 00
30	174	5.0000E-03	8.7000E-01

DO YOU WANT DATA TO G MACH.? - YES

INITIALIZE G MACHINE -

*** G MACH. MODE ***

?

0002.68072 03/22 14:08:44 0007

FILES / 1 1

1000R C3/22:601

Fig. 8-92. The Argus data acquisition system will be capable of basic data processing and provide the experimenter with near real time displays.

Fig. 8-93. In late 1976 a CAMAC serial highway will be added to the initial ADAS.

able. Initially, the applications and analysis programs will be written in Basic with the addition of Fortran-IV by the Summer of 1976.

In ADAS-II, it is envisioned that the experimenters will have full interactive graphics and access to not only the current shot's data but a limited number of other shots as well. The archiving of all target shot data will still be done in the Octopus system with MCP via magnetic tapes written by ADAS and transported to

Octopus. Extensive work is being done to enhance the interactive graphics and flexibility of the ADAS system. Real-time response in analysis of experiments, as well as system response to new experiments and applications, is the continuing goal of ADAS.

J. Greenwood
E. Frerking
D. E. Campbell

8.4.5 SHIVA TARGET DIAGNOSTICS

We have begun planning Shiva target diagnostics data acquisition system (STAS) (Fig. 8-94). The basic system is envisioned to be an upgrade version of the Argus system (ADAS) as well as being an integrated part of the overall Shiva control/monitoring system (see Sec. 3.2.4).

Configured around a minicomputer and CAMAC interfaces, STAS will operate using the resources of the total Shiva system or as a stand-alone system with reduced capabilities. Most of the expensive computer peripherals such as magnetic tape drives, printer/plotters, and interactive color graphics will be

Fig. 8-94. The Shiva target diagnostic data acquisition system will be an integral part of the overall Shiva control/monitoring system.

central resources available to the fusion experimenter and STAS through the main Shiva system. The system controls the target data acquisition and experimental environment and when running stand-alone will store all data on disks for later analysis by application programs. Final archival of data will be done in the main Shiva system.

The Argus systems are being designed to be directly transportable to Shiva, and based upon a real-time task operating system. Only one system's software package is envisioned for eventual Argus, Janus, and Shiva target data acquisition systems. Upgrades to systems and applications software will be developed off-line and then introduced onto one of the systems. When the software is proved useful and reliable in an operational environment it can be incorporated in the other two systems. The data formats and target description conventions are being defined in a general way such that all target data will be forwarded to the Octopus system in a standard manner.

All target diagnostics interfaces will continue to be standardized in CAMAC modules. Particular experiments should be transportable or duplicatable between laser systems. The addition of a CAMAC branch and byte-serial highway is envisioned to accommodate higher data rates and more diagnostics. Single crate failures on the highway should not affect other parts of the system. Employing fiber optic cabling wherever feasible and transformer coupling of all other crates will avoid noise and ground problems. The failure of the minicomputer can be accommodated by a properly designed Shiva controls/monitoring system incorporating a similar series computer such that the bus section with the CAMAC highways could be switched to the other machine. Experience on the Argus system will specify whether this is a necessary system feature for Shiva.

J. Greenwood

8.4.6 IMAGE DATA REDUCTION

Because of the large volume of film data generated in the laser fusion program, considerable interest has been focused on the problem of film scanning and subsequent data reduction, as well as on methods of directly digitizing video data.

A developmental two-dimensional image data analysis system has been assembled which consists of an Optical Data Digitizer (ODD) SEC Vidicon camera interfaced to a PDP 11/40-GT44 interactive graphic computer system. The unique feature of the SEC is its capability to retain an image for over half an hour at room temperature without degradation in image quality. This property, in conjunction with its high cathode sensitivity, enables the ODD to be coupled via fiber optics directly to the microchannel plate image intensifier on an ultrafast streak camera to record a streak image. A two-dimensional digital data array is immediately available after triggering the streak camera. Because of the large volume of data, most of the information is stored on disk. A single 512-point vidicon scan line or an average of several scan lines can then be displayed on the GT44 graphics terminal for analysis. Figure 8-95 shows a typical single-pulse streak camera result obtained with the ODD in the direct coupled mode. Reproducibility of the ODD and data calibration techniques are now being examined.

A second mode of operating the ODD has been investigated. The ODD was coupled with a 55-mm Nikkor lens system in order to study its application for scanning film on a light table. This mode of operation emphasized user-oriented, interactive graphic techni-

ques which would yield a fast turnaround. Necessary software routines and an application algorithm were written and implemented. After extensive study, the ODD was found to perform marginally for this application. The main reasons are traced to the ODD's exposure nonreproducibility and to the scattered light produced by the film. The scattered light problem in effect

Fig. 8-95. The computer output from the optical data digitizer when directly coupled to the microchannel plate output of an S-20 streak camera. The input light is a 0.53- μm , 40-ps pulse from a frequency-doubled 1.06- μm YAG laser.

induces a variable optical density reading which partially depends upon the average brightness surrounding the point being scanned and limits the resolution and dynamic range.

A third application is now being investigated in which the ODP output will be used to generate a

two-dimensional picture facsimile for the hard-copy output or on the CRT screen. This mode conforms well to the computer decoding requirements for a fiber optics image dissector camera now under development.

J. Cheng

8.4.7 COMPUTER ANALYSIS OF X-RAY MICROSCOPE IMAGES

Translation of x-ray images into quantitative target emission characteristics requires detailed computations.

A computer code, MISE, has been written to calculate the source x-ray emission from film data obtained using the LLL two-mirror, four-channel x-ray microscope. Figure 8-96 shows that the analysis goal of source emission is reached by knowing the geometry, magnification, mirror and filter photon energy calibration, film background, and film photon energy calibration. These values have been calculated and are input to the code.

The x-ray microscope film image data is developed with a specified standard technique. Usually, Kodak Type M at 6 min RXR (72°) is used, for which the x-ray photon energy calibration has been determined. The images are then digitized using a microdensitometer and stored in the computer as an x-y array of 256×256 points. Each point contains the relevant total specular film density corresponding to its position on the x-ray image.

The MISE code operates on this digitized file and calculates an average film background from which net

specular density values are determined. Generally, the array size is reduced by using 3×3 point averaging to form an 85×85 point array so that less computer core storage is needed.

Use of the filters and mirror surfaces determines an average photon energy E value over which the image was taken. This photon energy value is used with the film energy calibration values to convert net specular density to ergs/cm^2 at the film plane. At this point contour plots can be made and compared to target design codes, i.e., LASNEX, predictions.

The MISE code also will calculate equivalent source plane emission in ergs/cm^2 by using the mirror and filter energy calibration values at $\bar{E}$ and the experiment geometry and magnification. Contour plots at the source plane as shown in Fig. 8-97 are possible. Here, the target was a $60\text{-}\mu\text{m}$ diam ball-on-stalk target of run 7508-0711, and Fig. 8-97 is for the average photon energy 2.5-keV image.

Several assumptions are inherent in this data analysis procedure. The most important of these are: no time resolution, no correction for internal target absorption, perfect mapping from source to image, uniform

Fig. 8-96. The analysis goal of the x-ray microscope data is to determine the source emission $S(x, y, E)$ knowing: (a) the solid angle subtended by the mirror and filter set, (b) the filter transmission and mirror reflectivity, (c) the system magnification, (d) the background, and (e) the film calibration.

Fig. 8-97. Contour plots of the target emission can be obtained using the MISE computer code. Contour intervals: solid lines, 4.0×10^9 ergs/keV $\cdot$ cm 2 ; dotted lines, 2.0×10^9 ergs/keV $\cdot$ cm 2 ; maximum, 3.973×10^{10} ergs/keV $\cdot$ cm 2 .

film background over position, and average energy quantities used for filter, mirror, and film energy-dependent quantities.

Experimental and calibration uncertainties limit the accuracy of this data analysis technique. The two largest errors appear to be:

- Film energy calibration uncertainties are estimated to be about 20 to 40%.
- Mirror reflection photon energy efficiency uncertainties are estimated to be about 15 to 20%. Other sources of error such as geometry or film background errors are less than the above.

Spatial integration over the entire x-ray image can give some limited x-ray spectral energy information. Figure 8-98 compares x-ray microscope integrated image data with other spectral experimental results. Good agreement with Si-PIN diode spectral data is seen for the three ball-on-stalk targets studied.

T. L. Harper

Fig. 8-98. Spatial integration of the x-ray emission provides some information on the spectrum in the 0.8- to 5-keV range. Here data from three bare ball shots are shown to agree with high-energy data obtained from other experiments.

8.5 Experiments

In the past year target experiments have been performed using three laser systems: Valkyrie, the 50-GW CO₂ laser, Janus, the two-beam 400-GW Nd:glass laser, and Cyclops, the single-beam 1-TW Nd:glass laser. Many hundreds of experiments have been performed using microscopic disk targets, glass microshells 40 to 100 μm in diameter filled with DT gas, and many experiments which are as yet not released by ERDA.

The purpose of the flat-disk target experiments is to study the optical and plasma physics on simple isolated targets. Those experiments have confirmed the non-Boltzmann nature of the electron distribution function and its dependence on the laser intensity. We have also demonstrated a number of plasma phenomena such as beam filamentation, inhibited thermal conduction, and polarization-dependent scattering and absorption of the laser radiation.

The glass microshell targets were used to study the implosion and burn of the thermonuclear fuel (Fig.

8-99). These targets have produced up to 1.2×10^7 14.1-MeV neutrons from the D + T reaction. The yield ratio is quite low, only 10^{-6} . By design the glass pusher is exploded rather than ablatively accelerated to impinge and compress the fuel. This is done to make the implosions insensitive to irradiation symmetry and the temporal shape of the laser pulse. In 1976, Argus will have the capability of delivering uniform, temporally tailored intensity on the target sphere. Then ablation-driven nearly adiabatic compression experiments to high densities will be performed.

The exploding pusher experiments have demonstrated thermonuclear burn of the fuel, and they have been very useful in normalizing the code calculations.

We have implemented an extensive array of diagnostics, most of which are used for every target shot. Table 8-3 lists the diagnostics and the method used to record the data.

H. G. Ahlstrom

8.5.1 LASER IRRADIATION OF THIN PLASTIC TARGETS WITH A 10.6- μm CO₂ LASER

Polyethylene foils and Parylene disks 5 to 10 μm thick have been irradiated by CO₂ laser pulses focused to flux levels in the 10^{13} to 10^{14} W/cm² range.²⁵ These targets are shown in Fig. 8-100. Detailed measurements of the ion, electron (30 to 180 keV), and x-ray emission spectra were made on each shot. X-ray spectra were variable and resembled those reported in Ref. 56. Streak photographs of the blowoff plasma and accelerated foil were made with an S-20 ultrafast streak camera, while a slower STL camera insured that premature disassembly of the target due to a prepulse would be detected.

One of the most striking experimental results obtained was evidence of localized plasma heating, shown in Fig. 8-101, which could be due to trapping and/or filamentation of the laser beam. For comparison, on the left is shown the density contours of an x-ray pinhole photograph of a 1.06- μm laser-produced plasma. Although the 1.06- μm laser beam had several hot spots, there is a notable absence of any detailed features, and the intensity declines monotonically from a central maximum. By contrast, the right side of this figure shows detailed structures smaller than the diffraction limit of the 10.6- μm laser beam.

The results presented in Fig. 8-101 are consistent with the theoretical prediction of laser beam filamentation by Kaw, Schmidt, and Wilcox.²⁷ Figure 8-102 shows the calculated self-focus length and filament width for 1.06- and 10.6- μm laser experiments.

Filamentation is predicted for the 10.6- μm laser beam but not for the 1.06- μm case. The filament width of about 40 to 60 μm is in agreement with the dimensions of the spots observed in the 10.6- μm irradiations. Calculations assuming a Gaussian beam geometry as well as detailed numerical simulations reveal much the same behavior.²⁸

The following figures present additional comparisons between 10.6- and 1.06- μm irradiations of comparable energy and pulse duration. One parameter often measured in 1.06- μm laser-target interaction experiments is x-ray yield. 10.6- μm experiments with I_p in the 10^{13} to 10^{14} W/cm² range have generally shown lower x-ray conversion efficiency and a strong angular dependence as shown in Fig. 8-103. This implies that the bulk of the 10.6- μm heated plasma was simply not heated to temperatures typical of comparable 1.06- μm shots.

Substantial light refraction around instability-dominated plasmas in the 10.6- μm case is suggested by the charged-particle spectra shown in Fig. 8-104. This figure compares electron emission spectra taken at 45° on 1.06- and 10.6- μm experiments. The loss of such a large number of electrons in the 10.6- μm case would raise the target to megavolt potentials were it not for conduction paths to the target mounting structures. Variations in spectra correlate with differences in target geometry as demonstrated here.

Ion emission energy distributions also demonstrate a

40- μm ball, 2.13 J/ng

60- μm ball, 1.5 J/ng

80- μm ball, 0.76 J/ng

100- μm ball, 0.29 J/ng

Fig. 8-99. The implosion symmetry is dramatically dependent on laser energy per unit target mass. All micrographs are for glass microspheres with 2 mg/cm² DT fill seen in the 2.5-keV x-ray emission window.

target geometry dependence in 10.6- μm experiments not usually observed in 1.06- μm studies. Figure 8-105 compares large area foils to finite-size disks. Easily refracted 10.6- μm light impinges upon and heats foil over a large area producing a large quantity of low-energy ions. By contrast, the small disks showed only a "fast" ion group in the 10.6- μm case.

Finally, streak photographs reveal relatively low

velocities imparted to the luminous plasmas on the back surface of 10.6- μm irradiated targets. Substantially larger foil accelerations for comparable experimental conditions have been observed in 1.06- μm events, as can be seen in Fig. 8-106.

In summary, there is evidence which suggests localized heating in plasmas illuminated by 10.6- μm but not by 1.06- μm pulses; 10.6- μm heated plasmas

Table 8-3. Laser fusion experiment diagnostics

Measurement	Instrument	Record
Neutron count	6 fluor-PM tubes	10 traces
X-ray spectrum	Active TAP flat crystal	Computer and file
	KAP bent crystal	Film
	Lead stearate bent crystal	Film
	7-channel K-edge filters	Computer
X-ray spatial distribution	4-channel K-edge filters	4 traces
	2 x-ray microscopes	8 images
	5 filtered Si diodes	Computer and 5 traces
X-ray temporal character	3 x-ray pinhole cameras	48 images
	Fast x-ray diode	1 trace
X-ray calorimetry	Filtered x-ray streak camera	5 images
α spectrum	NE 111 fluor-photodiode	2 traces
Ion energy spectrum	Magnetic-ToF spectrometer	2 traces
Ion spatial distribution	Curved-plate electrostatic spectrometer	1 trace
	10 Faraday cups	12 traces
Electron energy spectrum	5 differential calorimeters	5 chart records
$\lambda/2$ optical image	Magnetic spectrometer	6 traces
Laser temporal and spatial distribution both incident and scattered	2 filtered telemicroscopes	2 images
	Target plane multiple image camera	~10 images
	Target plane streak camera	4 images
	Forward and backscatter streak cameras	2 images
Optical energy balance	2 forward and backscatter multiple image cameras	~20 images
	East and west incident calorimeters	Computer and 2 chart records
	East and west forward and back calorimeters	Computer and 3 chart records
Laser system performance	32 PIN diodes or Box calorimeter	Computer 5 chart records
	Oscillator streak camera	4 images
	Switched-out pulse energy diode	1 trace
	Pulse train monitor	1 trace
	2 prepulse monitors	2 traces
	Far-field ASE diode	3 traces
	4 interstage calorimeters	Computer and 4 chart records
	5 nearfield beam photos	5 images
	Output radial shear interferometer	1 image
Total for one shot:	Flashlamp current monitors	36 traces
	Faraday rotator field monitors	3 traces
89 oscilloscope traces		
7 computer printouts		
112 photographic images		
19 chart records

Fig. 8-100. The two types of targets used for experiments with the Valkyrie CO₂ laser system differ in the way they were mounted. Polyethylene foils were held onto an electrically conductive low Z frame whereas the Parylene disks were mounted on a dielectric glass stalk.

Fig. 8-101. For similar energy densities and pulse width, the x-ray emission from a Parylene disk irradiated at 10.6 μm shows a small scale structure whereas the emission from 1.06 μm is quite uniform.

Fig. 8-102. Filamentation prediction for a slab geometry agrees with the experimental results. (a) Self-focus length plot. (b) Filament width plot.

Fig. 8-103. The lower x-ray conversion efficiency at 10.6 μm shows that the plasma did not heat up to temperatures comparable to the 1.06- μm shots.

Fig. 8-104. The electron spectrum for 10.6- μm irradiation depends on the target configuration. Data presented are for irradiation in the range of 5×10^{13} to 2×10^{14} W/cm 2 .

Fig. 8-105. The ion spectrum is also target-dependent. Larger foils result in a dominance of low-energy ions, whereas Parylene disks show only a high-energy peak.

exhibit lower x-ray conversion efficiency, probably due to refraction of the incident beam. These observations raise doubts concerning the usefulness of 10.6- μm pulses in uniformly heating spherical plasmas to produce spherical implosions.

K. Manes
M. J. Boyle
S. Glaros
R. A. Haas
V. C. Rupert

1.06- μm laser
10- μm polyethylene foil
 $I_p \approx 5.1 \times 10^{13} \text{ W/cm}^2$
(Back surface)

10.6- μm laser
5- $\mu\text{m} \times 150\text{-}\mu\text{m}$ -diam Parylene disk
 $I_p \approx 5.7 \times 10^{13} \text{ W/cm}^2$

$I_p \approx 9.5 \times 10^{13} \text{ W/cm}^2$

Fig. 8-106. The plasma blowoff in back of the foils is much faster for 1.06- μm than for 10.6- μm irradiation.

8.5.2 LASER IRRADIATION OF PARYLENE DISKS WITH A 1.06- μm LASER

Current interest in fusion neutron production by short-pulse (~ 100 ps), high-intensity ($\sim 10^{15} \text{ W/cm}^2$) laser irradiation and implosion of DT filled glass microshells has focused attention on the physics of laser beam propagation and absorption in high-temperature plasmas, the subsequent electron energy transport processes that transfer the absorbed laser energy to the high-density ablation region, and the resultant general convective fluid dynamic development of the laser-heated plasmas. For instance, experiments indicate that the neutron yield for exploding pusher targets is a very strong increasing function (approximately fourth power) of the ratio of the energy absorbed by the target to the mass of the target. However, only 10 to 25% of the total laser energy incident on the target is generally absorbed. The physical mechanisms responsible for this low absorption are not presently well understood. Clearly, great gains can be made if the laser energy can be coupled more effectively to the target. The objective of the experiments reported on in this section was to use a relatively simple isolated target geometry to acquire basic data related to the short-pulse, high-intensity laser/plasma interaction regime. Although many experimental laser/plasma interaction studies have been performed in the past, only since the advent of the possibility of laser-induced fusion has practical interest⁵⁹⁻⁶⁴ in this high-intensity regime developed.

To simplify the interpretation and evaluation of the

experimental results, 10- μm -thick $\times$ 160- μm -diam Parylene (C_8H_8) disks supported in vacuum by slender glass stalks were irradiated. The 1.06- μm laser light beam produced by the Janus laser system was focused onto the target with an $f/1.1$ aspheric lens. The irradiation intensity level at the target surface was varied by changing the axial position of the target with respect to the focus of this lens. The nominal focal spot diameters at the target were 90, 30, and 10 μm . The face of the disk was always normal to the direction of propagation of the laser light. To minimize the effect of small-scale and whole-beam self-focusing on the laser beam quality, the laser was operated at focused powers $P \leq 100$ GW. In this regime of operation the B value or phase delay at the beam center with respect to a low-intensity beam for Janus varies^{65,66} as $B(\text{waves}) \approx 0.32 \times 10^{-2} P(\text{GW})$ and, hence, was typically about 0.3 waves. The pulse length was varied from 50 to 150 ps. The irradiation flux levels on target were consequently in the 10^{15} to 10^{17} W/cm^2 range.

Throughout the experiments emphasis was placed on determining: (1) the laser-light energy balance⁶⁷ by measuring the angular distribution of the scattered laser light with an array of photodiodes (Sec. 8.3.1) and an enclosing "box" calorimeter (Sec. 8.3.2); (2) the time dependence of the incident and reflected laser light pulses; (3) the spatial⁶⁸ and energy distributions of the x-ray emission from the heated plasma; and (4) the high-energy electron⁶⁹ and ion emission⁷⁰ spectra.

Target Damage Considerations

High-power target irradiation laser systems can emit enough low-level radiation to alter the state of the target prior to arrival of the main laser pulse. Therefore, prior to performing experiments with a new class of target it is generally necessary to determine the damage threshold of the target. The possibility of ASE damage (Sec. 8.2.1) was checked by blocking the oscillator output and firing the laser system at a level that would normally produce a 250-GW output pulse. Close examination of the target revealed no observable damage. Using only the oscillator and preamplifiers, the prepulse damage threshold was determined to be about 4.0 J/cm^2 . This result (Fig. 8-107) is consistent with optical element damage thresholds.⁷¹ An example of the target damage produced at 5.4 J/cm^2 is illustrated in this figure. At a $30\text{-}\mu\text{m}$ focal spot diameter this corresponds to about $40 \text{ }\mu\text{J}$ of laser energy. The limit of detectability of the prepulse measurement employed was typically ≥ 2 to $5 \text{ }\mu\text{J}$. No evidence of significant prepulses was obtained for the experimental results reported here. However, for the highest intensities, about 10^{17} W/cm^2 , the detection capability of the system was comparable to the target damage threshold.

Focused Laser Light Energy Distributions

Characterization of a laser-plasma interaction exper-

iment requires the measurement of the spatial and temporal dependence of the laser energy distribution at the target. For Janus the time-integrated focused laser energy distribution, measured with a multiple image camera,⁷² at two axial positions for an approximately 161-GW focused laser pulse is shown in Fig. 8-108. In the experiments reported here, the target was located at or near one of the axial positions shown on this figure. However, the laser output power was about 100 GW and consequently, the small-scale structure observed in these pictures was slightly less significant. Due to the astigmatism introduced by passage through the disk amplifiers the beam has an elliptical shape. The average diameters of these distributions are 65 to $70 \text{ }\mu\text{m}$ and 25 to $30 \text{ }\mu\text{m}$, respectively. The donut shaped structure is due to phase distortion produced by whole-beam self-focusing during amplification. The whole-beam self-focusing also produces a temporally dependent focal spot shift toward the focusing lens. In agreement with theory⁶⁵ the time-integrated shift is about $8 \pm 4 \text{ }\mu\text{m}$ at 161 GW and about $5 \text{ }\mu\text{m}$ at approximately 100 GW. The data reported in this paper have been corrected for this effect which is most significant for the high-intensity, small focal spot diameter experiments. The large amplitude, small-scale structure observed in the beam at position number one is a consequence of small-scale self-focusing of the beam as it passes through the amplifiers. Since much of

Fig. 8-107. Parylene disk target damage characteristics: (a) dependence on energy flux and (b) local damage at about 5.4 J/cm^2 .

Fig. 8-108. The time-integrated focused laser energy distributions for Janus measured with a multiple image camera⁷² near two of the axial irradiation positions used in the Parylene disk experiments. The focused laser power was 161 GW. The horizontal and vertical scans were averaged over 5-μm (-----) and 10-μm (—) wide regions.

this structure begins early in the laser chain, its amplitude is an exponential function of B , and hence at 100 GW is a factor of about 0.8 of the magnitude shown here. At position number two, much of this structure has been smoothed by diffraction.

Scattered Laser Light Characteristics

In Fig. 8-109 the fraction of the incident laser energy backscattered through the focusing lens is plotted as a function of the average peak incident laser intensity, I_i , on target. The fraction of the incident laser energy backscattered (ϵ_{18}/ϵ_i) decreases from 35 to 15% as the laser intensity, I_i , increases from about 10^{15} W/cm² to about 10^{17} W/cm². This, however, does not necessarily mean that a larger fraction of the incident laser energy was absorbed as the intensity was increased since the angular distribution of the scattered laser light was observed to vary with intensity, as shown in Fig. 8-110.

The polarization-averaged scattered laser light distribution, measured with the photodiode array, was generally highly peaked in the backscatter direction ($\Theta = 180^\circ$). These distributions are consistent with classical refraction and stimulated backscatter. The fractions of the laser energy scattered in and perpendicular to the plane of polarization of the incident laser beam were generally within a factor of 2, with more energy scattered into the perpendicular plane. This is consistent with the occurrence of some resonance absorption or Brillouin sidescatter. The bars on this plot represent the standard deviation of the data at each nominal flux level. The approximately 10^{15} W/cm² data are more highly peaked in the backscatter direction with less sidescatter than the higher intensity $\geq 10^{16}$ W/cm² data. In particular, the fraction of the incident laser energy side-scattered into the angular range $45^\circ \leq \Theta \leq 135^\circ$ increased from about 23% at ~ 100 GW/90-μm-diam, $\sim 10^{15}$ W/cm² to about 33% at ~ 100 GW/30-μm-diam, $\sim 10^{16}$ W/cm². Since the convex curvature of the critical surface is probably increasing in these experiments it is not clear whether this is due to

refraction, critical surface breakup, or stimulated side-scatter.

In Fig. 8-111 the fraction of the incident laser light absorbed by the Parylene disk plasmas is plotted as a function of the average peak laser intensity. From the graph it can be seen that according to the photodiode data, the fraction of laser light absorbed by the target plasma increases slightly with increasing laser intensity in the range $10^{15} \text{ W/cm}^2 \leq I_L \leq 10^{17} \text{ W/cm}^2$. However, the fraction absorbed remains nearly constant at about 35% according to the "box" calorimeter data. The photodiodes and calorimeters are being carefully recalibrated to determine if this is the cause of the difference in the results of these two measurements. For this range of parameters the enhanced absorption, if it indeed occurs, is possibly due to one or a combination of the following: sharp density gradients produced at the critical surface during resonance absorption, breakup of the critical surface into bubbles and then filaments within which enhanced absorption can occur, and a decrease in the importance of Brillouin backscatter as a consequence of the limited mass and heat capacity of the underdense plasma. The latter explanation

was first proposed by Krue, Valeo, and Estabrook,⁷³ to explain time-dependent reflectivity measurements made at the University of Rochester. In this mechanism, when the light pressure exceeds the background plasma pressure, the momentum deposition, which accompanies the light reflection, readily steepens the density profile, turning off the reflection.⁷³ With this model no time-dependent reflection is then expected for $I_L \leq 10^{15} \text{ W/cm}^2$. For higher intensity, the reflection is estimated to persist for a time $\tau_r \sim L[(m_e/m_i)^{1/2} V_{te}]$, where L is the initial gradient length. For I_L approximately 10^{16} W/cm^2 , $\tau_r \sim 15 \text{ ps}$, consistent with the observed period of enhanced reflectivity reported in the next paragraph.

Measurements of the time dependences of the incident and reflected or backscattered laser light pulses are presented in Fig. 8-112. The reflectivity measurements presented in this figure are typical of those obtained in these experiments. An LLL ultrafast S-1 streak camera was used to monitor the time dependence of a thin strip across the center of the incident and backscattered laser radiation. The strip width was about 5 to 10% of the width of each beam. A mirror pair with reflectivity 0.4

Fig. 8-109. The fraction of the incident laser energy backscattered through the focusing lens is plotted as a function of the average peak laser light intensity for Parylene disk targets.

Fig. 8-110. Based on photodiode measurements the fraction of the incident laser light scattered per unit solid angle is plotted as a function of the scattering angle θ for Parylene disks. Direct backscatter corresponds to $\theta = 180^\circ$.

and 0.8 was placed in front of the streak camera so that several images, usually three, of each beam, reduced in intensity with respect to each other by a factor of about 3, could be recorded simultaneously. The reflectivity measurements presented in this figure are typical of those obtained in these experiments. For incident laser fluxes of approximately 10^{15} W/cm² (Fig. 8-112a) the time dependences of the incident and backscattered laser light were very similar. However, for fluxes of about 10^{16} W/cm² (Figs. 8-112b-d) a significant difference was observed. As shown here, at $\geq 10^{16}$ W/cm² the reflected light pulse was significantly shorter than the incident pulse (Fig. 8-112b) or the reflected laser light pulse first increased rapidly reaching a maximum and then decreased to a much smaller value just after the peak of the incident laser pulse, Figs. 8-112c and 8-112d. It is interesting to note that the characteristic time over which the large reflection is observed to occur is comparable to the characteristic time τ_R . The accuracy of these measurements can be evaluated by examination of Figs. 8-112c and 8-112d where two image sets from the same experiment are displayed for an intensity value of $\sim 2.1 \times 10^{16}$ W/cm². The differences are due to the fact that inaccuracies in the alignment of the different images prevent each from representing the same portion of the incident or re-

Fig. 8-111. The fraction of the incident laser light absorbed is plotted as a function of the average peak laser light intensity for Parylene disk targets.

Fig. 8-112. Time-dependent reflectivity measurements for Parylene disk targets. The incident (—) and reflected (----) pulses are not plotted on the same intensity scale.

flected beam. Furthermore, since the temporal resolution of the streak camera was ~ 10 ps the very small scale structure can be interpreted as film and camera noise. It is, however, very likely that a high-frequency substructure is present on the incident beam due to the random temporal dependence of small-scale self-focusing events. The effect of this temporal structure on the results is not known.

X-Ray Emission Characteristics

It is now well documented^{61,64} that the time-integrated energy distributions of the x-rays emitted by laser-produced plasmas do not generally satisfy a single "temperature" Boltzmann function. This is not surprising since different parts of the spectrum come from different regions of the plasma and several absorption

mechanisms produce nonthermal electron distributions. The corresponding results obtained in the present experiments are consistent with earlier observations. The low-energy portion of the x-ray spectrum, 0.25 to 1.0 keV, was measured with a lead stearate bent crystal spectrometer⁷⁴ loaded with Kodak Type 101 x-ray film. The x-ray spectrum above 1 keV was measured using a multichannel K-edge filter spectrometer system.⁷⁵ Using these diagnostics, the time-integrated x-ray emission energy distribution has been measured over 7 orders of magnitude in amplitude and 3 orders of magnitude in photon energy. These results are presented in Fig. 8-113.

The low-energy portion, 0.25 to 1.0 keV, of the x-ray emission spectrum, as shown here, was observed to increase in amplitude as the laser energy was increased. The emission minimum near 490 eV is believed to be due to the K-edge absorption of hydrogen-like carbon. It can also be seen from these data that as the incident laser flux was increased from 10^{15} to 10^{17} W/cm² the high-energy tail of this distribution increased by 2 to 3 orders of magnitude. Measurements of the energy distribution of the high-energy (≥ 30 keV) electrons emitted by these plasmas were qualitatively consistent with these x-ray measurements. In particular, the number of high-energy electrons emitted increased rapidly with increased incident laser light intensity. However, since the spatial and temporal dependence of the plasma potential was not measured it has not been possible to quantitatively relate the electron and x-ray emission spectra.

In addition to the x-ray energy distribution the spatial distribution of the x-ray emission was measured with an x-ray microscope.⁶⁸ The x-ray microscope viewed the target from a position normal to the direction of the incident laser light. These measurements (Fig. 8-114) indicate that the characteristic dimension of the approximately 1-keV x-ray emission region parallel to the axis of propagation of the incident laser beam was about 10 μ m and remained essentially constant as the focal spot diameter was reduced. Also, as shown in the plot presented in this figure the FWHM diameter, D_x , of the x-ray emission region was generally less than the nominal FWHM diameter, D_L , of the laser beam for the approximately 100 GW/90- μ m-diam experiments. However, for the ≥ 100 GW/30- μ m-diam experiments the x-ray emission region was comparable to or greater than the laser beam focal spot diameter at the target.

Finally, ion emission measurements were obtained with Faraday ion collectors. The high-energy tail of the ion distribution was observed to increase slightly with increased laser intensity. From these data it has been estimated that $\geq 50\%$ of the total ion emission energy was carried away by ions with $E/A \geq 10$ keV.

Using an ion time-of-flight spectrometer,⁷⁶ ultrahigh energy proton emission was also measured. It was found that the number and energy of the high-energy protons emitted increased significantly as the laser flux was increased. At about 10^{17} W/cm² protons with energies ≤ 1 MeV were observed. A detailed regular structure was observed in the spectrum. This is very interesting and not understood at the present time. However, it clearly illustrates the danger inherent in assigning different charge and mass states to peaks in

Fig. 8-113. Time integrated x-ray emission spectra for Parylene disk targets. The results are averaged over several experiments of comparable irradiation intensity, as indicated.

Fig. 8-114. Characteristics of the spatial distribution of the x-ray emission for approximately 1-keV x rays as measured with channel No. 2 of filter set D of x-ray microscope No. 2.

Faraday collector measurements⁷⁷ of the charged-particle emission from laser-produced plasmas.

In summary, Parylene disks supported on glass stalks have been irradiated with 1.06-μm wavelength laser light pulses focused to flux intensities in the range 10^{15} to 10^{17} W/cm^2 . According to photodiode measurements the fraction of laser light absorbed, 25 to 50%, increased slightly as the laser intensity was increased. However, "box" calorimeter measurements implied that the fraction absorbed was about 35% and relatively insensitive to irradiation intensity. The error bars on both measurements are relatively large, and this issue remains unresolved at the present time. The reflected laser light pulse exhibited a time dependence

different from that of the incident pulse in the region of strong interaction, i.e., $I_L \sim 10^{16} \text{ W/cm}^2$. Consistent with the results of previous investigations, the number of high-energy x rays emitted by the plasma increased significantly with increased laser intensity. Furthermore, the diameter of the x-ray emitting region was comparable to the diameter of the laser energy distribution at the target surface.

R. A. Haas
D. W. Phillion
M. J. Boyle
H. N. Kornblum
V. C. Rupert

8.5.3 SPECTRAL MEASUREMENTS OF ELECTRONS AND X RAYS EMITTED FROM PLASMAS PRODUCED USING A 1.06-μm LASER

Absolute spectral measurements were made of electrons escaping from plasmas produced by focusing 5- to 10-J, 50- to 100-ps, 1.06-μm laser pulses on 10-μm-thick Parylene disk targets. Nine spectral bands with 3- to 7.5-keV resolution were obtained from 30 to 190 keV with a 90° focusing permanent magnet spectrometer and appropriately positioned silicon electron detectors. Electrons emitted into a small solid angle at an angle of 45° with respect to the incident laser beam were collimated into the spectrometer. The integrated output current from each of the nine silicon detectors

was used to derive the electron spectra. The results are summarized in Fig. 8-115, where the energy spectra have been averaged as a function of the beam diameter at the target. Isotropic emission is assumed, although this is presumably a poor approximation.

All of the electron spectra increase with electron energy from 30 keV, the lowest energy channel, to a maximum between 100 and 160 keV. From the shape of the electron spectra, most of the electron energy below 30 keV appears to be absorbed in the plasma. Despite a variation from shot to shot, there is a definite

Fig. 8-115. Average of the electron energy spectra emitted from 10- μ m-thick Parylene disks (5-J, 1.06- μ m, 100-ps laser pulses) as a function of laser beam diameter on target.

correlation between beam focusing diameter (hence, incident laser power density) and the amplitude of the emitted energy spectrum (hence, the total emitted electron energy).

Assuming that 30% of the total electron energy is emitted with energy greater than 190 keV, as estimated from the fall-off of the spectra, and integrating under the curves in Fig. 8-115, the value, for the total measured energy of electrons have been determined and are presented in Table 8-4.

The x-ray spectra were measured simultaneously with the electron spectra by means of a K-edge filter technique. Elemental filters were chosen to provide nine spectral cuts from 1.5 to 88 keV.

Figure 8-116 shows the results of averaging x-ray

Fig. 8-116. Average of x-ray energy spectra as a function of laser beam diameter on target.

spectra obtained from laser shots with 10-, 30-, and 90- μ m beam diameters. As in the case of the electron energy spectra, the increasing effect of laser irradiation intensity on x-ray fluence with increasing x-ray photon energy is easily discerned from the plots. To show this dependence more clearly, we have plotted the x-ray fluence derived from the 88-keV channel vs laser intensity in W/cm² in Fig. 8-117 and the total electron energy for electrons above 100 keV vs laser intensity in Fig. 8-118.

The correlation of the high-energy x-ray fluence (the 88-keV channel) and the electron energy fluence greater than 100 keV is evident from Fig. 8-119. Application of the Spearman rank-correlation test provides an estimate of 99.7%, as the probability that the two are correlated.

Calculations indicate that bremsstrahlung associated with the measured electron spectra is less than 0.1% of the total measured x-ray energy greater than 20 keV and, therefore, that each of the measured electron spectra contains only a small fraction of the energy of the electron distribution in the plasma. The measured electron spectra may not, then, be entirely representa-

Table 8-4. Total measured electron energy

Beam diameter (μ m)	Total electron energy (mJ)	
	Electrons >30 keV	Electrons >100 keV
10	5.7	4.5
30	2.25	1.6
90	0.72	0.53

Fig. 8-117. Measured 88-keV x-ray fluence as a function of incident laser intensity.

Fig. 8-119. Correlation between emitted electron energy for electrons above 100 keV and emitted x-ray energy for the 88-keV x-ray channel.

Fig. 8-118. Measured total electron energy for electrons above 100 keV as a function of incident laser intensity.

Fig. 8-120. The average of electron spectra emitted from DT-gas-filled glass microspheres (30-J, 70-ps, 1.06-μm laser).

tive of the electron energy distribution in the plasma.

The average of electron energy spectra emitted from small DT-gas-filled glass microspheres is shown in Fig. 8-120. These electron spectra reach a maximum between 50 and 80 keV and tend to fall off more rapidly than the spectra observed for Parylene disks. The value obtained for the total emitted electron energy, 0.13 μJ, is much lower than those measured for Parylene disk experiments. Comparison of these results with x-ray

emission measurements and theoretical calculations of the electron spectra are in progress.

K. G. Tirsell
H. N. Kornblum
H. C. Catron
V. W. Slivinsky
R. A. Haas
E. Storm

8.5.4 BALL-ON-PLATE TARGET EXPERIMENTS

The ball-on-plate and the ball-in-plate laser fusion target designs (see Figs. 8-121 and 8-122) grew from the desire to symmetrically implode laser fusion targets without using extremely complicated low f number lenses and mirrors.⁶⁰ The single-beam ball-on-plate targets and the Parylene disk targets (Sec. 8.5.2)

formed the basis of the initial LLL laser plasma experimental program which began December 1974. At that time, computer simulations indicated that the ball-on-plate targets would produce measurable neutron yield and reasonable implosion symmetries. Experimental problems which were associated with laser-

Fig. 8-121. Front (a) and side view (b) of ball-on-plate laser fusion target. The ball diameter was $55\text{ }\mu\text{m}$ and the neutron yield was 1×10^4 .

Fig. 8-122. Front (a) and side view (b) of ball-in-plate laser fusion target. The ball diameter was $75\text{ }\mu\text{m}$, and the neutron yield was 4×10^4 neutrons.

Laser energy to target	15 J
Laser pulse duration	90 ps (Gaussian)
Energy absorbed	3.6 J
Neutron yield	1.1×10^4

Compression (calculated)	50
Ion temperature	700 eV
Electron temperature	350 eV

Fig. 8-123. Schematic of the ball-on-plate laser fusion target shown in Fig. 8-121.

target viewing systems, prepulse isolation, focal spot intensity measurements, and laser beam self-focusing were overcome.

Between December 1974 and April 1975, several different target designs (ball-on-plate is an example) were irradiated with the single-beam Janus laser, and a yield of 7×10^3 neutrons with 18 J in 101 ps was achieved. In April of 1975, the Janus laser was improved to its present two-beam, 0.4-TW capability, and it became feasible to shoot double-beam targets such as the two-sided ball-in-plate and the bare-shell targets. These experiments led to a yield of 1.1×10^7 neutrons with a laser performance of 31.5 J in 80 ps and the detection of thermonuclear α particles.⁷⁸ During this period, the interaction between experiment and theory was very fruitful and led to a reasonable understanding of the "exploding pusher target concept."

An example of the targets used during this period is the ball-on-plate target. It was formed by the addition of a glass plate to a DT-filled glass shell (see Fig. 8-123). This results in a target which can be symmetrically imploded with a single laser beam.⁷⁹ The symmetry of implosion is seen in the x-ray microscope photograph shown in Fig. 8-124. It should be compared to the implosion of a bare shell with no plate shown in the x-ray microphotograph in Fig. 8-125. The improvement in the symmetry of implosion is clear, yet the neutron yield of the two targets is comparable.

The measurement techniques used to determine the performance of these targets have been described in last year's annual report⁸⁰ and in the accompanying sections of this report. The importance of the optical, x-ray, and

Fig. 8-124. Densitometered x-ray microphotograph of 1.5 keV x-ray microscope image. Notice symmetry of compressed region.

neutron diagnostics can not be overemphasized. Repeatability of target response has only been realized by controlling the laser focusing characteristics (see Fig. 8-126), the prepulse level ($< 100 \mu\text{J}$), and the laser beam self-focusing.⁸¹

The neutron yield of the single-beam ball-on-plate target (1×10^4) was comparable to the single-beam ball irradiation (2×10^4). The x-ray yield of each of these targets is shown in Fig. 8-127. We conclude that the addition of the plate to the shell improves the convergence of the implosion at the expense of added heat capacity. Thus, the neutron yield is not improved. A more detailed discussion of this is to be found in Sec. 5.3.7.

The two-beam ball-in-plate target (Fig. 8-128) is to be compared to the two-sided irradiation of the bare-shell target. X-ray microscope pictures (Fig. 8-129) show again that the plate greatly increases the symmetry of implosion, but that the neutron yield is reduced due to the added heat capacity of the plate. The x-ray spectra of the two targets are shown in Fig. 8-130. Little difference is seen, indicating that the plate is not absorbing additional radiation. Also, experiments with the "box calorimeter" show that the ball-in-plate target absorbs no more laser radiation than the simple ball, and possibly less. In a 28-J laser pulse on target (70 ps), the bare ball absorbed about 6 J while the ball-in-plate absorbed 5.5 J. Thus, it appears that the

Fig. 8-125. Comparison of one-sided target experiments. All were irradiated with approximately 15-J, 80-ps duration laser pulses from right side of picture. Left image is incomplete implosion of ball-on-plate target when laser was focused on the plate and not on the edge of the ball. No neutrons were observed. Central image shows a computer-enhanced x-ray microscope picture of imploding ball-on-plate target. See Fig. 8-124. Initial ball diameter was $55 \mu\text{m}$, and it yielded 1×10^4 neutrons. Right image shows implosion of $80\text{-}\mu\text{m}$ -diam bare DT-filled shell, when irradiated from one side. Difference in implosion symmetry is apparent. Yield, 2×10^4 neutrons.

Fig. 8-126. The profile of the laser beam at the target is measured by imaging both the target and the laser beam focal profile with an auxiliary lens system. At low laser level, both the target and the laser spot can be imaged simultaneously. At full laser power, the target is removed, and an attenuated image of the focal spot is recorded. Nonlinear effects cause additional aberrations to occur which enhance the intensity at the edges of the focal spot envelope. These effects must be included in the detailed target analysis. (a) Beam shape at target. The vertical line indicates the image plane in Fig. 8-126b. (b) Frontal view of the beam shape at the target. Major axis, 63 μm ; minor axis, 42 μm . (c) Time averaged profile of 250-GW focal distribution.

added heat capacity of the plate detracts more than the improved implosion symmetry adds to the neutron yield. The detailed analysis of this target is to be found in the next section.

J. F. Holzrichter
E. K. Storm

H. G. Ahlstrom
D. R. Speck
J. E. Swain
L. W. Coleman
C. D. Hendricks
H. N. Kornblum
F. D. Seward
V. W. Slivinsky

Fig. 8-127. Semilog plot of x-ray spectra from ball and ball-on-plate laser fusion targets. Very little difference is evident.

Fig. 8-128. Schematic of ball-in-plate laser fusion target experiment. The neutron yield for this target was 4×10^5 . The best performance from the target class was about 1×10^6 , which is less than a bare shell ($\sim 3 \times 10^6$ N).

Fig. 8-129. Nonenhanced x-ray microscope images of ball-in-plate target implosions compared to bare-shell implosions. Implosion symmetry is better with ball-in-plate targets. The 800-eV and 2.5-keV captions refer to the x-ray microscope channels.

Fig. 8-130. X-ray spectra of bare-shell and ball-in-plate target experiments. Laser conditions were similar for the two experiments.

8.5.5 LASER IMPLOSION AND FUSION WITH DT-FILLED GLASS MICROSHELL TARGETS

A series of laser fusion microimplosion experiments has been performed with the two-beam laser system, Janus. The Janus laser is capable of focusing approximately 450 GW of 1.06- μm power (36 J in 80 ps) on laser-fusion-type targets. In these experiments, the targets were deuterium-tritium (DT) filled glass microspheres with aspect ratios* of 50 to 200. These targets operate in what is commonly called the exploding pusher mode. This mode of operation requires that the laser energy be deposited rapidly enough for the thermal wave to propagate supersonically through the glass shell. The glass shell surrounding the DT gas effectively explodes, and consequently from geometry also implodes, compresses, and heats the DT gas to ther-

monuclear conditions. Although the final stages of the microimplosion approach an adiabatic compression, the process as a whole is severely nonisentropic, as compared with the high-density isentropic implosion target of the future.

A summary of the salient points of each type of experiment is illustrated in Table 8-5. With present laser outputs in the 100-J, 100-ps range, the exploding pusher target offers the possibility of doing low density and low yield laser-driven thermonuclear implosion experiments. Although it is clear that this type of target and laser irradiation scheme will not be practical for power generation, it provides a testbed for code development, experimental confirmation of theoretical predictions of fundamental importance in laser/plasma interaction, and diagnostic equipment development both for present and future needs.

Because of the importance of this type of target in

*Aspect ratio is defined as the ratio of the shell diameter to the shell wall thickness.

Table 8-5. Comparisons of laser implosions

	Exploding pusher	Isentropic
Fluid instabilities	Insensitive	Critical
Plasma instabilities	Insensitive	Critical
Entropy change	Large	Minimal
Pulse shaping	Not required	Required
Velocity	$\sim 5 \cdot 10 \times 10^7$ cm/s	$\sim 5 \times 10^7$ cm/s
Density	~ 1 g/cm ³	~ 1000 g/cm ³
Burn efficiency	$\sim 10^{-2}\%$ (10 kJ)	$\sim 10\%$ (10 kJ)

the early studies of laser fusion feasibility, it was decided to explore a portion of the matrix of parameters that affect the performance of these targets. Among the parameters varied were the SiO₂ microshell diameter, the amount of DT fill in the target, and the time separation of the two laser beams focused on the target. The targets typically absorbed 25% of the 1.06- μ m input energy, producing between 10^4 and 6×10^6 neutrons, with the neutron yield scaling roughly as the 4th power of absorbed energy per nanogram of target mass—all other parameters being the same. Of the typically 35 J of energy incident upon the target, 7 J were coupled to the target. Of these 7 J, 300 mJ were emitted in x rays between 0.1 and 20 keV. A definite asymmetry in the scattered 1.06- μ m radiation in and out of the plane of polarization of the incident beams was observed and is consistent with the existence of polarization-dependent resonant absorption processes and with stimulated Brillouin sidescatter.

The experiments were performed on the Janus two-beam laser system which is described in Sec. 8.2.2. Considerable care was taken in these experiments to minimize the effects of small scale beam breakup and target damage due to prepulses. The importance of obtaining as complete a data package as possible on each shot is well recognized. To this end, the plasma diagnostics covered in Sec. 8.3 are routinely employed on target experiments.

Figure 8-131a shows the target and laser input specifications together with a summary of experimental results and LASNEX predictions. Figure 8-131b shows the x-ray spectrum from this target. The typical "two-temperature behavior" characteristic of these targets is evident, the portion of the spectrum between 1 and 10 keV being representative of bremsstrahlung emission with the slope giving an indication of the plasma electron temperature, and the portion of the spectrum above 10 keV resulting from the superthermal electrons in the corona region of the plasma. The LASNEX

prediction of the x-ray spectrum is also shown in this figure. Figure 8-131c shows an x-ray micrograph of the implosion with emission from the 2.5-keV region of the spectrum. The imprint of the illumination from the two f/1 lenses and the resulting implosion, compression, and heating of the target are clearly seen. The reasonably close agreement between experiment and the LASNEX code runs provided motivation for doing a series of experiments exploring some of the parameters of the exploding pusher type targets, both as a guideline for the direction of future experiments, and as a severe test of the ability of LASNEX to track the experimental results.

Time Delay Series

The first set of experiments discussed is the time delay series. This series of experiments involved delaying the arrival of one converging laser beam focused onto the target with respect to the other. All the targets were SiO₂ microspheres with a nominal diameter of 80 μ m and wall thickness of 0.7 μ m. They were filled with an equimolar mixture of deuterium and tritium at a density of 2 mg/cm³. The converging beams from the two f/1 lenses were adjusted such that in the equatorial plane, the diameter at the one-third intensity points equalled the target diameter. Preliminary experiments indicated that, for the Janus laser, this focusing scheme maximized the implosion symmetry, compression, and neutron yield for these targets. This focusing scheme was followed for all the experiments described later in this section. A typical beam profile at full power is shown in Fig. 8-132. The ring profile observed is mainly a result of phase distortion due to the intensity-dependent index of refraction effects.

The series of color x-ray micrographs in Fig. 8-1 graphically illustrates the effect of temporal asymmetry in the illumination. The first of these shows a time-

Laser input: 26 J, 62 ps (FWHM)

Energy transmitted and/or

back reflected: 9 J

Energy scattered: 12 J

Energy absorbed: 5 J

Target mass: 33 ng

Neutrons: $9 \pm 2.3 \times 10^5$

Ions: Symmetric blowoff with fast ion component

LASNEX: 4J absorbed

0.9 to 3×10^6 neutrons

Good fit on x rays and scattered light-distribution

Target: 80-μm diam.
0.6-μm wall
2 mg/cm³ DT

Laser: 35 J
75 ps

No prepulse ($< 20 \mu\text{J}$)

No beam break-up

(c)

Fig. 8-131. A typical exploding pusher laser fusion experiment. (a) Schematic. (b) Plot of two temperature x-ray distribution. (c) Time-integrated x-ray micrograph.

Fig. 8-132. A ring beam is advantageous for two-beam implosion experiments. This shows the beam profile for an 80- μm -diam glass microsphere. Peak power, 260 GW.

integrated x-ray micrograph (in the 2.5-keV region) for the case where there was no delay between the two beams. The imprint of the focused laser beams on the initial position of the 80- μm -diam glass sphere is clearly seen. The final implosion stage or the remains of the glass shell at turnaround is indicated by the x-ray emission from the central portion. The "valley" in the center of the picture shows that, indeed, the pressure exerted by the DT gas fill limited the final compression to about 100. The second and third of the pictures show what happens when one of the beams is delayed 42 and 84 ps, respectively, and finally, the fourth shows the x-ray micrograph of a target hit by one laser beam only.

Fig. 8-133. Neutron yield is severely reduced by temporal mismatch of laser beams. Extrapolation tells us that a beam delay ~ 120 ps is equivalent to one-beam operation.

The deterioration of implosion symmetry is evident. The resulting degradation of neutron yield is shown in Fig. 8-133. From this figure, we can get a rough estimate of the target implosion time scale. Extrapolation indicates that a beam delay of ≥ 120 ps is equivalent to a one-beam experiment, or, conversely, the hydrodynamic implosion time scale is of the order of 120 ps.

Figure 8-134 shows the variation of the x-ray spectrum for this series. A very definite reduction of the

Fig. 8-134. X-ray spectrum vs beam delay. All targets are 2 mg/cm³ fill.

high-energy spectrum with increasing beam delay can be seen. The asymmetry of density gradients caused by increasing beam delay is a possible explanation for this phenomenon. The apparent hardening of the spectrum (i.e., flattening of the slope of the high-energy x rays) with increasing beam delay is somewhat surprising, and the "effect" is, indeed, within the experimental error bars. Referring back to the pictures in Fig. 8-1, we note the progression of the stagnation region towards the left, the direction of the delayed beam. Plotting the position of the center of the stagnation region away from the original center of the target as a function of beam delay produces Fig. 8-135. From the slope on this $x-t$ plot we infer a typical pusher implosion velocity of about 2×10^7 cm/sec.

Microdensitometer scans of implosions like that shown in Fig. 8-1 indicate the pusher travels typically 30 to 35 μm before stagnating at peak compression. Combining this with the velocity taken from Fig. 8-135 gives another estimate of the hydrodynamic implosion time scale, this one of the order of 150 ps.

Fig. 8-135. Motion of stagnation region provides measurement of average implosion velocity. Δt is the beam delay in ps. Δx is the displacement of the stagnation region from the center of the sphere.

Fill Series

The effect of the equimolar fill of deuterium and tritium on target performance is most graphically illustrated by the color x-ray micrograph in Fig. 8-136 and in Figs. 8-137 and 8-138. The decrease in compression, or inversely, the increase in the distance of closest approach of the converging pusher as a function of fill is plotted in Fig. 8-137 and compared with a simple model equating kinetic energy of the pusher with pdv work done on the gas. The effect of fill on neutron yield is shown plotted against target fill. The shape of the curve is a result of two competing effects. In a simpleminded way of looking at the problem, increasing the fill provides more thermonuclear fuel to burn, hence, increasing the neutron yield. However, for fixed laser energy on target, increasing the fill decreases the compression and the temperature in the compressed region and results in turning the curve over for higher fills. A more sophisticated analysis yields the curve shape seen on Fig. 8-138.

Size Series

The effect of varying the size of the glass microsphere is illustrated by the color photos in Fig. 8-99. X-ray micrographs (from the 2.5-keV region of the spectrum) show the results from 40-, 60-, 80-, and 100- μm diam targets, respectively. The tendency towards a more spherically symmetric compression as the

initial radius decreases is evident. Since all the targets typically absorbed 20% of the incident energy, the increasing symmetry is most likely a result of the increase in specific energy absorption with decreasing target mass. The resulting neutron yield normalized by $(J/\text{ng})^{4.5}$ is shown in Fig. 8-139. When the absorbed energy is corrected for the temporal mismatch of the laser FWHM and hydrodynamic time scale, the data agree reasonably well with the expected behavior. The x-ray spectrum from the size series is given in Fig. 8-140. The increase both in magnitude and hardening of the high-energy tail with decreasing size is clearly indicated. This trend is to be expected from the increase in intensity at the target surface. Since both the input energy and the laser pulse length was kept constant, we have a sixfold increase in intensity in going through the target range of these experiments. The dependence of resonant absorption on intensity has been calculated, and the hardening of the high-energy x-ray spectrum agrees well with code predictions.

Other Experimental Results

The first confirmation that the neutrons produced in these experiments do, indeed, come from thermonuclear burn conditions was achieved with α -particle time-of-flight measurements. These measurements and their results are described in more detail in Sec. 8.5.9.

In the previous sections, neutron yields have been discussed based upon normalization by the absorbed energy. The actual absorbed energy was determined in one of two ways. The most accurate, and most satisfying from the experimental point of view, involves using the "box calorimeter" described in Sec. 8.3.2. With conventional laser calorimeters measuring 1.06- μm energy transmitted and reflected through the f/1 lenses, the box calorimeter covers about 90% of the total remaining solid angle, and measures the optical energy not coupled to the target. Since the use of the box calorimeter precluded almost all other diagnostics, it was not used on a regular basis. In usual experiments, absorbed energy was deduced from an optical energy balance as discussed in Sec. 8.5.7. Although there is more scatter in these data, the numbers are generally consistent with about 25% of the incident energy being absorbed.

From the photodiodes we can also obtain information on the angular variation of the light that has interacted with the plasma, as shown in Fig. 8-141. A very definite polarization effect is seen, particularly for

No DT fill

3 mg/cm³ DT

5 mg/cm³ DT

7.5 mg/cm³ DT

Fig. 8-136. Variation of DT fill in exploding pusher experiments affects the compression efficiency.

the one-sided target shots, and is consistent with enhanced resonant absorption in the plane of polarization of the incident light. This observation is also consistent with stimulated Brillouin side scatter.

E. 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
V. W. Slivinsky

Fig. 8-137. A simple model gives reasonable fit with experimental data. Δ is the width of the stagnation region.

Fig. 8-138. Neutron yield as a function of DT gas fill. At low pressure $N \sim \text{fill}$. At high pressure $N \sim (\text{fill})^{-2}$.

Fig. 8-139. Simple scaling laws predict neutron yield as a function of ball diameter reasonably well.

Fig. 8-140. X-ray spectrum vs target size for exploding pusher targets.

Fig. 8-141. Scattered light shows polarization dependence.

8.5.6 X-RAY CRYSTAL SPECTROMETER RESULTS

Because of the interest in the x-ray emission of laser produced plasma, a number of spectrographs were used to look at the line radiation in the 1-keV range.⁸³ One such instrument is discussed in Sec. 8.3.8. Results obtained with two other instruments are discussed here.

The first instrument is a crystal spectrograph which measures the spectrum from 1.1- to 4-keV. It uses a curved acid phthalate salt ($2d \sim 24$ to $26 \text{ \AA}$) usually

of potassium with curvatures of 75 to 130 mm. The data tend to be intensity limited so that the most sensitive film (Kodak no screen) is used as close as possible to the source (100 to 150 mm). The data are recorded on film, then converted to spectral output in $J/(sr \cdot keV)$ using measured crystal efficiencies and film calibrations.

Many spectrograms have been taken from targets

containing silicon. A typical example is shown in Fig. 8-142. The most prominent features are the lines from one- and two-electron (Si XIV and Si XIII) silicon ions and their bound-free continua. Sodium lines and, occasionally, calcium lines are also present.

The relative intensity of the Si XIV and Si XIII lines varies from shot to shot and provides a measure of the electron temperature. The temperature thus obtained can be confirmed by a study of the slope and height of bound-free continuum at the edge of He- and H-like lines. Finally, the average density can be estimated from the intensity of the bound-free continuum. These data are discussed in detail in Sec. 6.7.1.

An important feature of the spectra is the line width from which an estimate of the ion pressure can be obtained. If one of the lines from these spectra is examined (see Fig. 8-143) a line width FWHM of 5 to

10 eV is measured. Since this spectrograph is optimized for sensitivity and not for energy resolution, some uncertainty in the validity of the line width data remained.

To improve the line width measurement, a high-resolution spectrograph was designed and used on several intense shots with silicon-containing targets. The spectrograph used a flat ADP ($2d = 1.065 \text{ \AA}$) crystal looking only at the silicon line containing region (1.82 to 2.02 keV) from a larger distance with finer grained film (AA). A typical result is shown in Fig. 8-144. The observed FWHM for the 1.84-keV Si XIII line was 4.4 eV and the 2.0-keV Si XIV line was 5.7 eV. The possible instrumental line width distortion (in $h\nu$ space) is summarized in Table 8-6. The crystal contribution is taken from published data⁶³ and varies from 0.4 to 1.6 eV. With the flat geometry of this spectrometer, the data are probably near the lower limit. Therefore, the

Fig. 8-142. Typical glass shell target spectrum.

Fig. 8-143. Hydrogen-like silicon (1s-2p) line of spectrum of Fig. 8-142 in expanded scale.

Fig. 8-144. Hydrogen-like silicon line (1s-2p) measured with high-resolution spectrometer.

Table 8-6. Instrumental and source contributions to observed line widths

Line $h\nu$ (keV)	Crystal $\Delta h\nu$ (eV)		$\Delta h\nu$ from 80 μm Extended source (eV)	Observed FWHM (eV)
	Good	Distorted		
1.84	0.4	1.0	0.62	4.4
2.00	0.55	~ 1.6	0.74	5.7

minimum unfolded line width is 3 eV for the Si XIII line.

As discussed in Sec. 6.7.1, the data from these two instruments can be combined to obtain an electron temperature of the order of 700 eV and a He-like

silicon population of the order of 10^{21} cm^{-3} in the emitting region.

L. Richards

8.5.7 INTENSITY DISTRIBUTION OF THE SCATTERED 1.06- μm LASER LIGHT AND ENERGY ACCOUNTING

Study of the scattered light from the laser-produced plasma is essential to understanding the stimulated scattering and anomalous absorption processes which determine both the fraction of the incident light absorbed and where and how it is deposited into the plasma. Extensive experimental data have been obtained on the time-integrated scattered 1.06- μm light distribution using arrays containing large numbers of photodiodes for all classes of target experiments on both Janus and Cyclops. Accurate measurements of the absorbed energy have been made in a series of experiments with a calorimeter that almost completely enclosed the target. The photodiode diagnostic and box calorimeter are described in Secs. 8.3.1 and 8.3.2, respectively, of this report.

Figure 8-145 shows the diagnostics of interest on the Janus two-beam facility. Both the incident beam energies and the energies in the light collected by the f/1.1 lenses in the target chamber are measured with calorimeters that have been calibrated in place. Both beams were linearly polarized in the same plane at 45° from the vertical. Photodiodes within the chamber were mounted on semicircular rings lying in planes either parallel or perpendicular to the electric field. A crossed array of eight photodiodes external to the chamber mapped the light distribution within the angular region subtended by one of the lenses. Figure 8-146 shows an averaged scattered light intensity distribution for Janus two-beam experiments on 80- μm -diam glass microshells filled with DT³He gas. The beams were

"tangentially" focused so that the periphery of the beams illuminated the equator of the ball. The polar angle θ is measured from the beam axis, and the brackets indicate the one sigma scatter. The intensity distribution peaks near the poles due to the large amounts of light that are either transmitted around the target or back scattered, and flattens out for large-angle sidescatter. Isotropic scatter would be expected if a mirror-like ball were uniformly illuminated by a collimated beam.

A large azimuthal dependence in the scattered light is also noted: light preferentially scatters in a plane which is normal to the electric field direction. In one-beam experiments with lead-glass disks on Cyclops, a ring of 12 diodes looked at light backscattered at an angle of 26° to the incident beam. Figure 8-147 shows the polarization dependence to be dramatic. Both these shots were for nominally 400- μm spot diameters and 100-ps pulsewidths, giving intensities of 10^{14} - 10^{15} W/cm 2 . In one-beam experiments performed on polyethylene slabs at a power density of 10^{16} W/cm 2 , a strong polarization dependence was also observed. The pronounced azimuthal asymmetry observed is consistent with at least two collective processes:

resonance absorption⁸⁶ and Brillouin scattering.⁸⁵ Only light with its electric field in the plane formed by its $\vec{k}$ vector and the density gradient vector $\vec{n}$ will create at the critical density surface a driving electric field parallel to $\vec{n}$ at this surface. This wave couples into an electron plasma wave resulting in resonance absorption. To explain the high absorption efficiencies implied by this mechanism, the existing density gradient must be extremely steep.^{86,87}

Brillouin scattering, whose polarization dependence is also consistent with observation, occurs in the underdense plasma region and is a parametric process in which an incident light wave is scattered off an ion acoustic wave. The coupling coefficient and hence also the gain coefficient for this instability are proportional to the dot product of the polarization vectors of the incident and scattered light waves.⁸⁷

As discussed in Sec. 8.5.8, an azimuthal asymmetry in the particle blowoff from DT-filled glass microspheres shot at Janus has been observed by ion calorimetry, only with the most energetic blowoff occurring at those azimuths where the scattered light was least. This indicates preferential heating of those sectors of the ball where the surface

Fig. 8-145. Energy balance diagnostics on Janus. Photodiodes mapping the three-dimensional distribution of scattered light and calorimeters measuring both the incident energy and the light energy scattered back through the lenses give one estimate of the absorbed energy. Ion calorimeters, which absorb the energies carried by particles and x rays, as well as a fraction of the scattered light, give another. The light contribution is cancelled either afterwards by knowing the light intensity seen by a nearby photodiode or directly by using a differential design (Sec. 8.3.3).

normal is in the plane of polarization formed by the electric field vector and the wave vector $\vec{k}$ of the incident light, a result that is certainly consistent with resonance absorption. Brillouin scattering, however, could also cause nonuniform heating by more efficiently scattering light out of some regions of the underdense plasma than others. Light so scattered would transfer little energy to the plasma since it would never reach the critical density surface, near which most absorption is thought to occur, principally by a combination of resonance absorption, the parametric decay instability, and the oscillating two-stream instability. The azimuthal asymmetry of the Brillouin-scattered light is not necessarily indicative of any nonuniform heating, though.

Typical experimental results with the LC-16 calorimeter are summarized in Table 8-7. This

calorimeter is described in Sec. 8.3.2. For the Janus experiments only 7% of 4π solid angle was not collected either by the LC-16 calorimeter or by one of the calorimeters measuring the light scattered through the lenses. In the Cyclops experiments the same calorimeter was used, but the $f/2.5$ lens had a marginal ray angle of 11.3° , compared to 30.8° for the $f/1.1$ lens used on Janus. The annular gaps comprising 14% of 4π between the edge of the lens and the edge of the calorimeter were covered by rings of photodiodes.

D. W. Phillion
R. A. L. Liche
K. R. Manes
V. C. Rupert
S. R. Gunn
K. J. Pettipiece

Fig. 8-146. Time-integrated scattered light distribution for DT-He-filled glass microspheres. The dimensionless ordinate has been normalized to the total incident energy. The solid line represents light scattered in the plane of polarization, while the dashed line represents light scattered out of this plane. Error bars show the one-sigma scatter of the data. These data points are an average over five targets of 80- μ m diam. Typically, a total energy of 30 J was incident in a pulse of 80-ps FWHM.

Fig. 8-147. Time-integrated azimuthal distributions of light backscattered at an angle of 26° to the incident beam for two lead-glass targets. These were one-beam Cyclops experiments on $10\text{-}\mu\text{m}$ -thick lead-glass disks, for which the beam was focused to a $400\text{-}\mu\text{m}$ -diam spot by an $f/2.5$ lens. The pulse width was nominally 100 ps.

Table 8-7. Summary of results obtained with the LC-16 box calorimeter. Uncertainties in the scattered light numbers indicate maximum error limits in the measurements, not scatter in the data

Facility	Target description	Number shot	% of the $1.06\text{-}\mu\text{m}$ light scattered	% of the laser light absorbed	Comments
Janus	DT-filled glass microspheres	6	73 ± 3	27	Two-beam irradiation, tangential focusing with $f/1.1$ lenses
Cyclops	DT-filled glass microspheres	3	75 ± 4	25	Two-beam irradiation, tangential focusing with $f/2.5$ lenses
Janus	$10\text{-}\mu\text{m}$ thick Parylene disks	2	65 ± 9	35	One-beam irradiation, $90\text{-}\mu\text{m}$ focal spot with $f/1.1$ lenses
Janus	$10\text{-}\mu\text{m}$ thick Parylene disks	2	61 ± 7	39	One-beam irradiation, $30\text{-}\mu\text{m}$ focal spot with $f/1.1$ lenses

8.5.8 ABSORBED ENERGY MEASUREMENTS

The fraction of laser energy absorbed by the target is a determining factor in the efficiency of a laser fusion experiment. An indirect method of measuring this energy was presented in the preceding section where the scattered light was discussed. A more direct method of measuring the absorbed energy is now presented.

The energy absorbed by a laser fusion target results in the compression and ignition of the thermonuclear fuel as well as in kinetic energy of the ions and

electrons of the ablated material and x rays. In the exploding pusher type targets used thus far, most of this energy is recovered as directed kinetic energy of the ions at times large compared to the laser pulse width. The relative percentage of x-ray and electron energy varies with experimental conditions which define the relative importance of various absorption mechanisms. Hence the ion energy alone is not sufficient to determine the total absorbed energy.

Separate measurements of electron and x-ray energies in various energy bands have been made and are discussed in other sections of this report. Charge collector data⁸⁸ provide information on ion blow-off symmetry and show the existence of "fast ions."^{89,90} Figure 8-148 shows a typical "fast ion" peak in raw data format for a ball target and the unfolded energy spectrum for a Parylene disk target. However, conversion of these data to total energy is subject to large errors. Unless high-accuracy spectrometer data are available, the mass and degree of ionization of the ions contributing to the charge collected are not sufficiently well defined to allow unfolding of the data into an ion energy spectrum. Moreover, corrections for mass and charge-dependent secondary processes are not well understood and calibrations are often limited to a single ion species.⁹¹ Finally, large uncertainties result from processing photographically recorded data spanning several orders of magnitude.⁸⁹

In addition, low-energy x-rays and electrons are difficult to detect and therefore their total energy is not well known.

Clearly separate measurements of ion, electron, and x-ray energies are not adequate for total absorption measurements.

An alternate method of obtaining the integrated particle and x-ray energy was therefore developed. These measurements complement the light energy balance discussed previously and have provided valuable information on the absorption processes.

Special-purpose calorimeters described in Sec. 8.3.3 were used with different targets both at the Janus and Cyclops irradiation facilities. Initially, only two to three calorimeters were installed at various positions within the target chamber. Results were compared to calculated ion energy distributions. The general behavior of the blowoff as a function of polar angle was qualitatively verified. Figure 8-149 shows the relative magnitude of various calorimeter readings for Parylene disks irradiated with 2 to 3×10^{15} W/cm². Although it may at first be surprising to find comparable energy fluxes in front and back of a target irradiated from one side only, the computed distribution shows a "plume" of energy in back of the target (relative to the incident beam). In addition, data were obtained directly behind the target ($\Theta = 0$) for irradiations of 10^{16} to 10^{17} W/cm²; in these cases, the energy behind the target was approximately 4 times larger than at 135° . This again agrees qualitatively with the computed distribution. Insufficient data were obtained in these experiments to assess the effect of the azimuthal location of the calorimeters. Note that the calculated distribution would have suggested locating the front calorimeter closer to the target normal where the ion flux is large. However, the shadow of the focusing lens mount lim-

Fig. 8-148. Charge collector data show "fast ion" peaks. (a) Ion traces for an 8-J irradiation of a ball target at Janus. Both probes were located at 90° to the plane of polarization of the incident beam. Probe 1 was at 45° from the east beam, Probe 5 at 45° from the west beam. (b) The energy spectrum of the charge collected on Probe 1 for a 9-J irradiation of a Parylene disk is shown on the right. There is a definite peak around 20 keV/amu.

Fig. 8-149. Parylene disks at 10^{15} W/cm²: measured particles and x-ray energy fluxes qualitatively match the computed ion energy distribution. (a) The location of the calorimeters is indicated on a plot of a typical computed ion energy distribution. (b) The relative magnitude of the measured energy on the incident beam side of the target is compared to that measured behind the target at two locations. Because of the "plume" of energy behind the target, calorimeters 3 and 1 were expected to see comparable energies as verified experimentally. Calorimeter 2 is closer to the minimum in the distribution.

ited the space available for mounting diagnostics.

The energy measurements for bare-ball targets show the same qualitative agreement with calculations for calorimeter readings taken in the same azimuthal plane. For instance, Table 8-8 shows little variation with polar angle between calorimeter 2 and 3. However, calorimeters located in different azimuthal planes displayed larger differences than were predicted. For all

Janus experiments, a calorimeter located near the plane of polarization of the incident beam registered 2 to 4 times more energy than a calorimeter located at 90° to this plane, whereas calculations predicted at most a factor of 1.3 for the polar displacement of the calorimeters. Table 8-8 displays these results for bare-ball targets (calorimeters 1 and 2). Variations in irradiation preclude an exact proportionality between calorimeter readings but are not sufficient to explain the large systematic differences between the data.

The relative magnitude of the measured energies is consistent with polarization-dependent absorption mechanisms such as resonance absorption. Indeed, the coupled energy as measured by the calorimeters is maximum in the plane of polarization. This effect was also suggested by the scattered light distribution which is minimum in the plane of polarization as discussed in the preceding section, and emphasized the need for a better understanding of these absorption mechanisms.

Because of the potential importance of these mechanisms in the design of multiarm systems, a more detailed study of the blowoff structure was necessary. As a result several improved calorimeters (LC-17, see Sec. 8.3.3) were built and located in the Cyclops target chamber. Preliminary results indicate once again a dependence on both azimuthal and polar angles, although the azimuthal dependence is slight for the polar angle investigated. Additional calorimeters have also been installed to probe the energy lobes towards the focusing lenses.

The highly structured energy distribution precluded a precise determination of the total absorbed energy on the basis of the few calorimeters used in Janus. Thus, an energy distribution based on calculated values was assumed, scaled to the calorimeter data and used to estimate the total absorbed energy. This value was considerably lower than originally predicted by the code simulations. Using the absorbed energy deduced from the experimental data, the same order of magnitude was found for calculated and measured neutron yield. During experiments totally dedicated to absorbed energy measurements, the box calorimeter (Sec. 8.3.2) provided further improvement in neutron yield agreement.

At Cyclops, three to five calorimeters were used, allowing a better estimate of the absorbed energy. Using these measurements, 12 to 14% absorption was obtained for bare-ball targets compared to 20 to 25% at Janus.

Table 8-8. The particle and x-ray energy distribution for microspheres appears polarization-dependent. In spite of the near symmetry of incident energy, calorimeter 1 located close to the plane of polarization of the laser beam consistently recovers a larger fraction of the energy than calorimeter 2

Fill (mg/cm ³)	Incident energy (J)		Calorimeter data (mJ/sr)			Neutron yield
	East	West	1 ^a	2 ^b	3 ^c	
0	15.3	14.4	700	191	205	0
2	14.6	13.9	622	113	259	2×10^6
2	16.6	14.7	760	200	179	2.5×10^5
5	14.9	14.1	723	357	247	1.8×10^6
5	14.2	13.1	716	299	205	1.4×10^5

^a Calorimeter 1 at approximately 45° from the west beam, 12° from the plane of polarization.

^b Calorimeter 2 at approximately 60° from the east beam, 112° from the plane of polarization.

^c Calorimeter 3 at approximately 71° from the west beam, 101° from the plane of polarization.

Fig. 8-150. Scattered light and calorimeter measurements of the absorbed energy agree. For a given target, the particle and x-ray energy flux is proportional to the absorbed energy deduced from Si PIN diode measurements. The calorimeter is located close to the east beam and at 90° to the polarization plane of the incident radiation.

Comparison Between Absorbed Energy Measurements

Comparison of the energy recovered by one of the calorimeters to the absorbed energy as determined from light energy balance is shown in Fig. 8-150. This calorimeter was located near the east beam and in an azimuthal plane normal to the polarization plane of the incident radiation.

For a given type of target, the particle and x-ray flux in a given direction is expected to be proportional to the total absorbed energy. Figure 8-150 verifies this proportionality for Parylene disks irradiated with one beam and ball targets irradiated with two beams.

An increased number of calorimeters will enable us to map the energy carried by particles and x rays from laser fusion targets, as well as determine the fraction of incident energy absorbed independently of any calculated distribution on a shot to shot basis.

V. C. Rupert
S. R. Gunn

8.5.9 DETERMINATION OF THE DT ION TEMPERATURES OF LASER FUSION TARGETS

During the last year, we have obtained 10^7 neutrons and α particles by irradiating small glass microspheres containing a mixture of deuterium and tritium gases with a short laser pulse.

X-ray microscope images show that the glass pusher was imploded for these shots. The low-energy x-ray measurements indicate that the electrons in the glass were heated to a thermal temperature of about 0.5 keV. The measured temperature and calculated density are

consistent with thermonuclear burn producing the observed yield. However, previous to this time, no measurements have been made to determine the ion temperature of the compressed DT. There are other measurements which show that electrons with energies greater than 100 keV and fast ions (100 keV to several MeV) are produced from laser plasma targets. It is conceivable that deuterons and tritons may also be accelerated to high energies and that they, in turn,

produce neutrons and α particles from beam-target or beam-beam reactions rather than a true thermonuclear burn. This phenomenon has been documented in both magnetically confined and laser produced plasmas. Therefore, it was the purpose of this work to measure the spread in the α -particle energy distribution to determine the velocities of the interacting DT ions.

A unique advantage to present-day laser fusion experiments is that the glass wall of the microshell is thin, 0.5 μm ; hence, the 3.52-MeV α particles from DT reactions escape with little energy loss. The energy broadening as a function of ion temperature is the same for α particles and neutrons, and the neutron energy broadening experiment will be done when we achieve larger yields. For the present experiments application of the time-of-flight technique to the α particles rather than to the neutrons effects a large advantage in energy resolution, thus allowing us to place the α particle detector closer to the source and make an ion temperature measurement with the present yields. Since the energy E and the velocity v of the α particle are 0.25 times the energy and velocity of the neutron, then for the same temporal resolution $\Delta\tau$ and flight path d an increase of 16 in the energy resolution is gained by measuring the α -particle dispersion:

$$\Delta E = 2E(v/d)\Delta\tau.$$

The time-of-flight experimental setup is described in detail in Sec. 8.3.5.

These experiments were carried out at the Janus laser facility. Oscilloscope traces of α particles from two experiments are shown in Fig. 8-151 and pertinent data are given in Table 8-9. The time width is the FWHM of the distribution in Fig. 8-151. The energy width is corrected for the instrument response. In calculating the total α -source strength, isotropic emission was assumed. The results compare favorably with the neutron source strengths measured separately. The ion temperatures were calculated from the measured α -energy widths.

A background measurement was done with a 0.013-cm-thick mylar foil in front of the detector. The signal, normalized to the neutron measurements, was reduced the correct amount for α particles of 3.3 MeV. This measurement also showed that 1.6-MeV deuterons, which would be deflected the same angle in the magnetic field and have the same time of flight as the α particles, did not contribute to the measured signals. The estimated error in the α mean energy measurement is ± 30 keV.

The theoretical energy broadening of the α distribution as a function of ion temperature θ_i was calculated from the kinetic equations for the reaction. Monte

Experiment 1

Experiment 2

Fig. 8-151. Oscilloscope traces of α -particle distribution. Sweep speed, 10 ns/cm.

Carlo averages were taken over the angle between the incident particles, and over the angle between the emitted α and the center-of-mass motion. It was assumed that each particle species had a Maxwell-Boltzmann velocity distribution. The reaction rate was computed by folding the velocity dependent distribution function with an empirical cross-section function. The calculated α -particle distribution is approximately Gaussian with FWHM, $\Delta E = 177\sqrt{\theta_i}$ keV, in agreement with the analytical expression of Brysk.⁹² A second calculation was performed to determine the α -particle distribution that would be produced by beam-target interactions; i.e., a beam composed of an equal number of deuterons and tritons of equal energy spherically converging on a cold DT target. The distribution is square with a width $\Delta E = 150\sqrt{E_{D,T}}$

Table 8-9. Summary of α -particle distribution measurements and calculated ion temperatures

Experiment	Time width (ns)	Average α energy (MeV)	Energy width (keV)	Ion temp (keV)	α source strength ($\times 10^6$)	n source strength ($\times 10^6$)
1	12.2	3.27	340	3.7	4.0 ± 0.8	3.9
2	10.5	3.36	315	3.2	5.5 ± 1	4.7

(keV), where $E_{D,T}$ is the energy of the deuterons or the tritons in keV. Another calculation was done for the extreme case of a deuteron beam interacting with a triton beam of the same energy. The α -particle distribution from these reactions has a width of $\Delta E = 75\sqrt{E_{D,T}}$ keV. The measured widths would require either a beam energy of about 5 keV in a cold target or colliding beam energies of about 20 keV. Other situations, e.g., a beam interacting with a Maxwellian ion distribution, fall between these two calculated cases.

The inferred ion temperatures (Table 8-9) represent an upper limit, because other effects contribute to the α width: nonuniform or time-varying energy losses in the DT fuel and glass wall, Doppler broadening by the gross hydrodynamic motion of the fuel, and straggling. Using temperature density profiles taken from numerical simulations that reproduce the total DT yield and the measured x-ray spectrum, we estimated the energy loss through the glass shell to be 300 keV for experiment 1 and 120 keV for experiment 2 at the time of peak thermonuclear burn. Table 8-9 shows losses of 250 and 160 keV. The calculated increments to the α broadening were approximately 150 and 180 keV. After the experimental values are corrected for this broadening, the average widths of the two experiments resulting from kinematic broadening alone are 305 and

260 keV. These widths correspond to DT temperatures of 3.0 and 2.2 keV. This is in good agreement with 1.6- to 3.0-keV values calculated by numerically modeling these imploding microshells with the two-dimensional Lagrangian magnetohydrodynamic code LASNEX.

The measurements show that the reactions took place inside the glass microshell, because the α -particle energies are shifted 0.2 MeV below their original 3.52-MeV value. Thus, these experiments have demonstrated that the ions are heated and interact inside the microshell and have energies comparable to those found in a Maxwell-Boltzmann distribution with an upper limit temperature of 3.2 to 3.7 keV. This is significant evidence that the reactions are thermonuclear.

W. Slivinsky
H. G. Ahlstrom
K. G. Tirsell
J. Larsen
S. Glaros
G. Zimmerman
H. Shay
H. Catron

References

1. *Laser Program Annual Report - 1974*, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975), pp. 368-421.
2. See Ref. 1, pp. 354-368.
3. M. Born and E. Wolf, *Principles of Optics* (Pergamon Press, Oxford, 1970), p. 458.
4. See Ref. 1, pp. 200-210.
5. V. I. Bespalov and V. I. Talonov, "Filamentary Structure of Light Beams in Nonlinear Liquids," *JETP Lett.* **3**, 307 (1966).
6. E. S. Bliss, J. 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. See Ref. 1, pp. 434-438.
8. See Ref. 1, pp. 36.
9. G. Dube, "Background Energy Content of Mode Locked Laser Pulses," *Appl. Phys. Lett.* **18**, 69 (1971).
10. See Ref. 1, pp. 249-251.
11. See Ref. 1, pp. 71-73.
12. See Ref. 1, p. 298.
13. See Ref. 1, p. 300.
14. D. MacQuigg, "Focal Shifts, Chromatic Aberration, and Atmospheric Pressure Effects in Target Imaging Systems," Memorandum LPL 76-2-031, Feb. 18, 1976.
15. Schott Optical Glass Catalog, p. II-4.
16. A. Graube, "Advances in Bleaching Methods for Photographically Recorded Holograms," *Appl. Optics* **13**, 2942 (1974).
17. R. L. Lamberts, "Characterization of a Bleached Photographic Material," *Appl. Optics* **11**, 33 (1972).
18. J. T. Hunt and P. A. Renard, "Focusing Properties of the Janus Beam," Memorandum TDA 75-138, Oct. 27, 1975.
19. E. S. Bliss, D. Speck, and W. W. Simmons, *Appl. Phys. Lett.* **25**, 728 (1974).
20. C. E. Thomas, "Laser Fusion Target Illumination Systems," *Appl. Optics* **14**, 1267 (1975).
21. S. S. Glaros and A. J. Glass, *Compound Ellipsoidal Focusing System for Fusion Targets*, Lawrence Livermore Laboratory, Rept. UCRL-77249 (1975).
22. J. B. Trenholme and E. J. Goodwin, private communication, GHOST - A Ghost Focusing Computer Code by Goodwin, LLL.
23. T. T. Saito et al., *1.06- μ m, 150-psec Laser Damage Study of Diamond Turned, Diamond Turned - Polished, and Polished Metal Mirrors*, Lawrence Livermore Laboratory Rept. UCRL-76822 Rev. 1 (1975).
24. See Ref. 1, pp. 60, 467-480.
25. K. R. Manes, W. B. Lindquist, P. Renard, H. E. Eddleman, D. L. Smith, S. S. Glaros, T. C. Stewart, and R. A. Haas, "Valkyrie," A CO₂ Laser System for Laser Fusion Experiments," in Press.
26. C. E. Thomas, "Laser Fusion Target Illumination System," *Appl. Optics* **14**, 1267 (1975).
27. See Ref. 1, Chap. 5.
28. See Ref. 1, p. 296.
29. F. Rienecker, and S. Glaros, and M. Kobiernicki, *Argus Target Chambers*, Lawrence Livermore Laboratory, Rept. UCRL-77248 (1975).
30. S. R. Gunn, *Model LC-13 Laser Calorimeter Using Commercial Thermoelectric Modules*, Lawrence Livermore Laboratory, Rept. UCID-16608 (1974).
31. *Laser Fusion Program Semiannual Report July-December*, Lawrence Livermore Laboratory, Rept. UCRL-50021-72-2 (1972), pp. 49-50.
32. *Laser Fusion Program Semiannual Report January-June*, Lawrence Livermore Laboratory, Rept. UCRL-50021-73-1 (1973), p. 82.
33. See Ref. 1, pp. 290-291.
34. L. I. Smetanina, I. I. Metveeva, and Z. V. Bruk, "Calorimetric Probes for Measuring the Energy of an Ionized Beam," *High Temperature* **3**, 572 (1965).
35. E. R. Harrison, "The Design of Calorimeters for the Determination of Ion Beam Intensities," *J. Sci. Instrum.* **34**, (1957), p. 242.

36. R. A. Lerche, L. W. Coleman, and J. W. Houghton, "Neutron Time-of-Flight Spectrometer for Laser-Fusion Experiments," paper presented at the 1975 Annual Meeting of the Division of Plasma Physics of the APS.
37. E. F. Plechaty and J. R. Kimlinger, *TART Monte Carlo Neutron-Transport Code*, Lawrence Livermore Laboratory, Rept. UCIR-522 (1971).
38. J. B. Birks, *Theory and Practice of Scintillation Counting*, (McMillan, New York, 1964), p. 188.
39. L. C. Northcliffe and R. F. Schilling, *Nuclear Data Tables* **7**, No. 3-4 (1970).
40. See Ref. 1, pp. 315-319.
41. C. F. McConaghy and L. W. Coleman, *Appl. Phys. Lett.* **25**, 268 (1974).
42. L. W. Coleman and D. T. Attwood, *Bull. Amer. Phys. Soc.* **20**, 1267 (1975).
43. B. L. Henke, J. A. Smith, and D. T. Attwood, to be published.
44. H. J. Weaver, unpublished.
45. P. B. Lyons, C. R. Hurlbut, and L. P. Hocker, "Sub-Nanosecond Plastic Scintillators," to be published in *Nuclear Instruments and Methods* (1975).
46. N. S. Kapany, *Fiber Optics Principles and Applications* (Academic Press, New York, 1967), p. 269.
47. See Ref. 1, pp. 439-440.
48. J. L. Gaines and R. A. Hansen, Memorandum UOPE 76-14 (1976).
49. D. T. Attwood, L. W. Coleman, and D. W. Sweeney, *Appl. Phys. Lett.* **26**, 616 (1975).
50. J. Stamper and B. Ripin, *Phys. Rev. Lett.* **34**, 138 (1975).
51. V. E. Hampel and J. A. Wade, *Master Control - A Unifying Free Form Data Storage and Data Retrieval System for Dissimilar Data Bases*, Lawrence Livermore Laboratory, Rept. UCRL-71686 (1968).
52. Information Research Group, Master Control Users Manual, Rev. 8, 10/75.
53. Lawrence Livermore Laboratory Stock No. 5935-62627, Electronics Engineering Dept. Drawing LEA 75-9035-01, BNC/BNC Bulkhead Mount Jack with Isolated Bushings.
54. *CAMAC - A Modular Instrumentation System for Data Handling*, U. S. AEC Rept. Y3AT7:22 TID-25875.
55. C. E. Frerking and H. F. Finn, "Description of the XLASE Program," Lawrence Livermore Laboratory, Memorandum DAG 74-57, Oct. 7, 1974.
56. *Annual Report*, Los Alamos Scientific Laboratory, Los Alamos, N. Mex., 1974.
57. P. Kaw, G. Schmidt, and T. Wilcox, *Phys. Fluids*, **16**, 1522 (1973).
58. J. Thompson, private communication.
59. W. C. Mead, W. L. Kruer, J. D. Lindl, and H. D. Shay, *Bull. Am. Phys. Soc.* **20**, 1246 (1975).
60. G. Charatis, J. Downward, R. Goforth, B. Guscat, T. Henderson, S. Hildum, R. Johnson, K. Moncur, T. Leonard, F. Mayer, S. Segall, L. Siebert, D. Solomon, and C. Thomas, Proceedings 5th IAEA Plasma Fusion Conference, Tokyo, Japan (1974).
61. 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. Dizier, R. D. Bleach, J. A. Stamper, and E. A. McLean, *Phys. Rev. Lett.* **34**, 1313 (1975).
62. L. M. Goldman, J. Soures, and M. J. Tubin, *Phys. Rev. Lett.* **31**, 1184 (1973).
63. B. H. Ripin, J. M. McMahon, E. A. McLean, W. M. Manheimer, and J. A. Stamper, *Phys. Rev. Lett.* **33**, 634 (1974).
64. J. F. Kephart, R. P. Godwin, and G. H. McCall, *Appl. Phys. Lett.* **25**, 108 (1974).
65. J. A. Glaze, D. Speck, and J. T. Hunt, *Geometrical Theory of Nonlinear Phase Distortion of Intense Laser Beams*, Lawrence Livermore Laboratory, Rept. UCRL-76834 (1975).
66. D. R. Speck and D. MacQuigg, unpublished.
67. D. W. Phillion, R. A. Lerche, V. C. Rupert, K. R. Manes, and S. R. Gunn, *Bull. Am. Phys. Soc.* **20**, 1286 (1975).
68. M. J. Boyle, F. D. Seward, T. L. Harper, L. N. Koppel, K. J. Pettipiece, and H. H. Ahlstrom, *Rev. Sci. Instr.*, April, 1976.
69. K. G. Tirsell, R. A. Haas, H. C. Catron, and V. W. Slivinsky, *Bull. Am. Phys. Soc.* **20**, 1246 (1975).
70. V. C. Rupert, S. R. Gunn, and J. F. Holzrichter, *Bull. Am. Phys. Soc.* **20**, 1286 (1975).
71. A. J. Glass and A. H. Guenther, *Appl. Optics* **12**, 637 (1973).
72. D. R. MacQuigg, J. F. Holzrichter, J. T. Hung, J. E. Swain, D. R. Speck, E. Storm, and K. J. Pettipiece, *Bull. Am. Phys. Soc.* **20**, 1285 (1975).
73. W. L. Kruer, E. J. Valeo, and K. G. Estabrook, *Phys. Rev. Lett.* **35**, 1076 (1975).
74. See Ref. 1, p. 321.

75. See Ref. 1, p. 310.
76. V. W. Slivinsky, H. G. Ahlstrom, K. G. Tirsell, J. Larsen, S. Giaros, G. Zimmermann, and H. Shay, *Measurement of the Ion Temperature in Laser Driven Fusion*, Lawrence Livermore Laboratory, Rept. UCRL-78938 (1975).
77. A. W. Ehler, *J. Appl. Phys.* **46**, 2464 (1975).
78. V. W. Slivinsky, H. G. Ahlstrom, H. G. Tirsell, S. S. Giaros, G. B. Zimmerman, and H. D. Shay, *Phys. Rev. Lett.* **35**, 1083 (1975).
79. J. F. Holzrichter, H. G. Ahlstrom, D. R. Speck, E. 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 Asymmetrically Irradiated Laser Fusion Targets*, Lawrence Livermore Laboratory, Rept. UCRL-76860 Rev. 1 (1975).
80. See Ref. 1, pp. 289-353.
81. J. F. Holzrichter and D. R. Speck, *Laser Focusing Limitations from Nonlinear Beam Instabilities*, to be published in *J. Appl. Phys.*, **47**, 2459 (1976) 1976; Lawrence Livermore Laboratory, Rept. UCRL-77107 (1975).
82. See Ref. 1, pp. 320-325.
83. N. G. Alexandropoulos, *Appl. Spectra* **28**, 155 (1974).
84. V. L. Ginszburg, *Propagation of Electromagnetic Waves in Plasmas*, 2nd Ed. (Pergamon Press, New York, 1964), pp. 260-280.
85. J. M. Dawson and A. T. Lin, *Parametric Instabilities in Plasmas*, UCLA Plasma Physics Laboratory report (September, 1974), p. 191.
86. K. G. Estabrook, E. J. Valeo, and W. L. Kruer, "Two Dimensional Relativistic Simulations of Resonance Absorption," *Phys. Fluids* **18**, 1151 (1975).
87. D. W. Forslund, J. M. Kinde', Kenneth Lee, and E. L. Lindman, *Absorption of Laser Light on Self-Consistent Plasma Density Profiles*, Los Alamos Laboratory Rept. LA-UR-74-1636.
88. See Ref. 1, pp. 334-335.
89. KMSF - U298, ERDA - A Data Report, p. V.18, 1975.
90. A. W. Ehler, "High Energy Ions From a CO₂ Laser Produced Plasma," *J. Appl. Phys.* **46**, 2464 (1975).
91. J. E. Osher, *Limitations and Calibrations of Gridded Ion Detectors*, Lawrence Livermore Laboratory, Rept. UCRL-77537 (1975).
92. H. Brysk, *Plasma Phys.* **15**, 611 (1973).

9. QUANTUM ELECTRONICS RESEARCH

Section Editor: E.V. George

9. QUANTUM ELECTRONICS RESEARCH

- Efficiency measurements in the rare gas excimers show that up to 50% of the energy deposited in a high-pressure rare gas by an electron beam can be converted to excimer fluorescence.
- The production kinetics and radiative properties of rare gas oxide excimers have been explored and show that short pulse lasers near 1% efficiency with energy storage of 10 J/liter can be constructed.
- The rare gas-halogen and dihalogen systems have been explored as a class of efficient radiators to complement the rare gas excimers. A Br_2 laser at 292 nm has been demonstrated, and XeBr fluorescence efficiency of 11% has been measured.
- An XeBr excimer-pumped atomic iodine laser has been demonstrated, and the systems considerations involved in scaling atomic iodine lasers to large sizes have been identified and are discussed.
- Oxygen, sulfur, and selenium have been analyzed as candidates for an optically pumped, visible energy storage laser.
- The physical and radiative properties of gaseous rare earth compounds, which may be suitable for energy storage lasers, have been measured and are discussed.
- Scaling considerations have been identified for drivers for large, electron-beam-pumped lasers.
- Theoretical studies bearing on an understanding of the basic atomic and molecular physics which must be understood for laser development and isotope separation projects have been carried out. These include efforts to develop a theoretical understanding rare-gas halogen structure and kinetics, copper vapor laser kinetics, electron interactions such as dissociative attachment, and other areas.

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9. QUANTUM ELECTRONICS RESEARCH

9.1 Overview

The Advanced Quantum Electronics (AQE) element of the LLL Laser program was organized as a broadly based, cohesive activity in 1975. It is structured with two groups: an expanded Advanced Lasers Group (ALG) and a newly-created Theoretical Atomic and Molecular Physics Group (TAMP). Through a balanced application of theoretical, analytical, computational, and experimental skills, the AQE activity seeks to fulfill two primary programmatic needs: (1) to identify, demonstrate, and pursue the technological development of new laser devices and systems in Laser Fusion (LF) and Laser Isotope Separation (LIS) applications; and (2) to provide theoretical, analytical, and computational expertise in areas of atomic and molecular physics and chemistry relevant to LIS and laser photochemical processes. The broadly based, multidisciplinary character of the AQE effort responds to the recognition that both LF and LIS applications require the development of concepts and quantum electronic devices which are at or beyond the frontiers of our present knowledge. Moreover, both LF and LIS programs are in the earliest phases of defining applications and their attendant laser requirements, based on a rapidly expanding body of knowledge of the relevant fundamental processes. As these programs mature and as the applications requirements harden, it is the function of the AQE effort to anticipate laser problems and ensure that conceptual and technological solutions have been identified. To place the current AQE activities in perspective, we first describe the general technical objectives for advanced laser R&D and the methodology which we have adopted in an effort to reach these objectives.

In the laser fusion program, our current understanding of fusion implosion processes and our application of this understanding to various reactor concepts leads

to a range of laser systems performance requirements summarized in Table 9-1. The parameter ranges shown are based, in part, on fairly cursory assessments of current and projected levels of associated technologies (power conditioning, energy transport, optical materials, etc.) and are therefore not to be construed as rigorous. Given these requirements, we have performed an analysis to determine the physical, spectral, and collisional properties of atoms and/or molecules which are technically consistent. A summary of the physical and dynamical properties on potentially viable laser media is presented in Table 9-2 together with an indication of the principal constraining phenomena. Although many gaseous species provide a few of the desired properties, those which are likely to satisfy all requirements simultaneously are indeed quite rare. Unfortunately, precisely those atomic and molecular species which are of interest (metastable electronic states) have been least studied in the past; thus we have very little data for immediate conceptual assessment. Another critical factor which dictates our search methodology also emerges from the information in Table 9-2. By design, large lasers for fusion applications will be characterized by a low small signal gain coefficient (i.e., $\alpha \sim 0.01 \text{ cm}^{-1}$) and a relatively high saturation energy density (i.e., $E_s \sim 1 \text{ J/cm}^2$). This implies that we can verify dynamical models of laser performance only with the commitment of substantial resources, both in facilities and manpower. A premium is therefore placed on the highest level of sophisticated laser modeling and "off-line" kinetics measurements to allow for a critical evaluation of candidate laser media before we undertake even preliminary scaling experimentation.

The circumstances outlined above have prompted us to adopt the "search and assess" methodology that is

Table 9-1. Advanced laser requirements for fusion applications

Wavelength	3000 Å-15000 Å
Energy storage density	10-100 J/liter
Pulse length	1-5 ns
Pulse energy	100-1000 kJ
Energy storage time	$\gtrsim 0.5 \mu\text{s}$
Pulse repetition rate	10-100 Hz
Efficiency	$\geq 1\%$
Beam quality	High, target-dependent

Table 9-2. Physical and dynamical constraints on fusion laser media

Metastable electronic transitions	(storage time)
Inversion density $\Delta n = 10^{17}$ to 10^{18} cm ⁻³	(energy density)
Gain cross section $\sigma = 10^{-19}$ to 10^{-20} cm ²	(parasitics; saturation)
Spherical or shielded electronic state	(collisional stability)
Minimum medium density	(nonlinear effects; beam quality)
Sparse level structure	(no excited state absorption)
Gas medium	(high average power; flow)

shown schematically in Fig. 9-1. The laser applications requirements indicated here simply as wavelength, pulsewidth, energy, etc., are actually much more sophisticated and derive from "zeroth order" systems analyses which attempt to take into account reactor constraints and the laser as a system, including beam quality, staging, etc. Further analysis (and exploratory experiments performed) indicate that scalable pumping techniques, which are also compatible with collisional (dynamical) constraints associated with viable laser media, are quite limited; consideration of viable pumping techniques must therefore be factored into the selection of systems for experimental studies very early. During the past three years, we have emphasized the identification of generic pumping techniques and generic classes of gaseous laser media which are compatible with the various pumping techniques and which meet the rigorous physical and dynamical requirements outlined above. We have identified to date three generic pumping techniques and have organized our basic research program around them: 1) direct electron beam pumping, 2) optical pumping using efficient e-beam driven, uv-radiating substances, and 3) electrical discharges. We prefer to think in terms of generic pump techniques because a single laser molecular species can quite often be excited by more than one pumping technique. Consistent with these generic pumping techniques, we have identified four generic classes of atomic/molecular gaseous media generally satisfying the technical requirements given above: 1) group VI A atoms, optically pumped; 2) rare gas-group VI excimers, e-beam pumped; 3) rare gas-metal excimers, e-beam pumped; 4) photolytic atom rare gas, halogen pumped; and recently an entirely new system, 5) trivalent rare-earth molecular vapors, optically and possibly e-beam pumped. We are continuing our efforts to identify additional generic gas laser media.

Having identified generic classes of laser media and compatible pumping techniques, we have selected specific molecular species within the class for detailed

study. For example, in the class of rare gas-group VI excimers, we are performing detailed experimental, theoretical, and computations studies on XeO and KrO laser media. As stated above, all of the basic structural, spectral, and dynamical information required to fully predict laser performance generally will not be available. Theoretical estimates are made for unknown parameters we think are relevant, and these are combined with "off-line" experimental spectroscopic and kinetics measurements. Exploratory experiments to demonstrate stimulated emission are carried out together with the development of a dynamical laser model, which is then used to identify additional cross sections and rates required to fully describe observed laser performance and assess the scalability and utility of the laser medium for advanced applications. When a specific laser candidate has been adequately modeled and the model verified through rigorous small-scale experiments, we can decide on a systems-scaling experiment in the form of a staged master oscillator power amplified (MOPA) chain.

In order to implement this search methodology in an efficient manner, we have invested in the development of a number of complementary experimental facilities. During 1975 we designed and constructed two new facilities (LAMP and PEBS) which will complement the larger, existing laser testbed facilities. Taken together, these facilities provide a flexible capability to conduct exploratory research experiments addressing the issues outlined in Fig. 9-1.

In the context of the LIS program, we again must recognize that a wide variety of distinct physical and chemical processes can be driven by radiation to provide separation of isotopes and desirable photochemical products. Within a given process, many different atoms and/or molecules can be used, each demanding a unique set of laser properties and performance requirements. As the LIS program matures during the next decade, we must maintain a broadly based R&D effort to continuously interpret laser requirements for ad-

Fig. 9-1. Laser development methodology.

vanced LIS applications and provide for rapid development of useful laser devices and systems. At the present time, the LIS program is exploring uranium enrichment based on the photoionization of atomic uranium vapor. In direct support of these experiments, the near-term laser activity has centered on the technology and development of high pulse-repetition-rate copper-vapor lasers as coherent pump sources for organic dye MOPA chains. Looking at longer term needs, we have initiated an aggressive experimental and theoretical program addressing the rare gas-halogens as potentially useful lasers for advance LIS applications. Additional new laser media are being identified and evaluated in the context of the methodology represented in Fig. 9-1.

Detailed laser fusion experimental research is re-

viewed below under headings associated with the generic pumping disciplines: high energy electron beams, photon pumping, and gaseous electronics. Identified laser fusion project efforts are reported under a separate heading. Theoretical atomic and molecular physics efforts are presented in terms of facilities (codes, and data bases), disciplines (atomic and molecular structures, electron and heavy particle scattering, photo-ionization, and photon physics) and projects (rare gas-halogen lasers, copper/copper-halogen lasers, and actinide atomic structure analysis).

W. F. Krupke

9.1.1 ELECTRON BEAM FACILITIES

In support of both the LIS and LF gas laser research programs, several experimental electron beam facilities have been constructed. Their typical operating characteristics are summarized in Table 9-3. Two of these facilities, LAMP and PEBS, have just recently been completed; in the following subsections we discuss their characteristics in more detail. A description of the remaining facilities illustrated in Table 9-3 can be found in Ref. 1.

The LAMP (Laser Atomic and Molecular Physics) Facility

The advanced laser group has been given the tasks of identifying new laser media applicable to LF and LIS and establishing scaling relations prior to their insertion into on-line programmatic experiments. An important facet of this process involves building a data base of spectroscopic and kinetic information which permits us

Table 9-3. Summary of electron beam facilities used in the gaseous laser research program

Source	Voltage (keV)	Current (kA)	Characteristics			
			Current density (A/cm ²)	Beam area (cm × cm)	Pulse- width	Pulse rate
MEG I	1000	100	>1000	2 × 10	50 ns	
MEG II	1000	100	300	7 × 50	50 ns	
706	600	10	>1000	1 (diam)	1.6 ns	
S ³	300	10	10	10 × 100	1 μs	
Lamp	120	.03	10	0.1 × 2	2 ns-dc	100 Hz
PEBS	300	3	30	3 × 30	100 ns	60 Hz
422	2000	150	500	5 × 50	50 ns	

to assess whether a candidate laser medium is behaving as expected in terms of energy channeling. According to our experience determination of these traits does not proceed efficiently when attempted on large, single-pulse machines. Therefore, we have established a high-repetition-rate electron beam facility for small-scale direct electron beam and photolytic pumping studies in a manned area.

For the facility we have chosen an electron gun of the well-known LINAC injector (dispenser cathode) type, designed for reliable operation at high repetition rates. A schematic of the gun is shown in Fig. 9-2. A hot cathode established at a potential of 120 kV with respect to the front of the gun housing is maintained at + 200-300 V with respect to a grid located in front of it. The injection of a ~ 2kV pulse into the cathode causes electron bursts to proceed from the cathode to the front of the gun where suitable beam-shaping optics produce an approximately 2.5-cm-diam beam of 120-keV electrons at a current density of about 10 A/cm². The divergence of this beam is quite low as far as 20 cm from the front of the gun. Pulses widths as short as 2 ns at repetition rates of 0-100 Hz are available.

The electron beam is injected into a gas cell through a 2.5-μm-thick nickel foil attached to a nickel substrate containing a 0.25-mm-wide by 31.7-mm-long slot. Attachment is made via a 2-μm-thick slurry of nickel and high-temperature epoxy which is free of voids. The pressure of the gas in the cell can be adjusted over the range 0-10 atm. Since the electron gun and beam drift sections are evacuated, the thin foil deflects into the substrate slot and assumes a cylindrical configuration at stress levels near the yield point for the material. The substrate slot is designed such that the foil yield is less than 2% at the maximum allowable working pressure of 10 atm.

As shown in Fig. 9-3, this apparatus can be used for either direct electron beam pumping or photolytic/

optical pumping. The energy deposition can be varied from about 5-500 mJ/cm² in the electron-beam pumped cell simply by varying the pulsewidth of the gun. This flexibility is crucial in detecting excited-state-loss processes. Furthermore, while the total pumped volume is quite small in this case, the energy deposition per unit volume can be adjusted to simulate conditions in all of the larger machines operating within the program at this time.

The facility is presently being configured to study fluorescence lifetimes and the spectroscopy of rare-gas-halogen mixtures. A natural corollary to this work will be the use of these materials as photolytic sources.

J. Swingle

The Repetitively-Pulsed Electron Beam Source (PEBS) Facility

The LAMP facility is configured to acquire basic kinetics data on laser systems of interest to LIS and LF. To facilitate the evaluation of the laser properties for promising media at rapid data-acquisition rates, we have acquired a repetitively-pulsed electron beam source (PEBS) from Ion Physics Corporation (IPC). This source, shown in Fig. 9-4, is configured to study both direct electron-beam pumping and e-beam sustainer pumping of gaseous media and produces 50-J pulses of 300 keV and 100 ns at a rate up to 30 Hz continuously.

The source consists of a coaxially-housed eight-stage Marx generator. This low-inductance configuration provides a current risetime of 10 ns and a characteristic source impedance of 25 Ω. The rectangular pulse is shaped by a modified Type A Guilleman circuit developed at LLL. This rectangular pulse is applied directly to the diode.

PEBS was initially designed by IPC for industrial processing, but we have significantly modified it for

Fig. 9-2. Experimental cell for the LAMP e-beam gun.

Fig. 9-3. Internal layout of the LAMP e-beam gun.

Fig. 9-4. PEBS configured for direct e-beam pumping of RGH laser.

laser pumping. The major modifications include diode design, pulse forming circuit, trigger system, vacuum system, and shielding.

We have designed two diodes and three cells for use with PEBS. One diode produces 3×40 on e-beam at 30 A/cm^2 transverse to the cell axis for laser pumping. The two cells used in conjunction with this diode are a direct-pumped cell and an e-beam augmented discharge cell. The latter cell has a low inductance feed for the transverse electric discharge field. The third diode-cell configuration employs a coaxial geometry whereby the electrons are injected radially inward through a thin metal-foil cylindrical cell. We expect this latter cell to produce more uniform direct e-beam pumping and higher efficiency whereas the former cells, having

transverse gas flow, are optimized for higher repetition rates.

The diode-cell configuration is surrounded by a contiguous lead shield to attenuate the x rays produced by the bremsstrahlung radiation to a safe level and permit "hands on" operation. This will permit the experimenter to manipulate the laser and auxiliary equipment during operation.

The main object of developing PEBS, and also LAMP, is to provide compact, reliable repetition-rate sources for a variety of e-beam pumping experiments relevant to new-generation gas lasers.

L. Bradley
C. Duncan

9.2 High Energy Electron Pumping of Media

The studies in this program element are presently directed towards both theoretical and experimental understanding of the interactions of high energy (100 kV - 2 MV) electrons with high pressure (approximately atmospheric or greater) gaseous media. This work is multidisciplinary and encompasses such scientific areas as collisional physics, kinetic processes, and quantum

electronics. An important part of this effort is the development of comprehensive laser system computer models, including electron transport and deposition, dynamical photon and particle interactions, and radiation transport. Predictions from these models are validated by numerous experiments, some of which are described in this section.

9.2.1 EFFICIENCY MEASUREMENTS IN THE RARE GAS EXCIMER

Reliable measurements of fluorescence efficiency in electron beam pumped gases can be essential to systems analysis in the search for lasers suitable for scaling to very high peak or average power. This is obviously true for photolytic lasers driven by electron-beam excited fluorescence, such as has been proposed for the group VI atomic metastables and was recently demonstrated for atomic iodine (see Sec. 9.3.1).

The group VI metastables $G(^1S)$, $St(^1S)$ and $Se(^1S)$ appear to have several advantages for fusion applications and can be produced at high quantum yield by appropriate vacuum-uv (vuv) excimer fluorescence from Ar, Kr, or Xe. A significant factor in the evaluation of this type of laser is the efficiency for electron-beam production of the excimer radiation. By invoking energy balance constraints, this efficiency has been estimated² to be potentially as high as 50% for Ar, Kr, and Xe in the absence of several possible loss processes that depend on the excitation conditions. However, experimental measurement for a variety of excitation sources and particle densities has given efficiency values ranging from a few percent to as high as 100%.

Previous Measurements

At very low excitation densities experimental efficiency measurements of unspecified accuracy have approached the 50% "theoretical" limit. Condensed phase fluorescence³ excited by 5.3-MeV α -particles resulted in a crude efficiency estimate of between 10 and 100% for krypton and xenon. More recent condensed phase studies⁴ using a pulsed electron source (10-30 kV, 1-30 mA, 0.08-8 μ s) gave an efficiency of 50-55% for xenon. The efficiency for solid argon and krypton "was estimated to be of the same magnitude" in the same paper. Room temperature gas phase fluorescence⁵ was excited by 4-MeV protons at an efficiency of 29% for Ar at 400 Torr, 12% for Kr at 400 Torr, and 9% for Xe at 300 Torr.

Unfortunately, it was not certain that the higher efficiency values applied for practical excitation densities and sources. Substantially lower fluorescence

efficiencies were obtained at the very high excitation densities associated with e-beam pumped high-pressure rare-gas excimer lasers.^{6,7} Typical e-beam parameters were a few kA/cm² at 1 MeV for 50 ns. For pressures greater than 15 atm, the resulting energy deposition is at least several tens of J/cm². The efficiency values quoted were $15 \pm 7\%$ for Ar, $4 \pm 1.6\%$ for Kr, and $10 \pm 4\%$ for Xe. The reduction in fluorescence efficiency at high excitation density is attributed to excited-state excited-state losses (Penning ionization). The laser efficiencies are even lower (no more than 1%) due to the additional problems of photoionization and reduced gain resulting from elevated gas temperature.

Rationale for Moderate Excitation Density

Obviously, the prior measurements applied to the extremes of excitation density. If fluorescence pumping times can be significantly increased, the fluorescence rate and excitation density can be substantially reduced while maintaining a useful integrated fluorescence energy. Since Penning ionization losses scale as the square of the excited state density, we would expect increased efficiency. In the case of the group VI metastables, we expect that photolysis times as long as 1-10 μ s can be used. Thus, we must seriously consider moderate excitation density conditions such as those accessible with the EB-300 facility, namely, current densities of 1-10 A/cm² at about 200 keV for a few microseconds. For rare gases at 1-3 atm, the resulting energy deposition would typically be in the 10-100 mJ/cm² range.

Increased efficiency at moderate excitation density conditions has been predicted by some computer calculations based on a kinetic model⁸ that has successfully predicted certain fluorescence and laser characteristics in high pressure xenon and krypton. The calculations, performed for krypton at 2 atm and EB-300 beam parameters, gave encouragingly high values of about 50%. The model includes estimated Penning ionization, photoionization, gas temperature, and electron

temperature effects. (Some unknown cross sections were established by fitting high pressure data, and the model validity may deteriorate at low pressure.)

Experimental Objective

Encouraged by the above optimistic expectation, we began a program to measure the fluorescence efficiency for e^- -beam-produced rare gas excimers (Ar_2^* , Kr_2^* and Xe_2^*) using the relatively gentle pumping capabilities of the EB-300 facility. This program was required because 1) a factor of two uncertainty in a 20-50% efficiency can have a critical impact on device feasibility analysis, and 2) no reliable information was available for conditions expected to be optimum for group VI metastable pumping.

The desired absolute fluorescence efficiency is a deceptively simple ratio of radiated energy per unit volume to electron beam energy deposited per unit volume. To obtain this quantity reliably, we have to carefully attack both the numerator and the denominator. The techniques developed in our program are generally applicable. The fact that the rare gases play an important role in such a wide variety of electron-beam-pumped lasers (e.g., rare gas oxides, rare gas halides, and other energy transfer systems such as Ar^*-N_2 and $Ar_2^*-Br_2$) has made our work on energy deposition especially useful for determination of other fluorescence and laser efficiencies (see Secs. 9.2.3 and 9.3.1). Below, we describe our optical techniques, present, in detail, our approach for determining the spatial distribution of electron-beam energy deposition in a gas cell, and, lastly, give some results of the application of these techniques.

Radiated Energy Density Determination

For the efficiency numerator, we measured the energy radiated from a well-defined truncated-cone field of view established by two optical-beam-defining apertures having radii r_1 and r_2 which were much smaller than their separation s . With this geometry, a very accurate approximate analytical formula for the effective radiating volume V_{eff} can be obtained in the case of a uniform, homogeneous, isotropic, transparent volumetric gaseous radiator which completely fills the field of view over a region of length L . The result is

$$V_{eff} \approx \frac{L}{4\pi} A \Omega = \frac{\pi}{4} \frac{r_1^2 r_2^2}{s^2} L,$$

where $A = \pi r_1^2$ is the area of the entrance pupil (first aperture) and $\Omega = \pi r_2^2/s^2$ is the solid angle subtended by the exit pupil (second aperture) at any point in the entrance pupil. It is also assumed that the index of

refraction n in the radiating gas and in the space surrounding the detection optics is essentially the same.

The above result is obtained by considering the radiating gas to consist of an infinite number of elementary sheets of thickness dz which are normal to the optical axis. Each sheet can be considered to be a Lambertian radiator whose radiance (W per cm^2 projected area per steradian) is $N = P_v dz/4\pi$, where P_v is the isotropic radiated power per unit volume. The power transmitted by the exit pupil from each elementary sheet is

$$dW = \iint N dA d\Omega,$$

where dA is an elementary area on the emitting "surface" and $d\Omega$ is an elementary solid angle subtended by an elementary area of the exit pupil at dA . The area integration is taken over the emitting sheet, and the solid angle integration is taken over the exit pupil surface. If P_v and, therefore, N are constant throughout the field of view, then the invariance of N/n^2 along a ray⁹ can be invoked to shift the area integration for each sheet to the entrance pupil. If, in addition, the aperture separation s is large compared to the aperture radii, then the area and solid angle integrations are separable. We obtain the result

$$dW = N \cdot A \cdot \Omega = \frac{P_v}{4\pi} A \Omega dz.$$

Integrating over a length L of radiating gas gives the total power transmitted by the exit pupil,

$$W = \frac{\pi}{4} \frac{r_1^2 r_2^2}{s^2} L P_v.$$

The expression for V_{eff} results from the definition

$$W \equiv P_v \cdot V_{eff}.$$

The above analysis shows that the power or energy collected from any sheet in a uniform volumetric radiator filling the field of view is the same. Thus there is no spatial discrimination along the optical axis. We note, however, that the optical collection efficiency on a sheet is a function of the distance from the optical axis, and this radial variation is different for different sheets. Therefore, deviations from a uniform radiator obviously modify the simple result given above for V_{eff} .

We chose the optical axis such that there was minimum spatial variation of the energy deposited both along and transverse to it (see below). No corrections to V_{eff} were made for nonuniform emission in the results reported below. We judged that they were not warranted by the overall experimental accuracy.

Our optical system was configured with apertures of equal radius ($r_1 = r_2 = 3.2$ mm), separated by a distance $s = 24$ cm, and viewed a length $L = 14$ cm of excited gas which was backed by a black anodized aluminum plate. The entrance pupil was located in the plane of a gas cell wall. A 3-mm thick MgF_2 window between the apertures separated the gas cell from the evacuated light pipe which contained the exit pupil, several scattered light baffles, and an ITT F4115 photodiode. The photodiode was placed behind the exit pupil in such a way that all the transmitted rays struck a region of the 1.9-cm-diam photocathode which was approximately the same size as that illuminated during the calibration (4-mm diameter). The photodiode sensitivity and MgF_2 window transmission were carefully measured in the vuv. The optics were protected from oil contamination by use of a liquid nitrogen cold trap in the vacuum line.

To minimize scattered light collection we used black anodized aluminum apertures and scatter baffles as well as blackened light pipe walls.

The spectral distribution of radiation was limited by the "solar-blind" photodiode to the 110-320 nm region. The portion of the optical signal transmitted through air was typically less than 7% and subtracted out on a multishot-average basis. Photographic spectra confirmed that the emission was mainly from the expected vuv excimer bands.

Electron Beam Energy Deposition Determination

To obtain the efficiency denominator, we have chosen a technique which avoids the pitfall of assuming that electrons travel a straight-line path losing energy in a one-dimensional fashion according to the tabulated Berger and Seltzer stopping powers.¹⁰ We experimentally determined the beam spatial profiles and fluence (J/cm^2) on the gas side of the cell foil. These data were then input to a sophisticated computer code SANDYL,¹¹ which calculated the spatial distribution of energy deposition by following electrons as they lost energy on a complicated three-dimensional path. The SANDYL-calculated energy deposition distribution was simply averaged over the zones along the optical axis to get the energy deposited per unit volume for calculation of the efficiency. In addition, we have verified the applicability of the SANDYL code in our operating regime by detailed calorimetry vs position along the longitudinal (horizontal) e^- -beam axis in the gas.

The electron beam source consisted of a two-stage Marx bank with a tantalum-blade cold cathode. Under typical operating conditions, the electrons entered the

gas with an average energy of about 205 keV after losing 30 keV in a 1 mil (25 μm) titanium foil. The e^- -beam excitation pulse observed by Faraday cup and current probe measurements in the gas cell was approximately trapezoidal with a FWHM of 1 μs and approximately 150 ns rise and fall times. The average current density over the 10×100 cm^2 cathode and 1 μs pulse duration was about 2.5 A/cm^2 . Diode voltage droop during the pulse was only about 7% since most of the stored energy was crowbarred. The output capacitance and maximum output voltage were 0.375 μF and 300 kV, respectively. The usual charge voltage was 130 kV for a 260 kV output voltage.

The calorimetric verification of SANDYL and fluorescence excitation was performed in a 15-cm-high $\times$ 100-cm-wide $\times$ 15-cm-deep gas cell. Two calorimeter arrays were constructed to measure the vertical and horizontal beam fluence distribution. These arrays could be mounted on a rectangular frame which did not affect the beam fluence at the calorimeters and which could be translated about 13 cm along the e^- -beam axis from outside the cell without disturbing the cell pressure. Pictures of the cell, arrays, and frame assembly have been published elsewhere.¹² The design features calorimeters that are essentially levitated and thermally isolated to facilitate clean data analysis and computer modeling.

The calorimeters were designed to have millisecond risetimes which were required to separate e^- -beam deposited energy from gas heating effects at gas depths approaching the effective electron range. Each calorimeter segment consisted of a 16-mm-square aluminum wafer having a 0.43-mm thickness, which is about twice the Berger and Seltzer range for 200 keV electrons, to insure total stopping capability. The thermal equilibration time τ across the 0.43 mm dimension l is predicted from the thermal diffusivity of aluminum α to be $\tau = l^2/\alpha = 1.7$ ms. At the rear center of each aluminum square, a fast intrinsic thermocouple junction of low mass was formed by spotwelding 0.08 mm diameter chromel and constantan wires in close proximity. Experimentally observed risetimes were about 1 ms. The vertical array was formed by five independent calorimeter wafers separated by 3 mm gaps. The horizontal array used 10 wafers separated by 1 cm gaps, but adjacent pairs were wired in parallel to give, in effect, only five calorimeters.

Additional precautions were taken to avoid systematic errors. The teflon-insulated thermocouple wires were protected from direct e^- -beam exposure by routing them through alumina beads and a hollow 3.2-mm-o.d. alumina rod to which the calorimeters were attached with silastic cement along an edge. Each calorimeter segment was grounded through a fine wire to the frame in order to prevent charge accumulation.

Maximum temperature rises were only about 10 K. In order to minimize the chance of gas contamination, the calorimeter hardware was removed from the cell during fluorescence measurements.

Some of the features of the SANDYL code that make it such a powerful tool are that it deals with electron energy loss in three dimensions and includes an enormous amount of physics implemented through a hybrid combination of Monte Carlo and analytical techniques. For example, it considers energy loss to atomic electrons, scattering from screened atomic nuclei, and generation and tracking of energetic secondaries. It accounts for the energy variation of the stopping power and cross sections. Radiation phenomena are also included. The energy, angular, and spatial distributions of the beam electrons can be specified to the required degree of realism. In addition, effects such as absorption, scatter, and backscatter associated with realistic gas cell construction (foil, foil support, and walls) can be incorporated.

Collective phenomena are not considered in SANDYL. However, the estimated contribution to energy deposition due to effects such as induced currents and charge accumulation was negligible for our current density, risetime, gas pressure, and cell geometry.¹³

In calorimeter calculations, the code effectively provides the measured quantity, namely, the net energy dose from all sides, taking into account both gas and calorimeter backscatter. For gas deposition, it calculates the detailed spatial distribution within the cell — information that is probably unobtainable by any other general method. However, to relate either type of calculation directly to an experiment, we must normalize computed and experimental calorimetry for some longitudinal position. This procedure basically determines the total incident beam energy for specified operating conditions.

In our SANDYL calculations, we used a monoenergetic 235-keV beam incident on the foil. This value represents the average of the energy distribution determined from the diode voltage and current time dependence. The standard deviation of the energy distribution was less than 5 keV. Our monoenergetic assumption was justified by the fact that ± 5 keV beam energy variations did not significantly affect the SANDYL calculations of interest. We also neglected any initial transverse electron energy. This assumption was justified by the following considerations. The foil thickness was less than 15% of the Berger and Seltzer range, so reasonable mean incidence angles would not significantly change the effective foil thickness or energy lost in the foil. Also, SANDYL calculations with such a "cold" beam gave mean foil exit angles of about 40 degrees which is significantly larger than, and hence insensitive to, reasonable estimates of the mean

angle of incidence. The input vertical profile on the diode side of the foil was iteratively adjusted with SANDYL to give self-consistency between the calculated and measured profiles at the foil in the gas cell. We found the beam fluence measured at the foil by the horizontal calorimeter array to be uniform within 10% error. Thus, the input vertical profile was taken to be independent of the horizontal transverse coordinate.

Figure 9-5 shows the excellent agreement between experimental calorimeter fluence and SANDYL as a function of depth in argon at a pressure of 2 atm for the five vertical calorimeters. The results at one atm are equally good. It is convincing to note that the same normalization constant was used for all five curves shown. The small arrows along the horizontal coordinate axes indicate the positions of the SANDYL calculations. The curves are offset by the amounts indicated in order to present all five calorimeters on a single figure.

Having verified the reliability of SANDYL for our operating conditions, we used it to calculate energy deposition in argon. Figure 9-6 shows longitudinal horizontal distributions at one and two atmospheres of argon. For comparison, 1-D Berger and Seltzer values are indicated by the horizontal dashes at the left. In the 1-D description, these values would not change significantly across the box. The important point is that the Berger and Seltzer values would seriously overestimate the efficiency by a factor of three near the foil, and such estimates are seen to be quite inadequate for reliable efficiency values. In the inset, the broad dotted arrow and square show, to scale, the e⁻-beam height and cell cross section. The curves apply to the dotted 3-cm-high strip across the vertical center of the cell. The dashed vertical lines across the figure indicate the region viewed by our optical system. Figure 9-7 shows the calculated vertical deposition profiles in this region. Note that the axes have the same relative scales as Fig. 9-6, and the vertical transverse profiles are relatively smooth compared to the longitudinal profiles of Fig. 9-6. The solid lines simply connect the SANDYL zone values whose standard deviations were typically about 8% for 32,000 particles distributed over a 12.3×35 cm² model beam area.

Experimental Efficiency Results

By combining the optical techniques described above with experimentally normalized energy deposition calculations, we have obtained the fluorescence efficiency results shown in Table 9-4 at the indicated

Fig. 9-5. Comparison of SANDYL and calorimetry for argon at 2 atm.

excited state densities.* The 1 atm argon result is considered to be the most reliable since, in this case, the SANDYL energy deposition is least sensitive to the beam energy used and the energy deposition profiles are most uniform. The overall combined statistical error in this result is estimated to be about $\pm 25\%$. For the other pure rare gas results, the energy deposition circulation at 9 cm into the gas is more sensitive to beam energy, and there is more potential for a systematic error. We would not expect a factor of two error in the worst case. Since the beam energy used in the

calculations may have been somewhat high, we would expect the efficiency values given to be too low. The combined statistical error due to all other effects is again estimated to be about $\pm 25\%$ for the pure rare gases.

The error with the fluorescence efficiency for XeBr* plus Br₂* emission is estimated to be $\pm 50\%$ of the tabulated value. The uncertainty is larger due to correction of the optical signal observed on a calibrated photodiode (through a narrow bandpass filter peaked at 281.2 nm) by a photographic spectrum covering the 260-350 nm fluorescence band.

The pure rare gas average excimer density values shown in Table 9-4 represent rough estimates. They depend on the ratio of triplet to singlet excimer density, N_3/N_1 , and lifetime, τ_3/τ_1 . The quantity $N_3\tau_1/N_1\tau_3$ was assumed to be negligible compared to one. The ratio

*The efficiencies, approximate excimer densities, and radiated energies (E_{rad}) for pure argon and krypton given in Table 9-4 are higher by a factor of about 2.1 than previously reported¹² due to a numerical error in the input data to the computer code used at that time to determine V_{eff} . The code and the analytic formula given above now agree to better than 1%.

Fig. 9-6. Longitudinal gas deposition profiles calculated by SANDYL in argon. The electron energy is 235 keV before the 25-μm titanium foil. The foil loss is about 30 keV.

N_2/N_1 depends in a sensitive fashion on the excitation conditions; however, we have used the statistical assumption $N_2/N_1 = 3$. The values shown were actually obtained by multiplying the total number of photons radiated per cm² by $4\tau_1/\tau_p$, where $\tau_p = 1 \mu s$ was the pulse length. If, instead, one were to assume $N_2/N_1 = 1$, the values would be a factor of two lower. For argon and krypton we used $\tau_1 = 4$ and 5 ns, $\tau_2 = 3$ and $1 \mu s$, respectively. The excited state density for XeBr^* plus Br_2^* emission was estimated by assuming a single effective radiative lifetime $\tau_{\text{rad}} = 15$ ns and multiplying the total photon density by $\tau_{\text{rad}}\tau_p$.

The high efficiency values in Table 9-4 are in excellent agreement with theoretical upper limits and model calculations even at the useful EB-300 excitation density conditions. This is in contrast to the low efficiencies observed previously for very high excitation densities. These near-50% fluorescence efficiencies give considerable hope for producing either excimer lasers or photolytically pumped group VI metastable lasers at reasonable efficiency.

We have recently modified our gas cell to allow location of the fluorescence optical axis anywhere be-

tween 2 and 10 cm from cell foil. This will permit us to extend our measurements to higher pressures and heavier gases. We are planning to look at xenon and reexamine some of the Kr and Ar results.

C. E. Turner, Jr.
P. W. Hoff
J. Taska
L. G. Schlitt

9.2.2 RARE GAS-OXIDE LASERS

In the 1974 Annual Report an initial characterization of rare gas-oxide lasers, their properties, and possible application as scalable fusion lasers was

Gas: Argon

Electron energy: 235 keV before foil

Foil: 25 μ m titanium (1 mil)

Foil loss: ~30 keV

Fig. 9-7. Vertical gas deposition profiles calculated by SANDYL in argon along the optical axis. The electron energy is 235 keV before the 25- μ m titanium foil. The foil loss is about 30 keV.

given.¹⁴ Energy storage in these devices is provided by oxygen atoms excited to the 1S state. The excited oxygen atoms result from energy transfer processes following ionization of rare gas-oxygen mixtures by an electron beam. The concentration of rare gas is typically ten or more atmospheres, the oxygen concentration several Torr. Like the Nd:glass lasers, the optical properties of the excited atoms are significantly modified by the host, in this case the rare gas. The $^1S - ^1D$ green auroral line exhibits a radiation rate orders of magnitude greater than its 1.25 s^{-1} free-space emission rate and is, hence, collision-induced. Some estimates of the optical cross sections, energy storage, and efficiency of these media were given in last year's report. These and several other issues have been carefully examined in the past year both within the Laboratory and through contractual support. A relatively small scaling effort is currently underway to study energy extraction from a folded-path amplifier having a gain length of several meters.

Radiative Properties of $O(^1S)$

Theory. A theory of the green emission from $O(^1S)$ induced by collision with Ar has been developed under ERDA contract by Julienne, Trauss, and Stevens¹⁵ at NBS. Potential curves for the molecules $O(^1S)\text{-Ar}$ and $O(^1D)\text{-Ar}$ were estimated by combining the long-range van der Waals attraction determined by empirical rules with the short-range repulsion calculated *ab initio*. As shown in Fig. 9-8, $O(^1S)\text{-Ar}$ produce a single molecular state $^1\Sigma^+$ which is optically connected to $^1\Sigma^+$ and $^1\Pi$ states arising from $O(^1D)\text{-Ar}$. The binding of the upper molecular state is very small, approximately one-third

Table 9-4. Fluorescence efficiencies

Gas	Pressure (Torr)	Efficiency (%)	Approximate excimer density ($10^{13}/\text{cm}^3$)	E_{rad} (mJ/cm^3)	E_{dep} (mJ/cm^3)
Ar	760	52	4.0	4.0	7.5
Ar	1520	45	4.0	4.2	9.6
Kr	760	47	3.6	2.5	5.5
Ar:Xe:Br ₂	1500:25:1	~10	11	~5	44

Fig. 9-8. Calculated potential curves for the Ar-O molecule.¹⁵ The state $2'\Sigma^+$ arises from Ar-O(1S) while $1'\Sigma^+$ and $1'\pi$ arise from Ar-O(1D). The energy splitting between O(1S) and O(1D) is omitted.

of the average energy of colliding pairs at 300 K. An optical transition moment arises from the dipole moment of lower state molecules induced by the electric field of the 1D atomic quadrupole. This quadrupole-induced dipole varies with internuclear separation as R^{-3} giving a radiation rate varying as R^{-8} . The emission intensity and lineshape were calculated quantum mechanically by a thermal average of the transition moment $|\langle \epsilon'J' | t(R) | \epsilon''J'' \rangle|^2$ over upper state energies ϵ and rotational quantum numbers J' , and a sum over final states. The predicted spectra and total emission rate are in approximate agreement with experiments discussed later.

Depending on whether the relative kinetic energy is less or greater than the binding of its molecular state, emission can arise from both bound and free molecules. In principle, spectral components bound-bound, free-bound, bound-free, and free-free are possible. The calculations of Julienne *et al.* predict that 94% of the ArO emission arises from free upper-states at 300 K. This is intuitively reasonable given the small binding compared to the average kinetic energy as well as the weighting of the transition moment toward short-range repulsive collisions.

The collisional nature of the induced emission relates to the possible energy extraction time in short-pulse laser applications. The primary energy storage in these media is in 1S oxygen atoms while the optical gain is provided by a relatively small number of rare gas-O(1S) molecules. The energy extraction time is limited by the cross relaxation rate. Free emission arising in bimolecular collisions exhibits a cross relaxation rate much greater than bound emission which requires a three-body stabilization event.

It is presumed that the effective spontaneous emission rate of O(1S) in rare gas buffer is given by

$$A_{\text{eff}} = A_0 + kn, \quad (1)$$

where A_0 is the free-space spontaneous rate, 1.25 s^{-1} , n is the density of rare gas, and k is the collision-induced emission rate having the units $\text{cm}^3 \cdot \text{s}^{-1}$. It is important to note that this emission rate refers to the concentration of O(1S); it does not determine the emission rate of a given rare gas-oxide molecule. This is a natural description where there is the possibility of free emission in which "molecules" can have various internuclear separations and, hence, various emission rates. Also, notice that this description does not distinguish whether the emission arises from bound or free molecular pairs. Their concentration in either case increases linearly with rare gas density causing a linear increase in the effective spontaneous rate.

Experiment. Collision-induced emission rates have been determined by a photolysis technique using the MEG I electron beam facility. A 50-ns pulse of Ar_2^* radiation in a wavelength band centered at 126 nm and containing several mJ energy was used to photolyze N_2O in a separate cell producing O(1S).¹⁶ For the experimental conditions of 0.1 - 3.0 Torr N_2O , the O(1S) decay is normally dominated by collisional deactivation with N_2O (decay rate of approximately $1 \times 10^{-11} \text{ cm}^3$) rather than deactivation caused by the rare gas. The addition of rare gas to the photolysis cell causes the O(1S) to emit more intensely but does not change its density or time dependence. We used a photomultiplier tube having a flat spectral response to view the O(1S) fluorescence through a 10-nm-width bandpass filter centered at 555 nm. The filter was necessary to discriminate against scattered visible light from the Ar_2^* source as well as vuv-generated, visible fluorescence from the MgF_2 input window to the photolytic cell. Such background levels were constant and could be subtracted from the signal.

An O(1S) atomic fluorescence signal is compared to a collision-stimulated signal in Fig. 9-9. The atomic signal contains some background; the collision-stimulated signal, however, greatly exceeds the background and was attenuated by a neutral density filter to

prevent photomultiplier saturation. According to Eq. (1), the fluorescence signal at a perturber density n is given by

$$S \propto (A_0 T_A + kn T_M). \quad (2)$$

The constant of proportionality involves collection efficiency and detector sensitivity while T_A and T_M represent the bandpass filter transmission factors for the atomic and molecular signals which differ in their spectral composition. By comparing the collision-induced and atomic signals, one obtains

$$\frac{S}{S_A} - 1 = \frac{kn}{A_0} \frac{T_M}{T_A} \quad (3)$$

Fig. 9-9. (a) Atomic quadrupole fluorescence $O(^1S)$ generated by its natural free-space lifetime of 0.8 s. The deactivation is caused by 1 Torr of N_2O . (b) Collision-induced fluorescence caused by the addition of 100 Torr of Kr for the same conditions as (a). An optical attenuation of 5.6 was used. The oscilloscope scales are the same.

Fig. 9-10. Collision-stimulated fluorescence vs perturber pressure (300 K). The signals are normalized to the atomic level, observed with no additive gas.

Graphs of this signal ratio vs perturber pressure are shown in Fig. 9-10. For our range of pressures, collision-induced radiation is observed to increase the fluorescence by as much as three orders of magnitude over the atom signal. The straight lines are drawn with unity slope as predicted by Eq. (3). The slight deviation from linearity in the Kr data is attributed to a loss of $O(^1S)$ caused by absorption of Ar_2^* radiation by the added Kr. The molecular transmission factor T_M was measured by alternately removing and inserting the bandpass filter for high pressure conditions where the background was negligible. The atom transmission factor T_A was determined by using scattered light from a narrow band 557.7 nm cw source which approximated the emitting volume. Obtaining reliable values for the atomic fluorescence signal posed the major difficulty in these experiments. Spectral measurements indicated that nitrogen first-positive emission was present near 558 nm under conditions of large vuv input fluxes. Such emission might arise from excited-state excited-state processes such as

since $N_2(A^3\Sigma)$ is also known to be a photolysis product at this wavelength. This problem was minimized by using the smallest input flux (1 mJ) and N_2O pressure (0.15 Torr) consistent with obtaining an atomic fluorescence signal. In Table 9-5 the rates obtained for these conditions are shown and compared to those

Table 9-5. Collision-induced emission rate for $O(^1S)^a$

	(300° K)			
	LLL ¹⁷	Black, Sharpless, and Slanger ¹⁸	Atkinson and Welge ¹⁹	Cunningham and Clark ²⁰
Ar	4.9×10^{-18}	4.7×10^{-18}	4.8×10^{-18}	3.9×10^{-18}
Kr	2.27×10^{-17}	2.1×10^{-17}	1.95×10^{-17}	—
Xe	3.2×10^{-15}	2.1×10^{-15}	3.7×10^{-15}	1.7×10^{-15}

^aUnits: $\text{cm}^3 \cdot \text{s}^{-1}$

obtained by workers. The measurements of Black *et al.* at SRI were supported by ERDA contract and employed a similar photolytic technique.

In contrast with the Ar and Kr cases, the Xe-induced fluorescence was observed to exhibit a finite risetime consistent with a three-body formation process. Examples of this dependence are given in Fig. 9-11. A simple kinetic model for this process is given by the rate equation

$$\frac{d}{dt}(\text{XeO}) = \sum_i k_f^i(M_i)(\text{Xe})(\text{O}) - \sum_i k_r^i(M_i)(\text{O})(\text{XeO}) \quad (4)$$

$$- \tau^{-1}(\text{XeO}),$$

where k_f^i and k_r^i are the formation and destruction coefficients for $\text{XeO}(^1S)$ by the specie i , and τ is the $\text{XeO}(^1S)$ radiative lifetime. For an instantaneous source of $O(^1S)$, the XeO time-dependence is given by

$$\text{XeO}(t) = \frac{\sum_i k_f^i(M_i)(\text{O})(\text{Xe})}{\sum_i k_r^i(M_i) + \tau^{-1}} [1 - \exp(-\alpha t)], \quad (5)$$

where the approach to equilibrium is governed by the net destruction rate

$$\alpha = \sum_i k_r^i(M_i) + \tau^{-1} \quad (6)$$

For sufficiently low Xe pressure, the fluorescence risetime should simply be the XeO A-coefficient, τ^{-1} . By this argument, the trace in Fig. 9-11a implies a radiative lifetime of about 250 ns. As demonstrated by Fig. 9-11b, the approach to chemical equilibrium becomes extremely fast with the addition of a diluent. In reality, the chemical kinetics are somewhat more complex than this simple view because of vibrational relaxation and the possible change of radiative lifetime with vibrational level.

Fig. 9-11. Risetime of XeO fluorescence following the photolysis of H_2O by a 50-ns-duration vuv pulse. The gas pressures were 0.2 Torr N_2O and 3 Torr Xe at (a) 3 Torr He and (b) 100 Torr He.

We undertook study of the temperature dependence of the collision-induced emission rates to determine whether the emitting molecules are bound or free.

Bound emission should decrease with temperature because of molecular dissociation while free emission should remain constant or increase slowly. When we repeated the MEG I experiments with the photolytic cell heated to 400 and 500 K, it became increasingly more difficult to obtain reliable atomic fluorescence signals and hence induced rates at elevated temperature because of the more rapid deactivation by N_2O . However, the ratios of Ar, Kr, and Xe stimulation could be determined accurately. An alternative basis for absolute emission rates was provided by kinetic deactivation of O^1S by Xe.

Xenon pressures of a few hundred Torr were directly observed to increase the O^1S kinetic decay rate. Measurements of the Xe deactivation rate at room temperature were only 25%, greater than the induced rate of green emission. This is consistent with the view that the Xe deactivation arises solely from radiative processes in the visible [$\text{Xe O}^1\text{S} \rightarrow \text{Xe O}^1\text{D} + h\nu$] and ultraviolet [$\text{Xe O}^1\text{S} \rightarrow \text{Xe O}^3\text{P} + h\nu$]. Measurements of the Xe deactivation rate were then used to assign absolute stimulation rates. The results are given in Table 9-6.

The Xe deactivation rate clearly exhibits a negative temperature dependence; its slope is in good agreement with the spectroscopically determined binding energy of Xe O^1S , namely 0.06 eV.²¹ The Ar and Kr rates exhibit no strong temperature dependence. These data as well as the kinetic risetime information lead us to conclude that the ArO and KrO emission at room temperature and above is dominated by free molecules.

Optical cross sections referenced to the O^1S concentration are determined by the formula

$$a = \lambda^2 (8\pi)^{-1} A g(\nu), \quad (7)$$

where A is the spontaneous emission rate and $g(\nu)$ is the spectral lineshape factor. Accurate lineshape factors for ArO and KrO have been obtained photographically using neutral density step wedges. The optical cross section results ($2.6 \times 10^{-21} \text{ cm}^2 \cdot \text{atm}^{-1}$ for ArO, $1.1 \times 10^{-20} \text{ cm}^2 \cdot \text{atm}^{-1}$ for KrO) are in good agreement with previous estimates.¹⁴ A value for the XeO cross section is not given because of its strong temperature dependence and complex spectrum.

Electron Beam Pumping of O^1S

Theory. The production mechanism of O^1S in electron-beam excited rare gas-oxygen mixtures is not firmly established although an ERDA contract to SRI under the direction of Lorents and Huestis is now addressing this problem. A two-step mechanism has been suggested²² which explains peculiarities in the Xe_2^* kinetic decay dependence on O_2 and which also explains the similar yields of O^1S from various oxygen donors (O_2 , CO_2). Ground state oxygen atoms are first produced by a dissociation step and are then excited to the ^1S state by collision with a rare gas excimer. Huestis has modeled his XeO results using the oxygen reactions

and

Table 9-6. Collision-induced emission rates for O^1S at 300, 400, 500 K^a

Temperature (K)	Ar*	Kr*	Xe*	Xe deactivation rate
300	4.9×10^{-18}	2.27×10^{-17}	3.2×10^{-15}	
	—	—	—	4.2×10^{-15}
400	4.2×10^{-18}	1.96×10^{-17}	1.53×10^{-15}	
	5.3×10^{-18}	2.5×10^{-17}	1.98×10^{-15}	2.6×10^{-15}
500	—	—	—	
	5.9×10^{-18}	2.8×10^{-17}	1.34×10^{-15}	1.76×10^{-15}

^aUnits: $\text{cm}^3 \cdot \text{s}^{-1}$. The upper rate is based on the atomic fluorescence intensity; the lower is based on the Xe deactivation rate.

The first step is experimentally observed in the time-decay of Xe_2^* excimer radiation at O_2 pressures greater than several Torr. The second step is suggested to proceed via an ionic intermediate state Xe_2^+O^- which predissociates to the outgoing channel. A bound ionic state, Xe^+O^- , has been observed in emission near 230 nm from the reaction of Xe metastables with N_2O .²³

For the mechanism given by Eqs. (8) and (9), three xenon excimers are used to produce two excited oxygen atoms. If the xenon excimer efficiency is 25-50% as measured for low current density conditions (see Sec. 9.2.1), an upper limit on the oxygen laser efficiency is 5-10%. This assumes that the deactivation caused by electrons is negligible.

The effect of electron deactivation has been investigated²⁴ by modifying the Xe_2^* excimer code of Werner, George, Hoff, and Rhodes²⁵ to include reactions (8) and (9) as well as electron processes with atomic oxygen:

The deactivation of $\text{O}(^1\text{S})$ to $\text{O}(^1\text{D})$ is the dominant electron process having a rate of $1.1 \times 10^{-10} \text{ cm}^3 \cdot \text{s}^{-1}$ at 1 eV found by integrating over calculated cross sections.²⁶ Results of the computer model are shown in Fig. 9-12 assuming that the rate of reaction (8) is $1 \times 10^{-10} \text{ cm}^3 \cdot \text{s}^{-1}$ and the rate of (9) is $3 \times 10^{-10} \text{ cm}^3 \cdot \text{s}^{-1}$. A saturation of the $\text{O}(^1\text{S})$ production with input current is clearly observed. The peak $\text{O}(^1\text{S})$ density at $150 \text{ A} \cdot \text{cm}^{-2}$ corresponds to a maximum extractable energy of $6.3 \text{ J} \cdot \text{liter}^{-1}$ with a medium efficiency of 1.3%. These predictions can be expected to have an accuracy no better than a factor of two. However, the general trend with electron current is clearly seen.

Experiment. Rare gas-oxide fluorescence intensities as a function of input current have been measured using the MEG I facility. The current was attenuated at constant voltage by placing a perforated carbon beam stop within the drift region. The beam profile was found to homogenize spatially very quickly after passing through this "holey plate." Relative deposition was measured from the pressure rise in the gas. Peak fluorescence intensity as a function of deposition is shown in Fig. 9-13. The Xe and Kr curves are normalized to lie on the Ar curve at low current. The maximum deposition point is the normal operating condition for MEG I and corresponds to the efficiencies given previously.¹⁴ Optimized efficiency clearly occurs for much smaller current densities, that is, less than $100 \text{ A} \cdot \text{cm}^{-2}$.

The characteristic current saturation for other ox-

Fig. 9-12. Calculated peak $\text{O}(^1\text{S})$ density vs O_2 pressure produced by a 50-ns-duration e-beam in 180-psi Xe for various current densities.

Fig. 9-13. Rare-gas oxide fluorescence intensity vs energy deposition. The gas pressures were: Ar, 53 atm; Kr, 26 atm; Xe, 13 atm; O_2 , 7 Torr. A deposition of 1.0 corresponds to an input current $\approx 1000 \text{ A/cm}^2$.

xygen donors was found to differ from O_2 . At the smallest current densities (about $25 \text{ A} \cdot \text{cm}^{-2}$), the $O(^1S)$ fluorescence using an N_2O mixture exceeded the O_2 value by a factor of two. At four times this current the two mixtures yielded equal fluorescence; however, in contrast with O_2 , the N_2O mixture had reached its fully saturated intensity.

A modest scaling experiment designed for current densities of $\approx 100 \text{ A} \cdot \text{cm}^{-2}$ is underway using the MEG II facility. An oscillator-amplifier arrangement is being assembled to extract energy from a gas volume having a useful optical aperture of $3 \times 10 \text{ cm}^2$ and an excitation length of 50 cm. By using multiple passes, the net gain length will be extended to several meters. A sketch of this experiment is shown in Fig. 9-14.

Dye laser gain measurements at the appropriate pumping density have been made using a smaller volume 50 cm cell. Examples of the single-pass gain observed in Xe/O_2 and Kr/O_2 mixtures are shown in

Fig. 9-15. The cw dye laser level appears at the left; a strong absorption occurs during the pumping followed by a sizable gain which follows the fluorescence decay. SANDYL code calculations have been made²⁷ to determine the energy deposited in the region probed. From the optical cross section and gain measurements, the extractable energy stored in $O(^1S)$ can be determined. Preliminary evaluation of the Kr results implies $4 \text{ J} \cdot \text{liter}^{-1}$ energy storage density with a medium efficiency of 1.2%.

Energy extraction from the rare gas oxides is being attempted by amplifying a $10^7 \text{ W} \cdot \text{cm}^{-2}$ flashlamp-pumped dye laser beam. Time-dependent gain saturation will be studied. Based upon the photolytic results, cross relaxation is not expected to pose an obstacle to energy extraction at this power level.

H. Powell
J. Murray

9.2.3 RARE GAS-HALIDE AND DIHALOGEN LASERS

A new class of electronic transition lasers has been discovered in 1975 which shows a great potential for

development as efficient sources in the 190-350 nm wavelength region to complement the similar class of

Fig. 9-14. Sketch of MEG II e-beam generator, several pass power amplifier, and pulsed dye laser driver.

(a) 50 ns/div

(b) 50 ns/div

Fig. 9-15. Small signal amplification at (a) 545.1 nm in XeO and (b) 555.8 nm in KrO. The operating pressures were: Xe, 12 atm and O₂, 6.5 Torr; Kr, 26 atm and O₂, 7 Torr.

rare gas excimer sources at shorter wavelengths. Laser oscillation has been observed with electron beam excitation on transitions of ArF* at 193 nm,²⁸ KrF* at 249 nm,^{29,30} XeBr* at 282 nm,³¹ XeCl* at 308 nm,³⁰ and XeF* at 353 nm.^{32,33} Laser oscillation has also been observed on the KrF* and XeF* transitions with electron-beam sustained discharges³⁴ and with direct discharge pumping.^{35,36} A number of other emission bands from species such as XeI and other krypton and argon halides have been observed^{37,38} but have not yet been shown to have gain. Oscillation has also been observed under similar electron beam excitation conditions on the high pressure bands of I₂ at 342 nm^{39,40} and Br₂ at 292 nm.⁴¹

Several of these new lasers, in particular the fluorides and I₂,⁴² show considerable potential for high efficiency, high energy sources in the ultraviolet and may have important applications as efficient pump sources for optically-pumped fusion lasers as well as their clear applications as efficient, moderately tunable sources for various isotope separation processes.

Structure of the Rare Gas Halides

The electronic structure of the rare gas-halide molecules is shown for a representative example, XeF*, in Fig. 9-16. There are a number of bound excited states of ionic character (Xe⁺F⁻) at large internuclear separations. These states may be rather accurately modeled^{33,37} by noting that the Xe* metastable closely resembles the Cs atom and will bind to F on a potential curve very similar to the CsF* ground state potential. Collisional quenching takes the molecule to the lowest of these ionic electronic states, a ²Σ, which then radiates to the ²Σ and ²Π states produced by the interaction of ground state Xe and F atoms. The ²Σ ground state of XeF has been shown to be slightly bound, as may also be the case for XeCl and perhaps other rare gas halides. Some other molecules, such as KrF*, have shown no evidence of binding in the ²Σ lower state.

Figure 9-17 shows a spectrum of the XeF* fluorescence excited in a mixture of 5 atm Ar, 150 Torr Xe, and 6 Torr NF₃. The intense, bound-bound transition at 353 nm which has been made to oscillate is identified as ²Σ⁺ - ²Σ⁻, while the weaker, bound-free transition at

Fig. 9-16. Estimate potential curves for xenon fluoride.

Fig. 9-17. Xenon fluoride fluorescence (logarithmic densitometer trace).

longer wavelengths is identified as $2\Sigma \rightarrow 2\Pi$. The intensity of this $\Sigma \rightarrow \Pi$ transition increases with respect to the narrow, $\Sigma \rightarrow \Sigma$ transition for heavier halogens such as Br and I. Laser oscillation has not yet been observed on the $\Sigma \rightarrow \Pi$ transition of any of these molecules, but the potentially wide tunability and lack of lower level bottlenecks in such a transition will stimulate considerable effort at achieving such oscillations in the near future.

The laser transitions in I_2 and Br_2 are of similar character to the rare gas-halide lasers, being transitions from the lowest bound ion-pair ($1^1\Sigma^+$) excited state to a weakly bound lower state which may be the $B^3\Pi_u(O_u^+)$ upper state of visible absorptions in I_2 and Br_2 , as shown⁴³ in Fig. 9-18. Several other possibilities have been proposed, and the state assignments for these transitions—as for the rare gas halides—are not at all clear at present. The Br_2 laser, which was first demonstrated at Livermore this year, will be discussed in more detail presently.

Production Mechanisms for Rare Gas-Halides and Excited Dihalogens

The mechanisms by which excited states of the rare gas-halides and dihalogens are efficiently formed by electron beam and discharge excitation has been a matter of intense speculation. It is known³⁸ that rare gas metastable attack on some halogen-containing molecules, such as the reactions

proceeds rapidly with high yield of excited rare gas halides. The production mechanism in the discharge

lasers presumably involves production of these metastables by discharge electrons and their subsequent collision with F_2 or NF_3 . In electron beam excited systems, which typically contain about 5 atm Ar, 150 Torr Xe, and 5 Torr F_2 or NF_3 , the production mechanism may involve the rare gas excimer chain to produce Ar_2^* , followed by Ar_2^* collisions with Xe to produce Xe^* and subsequent attack on NF_3 . Some ArF^* emission is seen from such systems, however, so the kinetic chain might involve the exchange

with ArF^* produced by argon atomic metastable or excimer collisions. It has also been speculated that ionic reactions such as

may be important. Much more work will need to be done before these systems are well understood; for the moment researchers must merely take advantage of the observed fact that efficient, if unknown, kinetic mechanisms do produce these excited states.

The 292 nm Br_2 Laser. Laser oscillation^{39,40} and efficient fluorescence⁴² have recently been studied on the 342 nm "high pressure" bands of I_2 excited by an electron beam in the presence of several atmospheres of argon. Evidence of gain on the analogous Br_2 292 nm bands has also been reported.⁴⁴ We confirm that these bands are inverted and can be made to oscillate in an argon-bromine mixture under such conditions.

The laser medium consisting of 2 atm of argon plus a few Torr of Br_2 is transversely excited by a 235 keV electron beam over a $10 \times 100 \text{ cm}^2$ area. The cell and e-beam machine and the method for determining current density and energy deposition are discussed in more detail in Sec. 9.2.1. Fused silica Brewster's-angle windows separated by 110-cm and 10-m-radius dielectric mirrors of about 99% reflectivity at 292 nm separated by 2 m are used for the laser experiments reported here. Fluorescence and laser signals are detected using biplanar photodiodes, with appropriate narrow band interference filters; or a thermopile calorimeter. Photographic spectra are obtained with a 1-m grating spectrograph.

Figure 9-19 shows the peak intensity of laser and fluorescence signals as a function of Br_2 pressure at constant argon pressure and excitation conditions. Note that above 1 Torr the fluorescence decreases monotonically with increasing Br_2 pressure, whereas the laser output maximizes for 3 Torr at a value corresponding to a cavity circulating power of 100 kW/cm². Figure 9-20 shows the time dependence of laser and fluorescence intensities for four Br_2 pressures covering the operating

range of the laser. At 3 Torr of Br_2 and below, there are two distinct time-resolved features in the laser emission. As the Br_2 pressure is increased to 3 Torr, the first and more energetic laser peak maintains constant delay to oscillation but increases in width and amplitude to follow the excitation pulse in spite of the decreasing fluorescence intensity. A likely explanation of this behavior is electronic or vibrational quenching of the laser lower level by Br_2 . As the Br_2 pressure is further

increased, the fluorescence intensity continues to decrease and the delay to lasing steadily increases until eventually the gain goes below threshold. We observe some contamination of the Brewster's-angle windows at higher Br_2 pressures which may contribute to the decline in laser performance. The second laser feature contains an increasingly smaller portion of the total emission as the bromine pressure is raised. At 1 Torr of Br_2 it lies in the tail of the fluorescence and shifts

Fig. 9-18. Estimated potential curves for I_2 . Two possible identifications for the 342-nm laser transition are shown. For a discussion see Ref. 43. The energies of the rare-gas excimers, which may transfer energy to I_2 , are also shown.

Fig. 9-19. Pressure dependence of Br₂ laser peak power and fluorescence.

toward the fall of the excitation pulse as the Br₂ pressure is increased. Above 3 Torr it can no longer be resolved. It appears clear from the behavior of the first laser pulse at low Br₂ pressure that lower level population effects are important in this laser. One might suspect, therefore, that the second pulse is governed by the kinetics of production and quenching of the lower laser level as the excitation terminates.

Some variation of output coupling was performed with available mirrors for the 3 Torr Br₂ plus 2 atm argon mixture. The laser small signal gain is estimated to be about 20% to 25% per meter from the observation of substantial output with a 70% reflector. The pulse energies transmitted by mirrors having reflectivities of 0.96, 0.92, and 0.70 were 5, 17, and 10 mJ respectively from a 3 cm² aperture. Although we have not fully optimized the output coupling, the energy available to be coupled out is clearly a few tens of millijoules, which is a very small fraction of the 15 J deposited in the 300 cm³ volume accessible to the laser field. A Br₂ laser is, therefore, not likely to be exceptionally efficient under the present conditions. The laser output energy may be limited by lower level bottlenecking since the laser self-termination at low Br₂ pressures implies that the lower level population is important.

Figure 9-21 shows the laser output spectrum at 3 Torr Br₂ plus 2 atm Ar with 99% mirrors, and Fig. 9-22 shows a fluorescence spectrum. Numerous rotational transitions of the most intense Br₂ emission bands are oscillating under these conditions, some more closely spaced than the 0.005 nm spectrograph resolution. Venkateswarlu and Verma¹⁵ have identified the bands between 291 and 293 nm as transitions from the 0-4 vibrational levels of an O_g⁺ state with ω_0 of 149 cm⁻¹ to the 11-16 vibrational levels of an O_u⁺ state with ω_0 of 166 cm⁻¹. The lower level has constants similar to the B³Π_g(O_u⁺) state which is the upper level of the visible absorption in Br₂ and may be that state. If the

Fig. 9-20. Oscilloscope traces of fluorescence and laser signals at: (a) 1 Torr, (b) 3 Torr, (c) 4 Torr, and (d) 8 Torr.

Fig. 9-21. Logarithmic densitometer trace of the Br₂ laser system.

Fig. 9-22. Logarithmic densitometer trace of the Br₂ fluorescence.

lower level is the B state, the $h\nu$ or upper level is at 51802 cm^{-1} or 6.4 eV above the bottom of the Br₂ ground state well. Energy transfer from more energetic species, such as Ar₂^{*} or Ar^{*}, might be expected to populate this state by processes such as those discussed above.

Summary and Conclusions

The extensive exploration of the rare gas-halogen and dihalogen lasers which we have been undertaking in the past year will shortly give way to intensive study of excited halogen kinetics and to development of practical devices. Our two principal goals at Livermore will be to explore electric discharge excitation of these systems for possible development into efficient, very rapidly pulsed sources for isotope separation projects (discussed briefly in Sec. 9.4) and to explore electron-beam or perhaps electron-beam-sustained discharge systems as efficient fluorescers or superfluorescers for optical pumping of fusion laser candidates, as discussed in Sec. 9.3.

J. Murray
H. Powell
J. Swingle
C. Turner, Jr.

9.2.4 MERCURY-XENON EXCIMERS

The metal vapor-rare gas excimer system was conceived as one of the first follow-on experiments after the initial, successful, xenon and krypton excimer laser work here at LLL. We sought a method by which the vuv photons could be converted into either near-uv or visible radiation because of 1) the materials problems encountered when working at wavelengths shorter than 200 nm, and 2) the fact that pure rare gas excimer lasers, by themselves, did not have all of the properties required for laser fusion lasers.

Mercury was selected, among other reasons, because of its high vapor pressure at reasonable temperatures. This was due to the geometrical constraints

imposed by the excitation source available at the time. The main objectives of the experiment were:

- 1) To measure the HgXe spectrum as a function of Hg density.
- 2) To measure the efficiency of the HgXe production. This efficiency is defined as the time-integrated fluorescence of the excimer band per unit volume, divided by the time-integrated energy deposition per unit volume.
- 3) To explore the possibility of laser action on the excimer band.

Figure 9-23 shows a schematic of the experiment and its diagnostics. The Febetron 705 (1.6 MeV, 8 kA,

Fig. 9-23. Schematic of the HgXe experimental apparatus illustrating the three diagnostic systems: Czerny-Turner spectrograph, photodiode, and Czerny-Turner spectrometer viewing the side light.

80 μ s FWHM, 2 cm diam) injected an electron beam into a cell in a configuration similar to that used previously.⁴⁶ The electron beam immediately diverges upon leaving the machine, thus requiring close coupling of the excimer cell to the e-beam generator. This particular cell geometry coupled to the Febetron was used in the xenon excimer work, and the e-beam energy deposition is adequately known.⁸ The close coupling, however, limited the cell temperature to about 200°C and the mercury pressure to a maximum of 10 Torr. The cell always filled cold to a pressure of 10 atm of xenon.

We took extreme care to reduce impurities by triply distilling the mercury, by vacuum bakeout of the gas fill, cell and vacuum lines, and by incorporating a molecular sieve in the xenon fill line. Separate temperature controls were provided for the cell and reservoir; the reservoir was isolated through a valve and a few centimeters of 5-mm-diam tubing. Temperature variations with time were less than 1°C over several hours. Mercury density changes were made by adjusting the reservoir temperature. This reservoir-cell geometry led to hysteresis problems in mercury density control when we wanted to reduce the density by lowering the reservoir temperature.⁴⁷ Density equilibrium was found to be very long (i.e., several days) when the reservoir temperature was lowered as opposed to a few hours when it was raised.

Tri-X film and a monochromator were used to record the spectral output of the (HgXe)* system as well as the Hg* spectral features at visible wavelengths. We determined the spectral response of the film and the data was appropriately corrected.

(HgXe)* spectra were taken at six mercury pressures between 0.1 and 10 Torr with the xenon pressure always being established at 150 psi when cold. Figure 9-24 shows the corrected time-integrated spectral emission at 200°C as taken from the spectrograph; the mercury pressure is 10 Torr. Emission begins at the excited atom resonance line ($^1S_0 \rightarrow ^3P_1$), 253.7 nm, and continues for about 40 nm to the red. The structure observed in the excimer band arises from mercury atom absorptions for the $^3P_{0,1,2}$ -states to higher lying D-states. Spectral emissions at the lower mercury pressures correspond very closely to that shown. The C_3F_7I absorption spectrum is included to show the spectral overlap between it and the (HgXe)* fluorescence, since the possibility exists of using the (HgXe)* output as an alternate pump source (to flashlamps) for the iodine laser. This absorption corresponds to the photodissociative process which leads to excited iodine atoms in the iodine laser. Visible Hg* bands, about 2 nm wide,

were also observed at 404.6 nm, 435.8 nm, and 546.1 nm.

The fluorescent efficiency of (HgXe)* production at 10 Torr mercury over the entire uv band, 253.7 nm to about 295 nm, was measured to be about 0.5%. This efficiency was determined by: 1) knowing the energy deposited in the gas as calculated with a modified three-dimensional SANDYL¹¹ code and verified on the Xe* experiments, 2) calculating the optical energy transport using the experimental geometry, and 3) measuring the fluorescence output with a calibrated photodiode. The variation of photodiode sensitivity over the spectral range was adjusted using the correct spectral output.

At each pressure of mercury, the Xe* emission was measured through the sidelight port. Figure 9-25 shows a monotonically decreasing Xe* fluorescence intensity with increasing mercury pressure. Both the (HgXe)* band and the visible Hg* lines show an intensity increase with increasing mercury density. The fluorescent time response of the Xe*, (HgXe)* and the visible Hg* lines followed closely that of the e-beam excitation.

We made no attempt to make a (HgXe)* laser because of the expected low gain due to the broad spectral band. Laser oscillation was attempted, but not observed, on the 404.6-nm and the 435.8-nm Hg* lines. Several technical problems with the cell were responsible, one of which was that dynamic thermal gradients were set up in the high pressure xenon. These gradients were easily seen and could not be eliminated no matter how closely the temperature of the various parts of the cell was controlled.

In summary, we obtained positive results on two of the three experimental objectives. The (HgXe)* fluorescent spectrum was measured as a function of mercury density, and the efficiency of this output was measured to be approximately 0.5%. We observed good spectral overlap between (HgXe)* and C_3F_7I absorption, but the low (HgXe)* efficiency negated considering it as a pump source. Laser action was not observed, and the kinetic chain for (HgXe)* production is still not well known.^{48,49} We note that sufficient technical problems were encountered with this cell design to warrant considering other types of cells, such as heat pipes, if future laser systems requiring elevated temperatures and high pressures become attractive.

C. Thompson
P. W. Hoff
C. K. Rhodes

Fig. 9-24. Time integrated (HgXe)* spectral fluorescent intensity output from spectrograph and the absorption profile of C₃F₇I.

Fig. 9-25. Xe₂* sidelight fluorescent emission at 1720 nm as a function of mercury pressure.

9.3 Photon Pumping of Media

Optically-pumped lasers can have significant advantages for high-energy storage devices if one can identify efficient pump sources well matched to appropriate pumping wavelengths. Excitation is usually more specific in optically-pumped devices, which thus avoid producing undesirable absorbing or deactivating species and the consequent loss of efficiency and storage time. The medium is free of the electrons and ions which will be present in discharge- or electron-beam-pumped systems and which can lead to further deactivation channels. The total particle density in optically pumped storage lasers will also be much lower than for high-voltage direct-electron-beam-excited devices; this reduces the magnitude of index-of-refraction gradients from nonlinear effects or density gradients and may allow the propagation of high-intensity beams of higher quality in optically pumped gas lasers than in comparable electron-beam or discharge-pumped devices.

High-gain, superfluorescent pump sources, such as the rare gas excimers, rare gas monohalides, and dihalogens discussed elsewhere in this report, have an additional advantage for optical pumping, since the efficient coupling of pump radiation to an absorbing medium is much simplified for a well-collimated pump

beam. A large pump source operating at relatively low excited-state density to enhance fluorescence efficiency can thereby be converted to a beam of very high brightness for optical pumping, avoiding the inevitable losses of complex reflective light-collecting optics.

In the remainder of this section, certain specific examples of potentially efficient optically-pumped energy storage lasers will be discussed. Section 9.3.1 (*The Group VI A Elements*) discusses potential energy storage lasers in atoms produced by photolytic decomposition of simple molecules by rare gas excimer or rare gas-halide radiation, and also discusses some of the properties of these efficient radiators and of a laser pumped by photolysis at very high energy fluxes. Section 9.3.2 (*Atomic Iodine Laser Experiments*) discusses the use of rare gas-halide radiation from XeBr or KrF to pump the photolytic atomic iodine laser, which has been widely discussed as an energy storage laser for fusion research. Section 9.3.2 introduces a different class of potential high-energy storage lasers using optical pumping of gaseous rare earth compounds, and Sec. 9.3.3 discusses certain nonlinear infrared processes which may be useful for optical pumping.

9.3.1 THE GROUP VI A ELEMENTS

The properties of the auroral and transauroral lines of Group VI A elements, specifically oxygen, sulfur, and selenium, were discussed in the 1974 Annual Report, where it was shown that these transitions have desirable properties for high-energy-storage, short-pulse lasers if efficient means for producing atoms in the 1S_0 state can be devised. It was also reported there that Ar_2^* photolysis of N_2O to produce $O(^1S)$ and Kr_2^* photolysis of OCS are efficient sources of 1S atoms. In this report we expand on these possible lasers and extend the class of interesting photolytic energy-storage laser possibilities to include Xe_2^* photolysis of $OCSe$, which has recently been shown to have a high yield of $Se(^1S)$, and to include ArF^* photolysis of CS_2 , which may be predicted to have a high yield of $S(^1S)$ by the same arguments used to predict high yields in the other three cases discussed.

Table 9-7 reviews the properties of the auroral and transauroral transitions of Group VI A elements. The 1S_0 highest-energy state of the ground electron configuration is characteristically highly resistant to collisional deactivation, while the 1D_2 and 3P lower levels of the auroral and transauroral transitions are much more

reactive. A more detailed discussion may be found in the 1974 Annual Report³⁰ and other reports.³¹

Efficient Production of Excimer Radiation

The production of rare gas and rare gas-halide excimer radiation from electron-beam-excited, high-pressure rare gases is one of a small class of processes which convert nonselective electronic excitation to narrow-band fluorescence with high efficiency. We will briefly review here the important kinetic processes in rare gas systems; they have been discussed and modeled in detail elsewhere.³² The rare gas halides are rather more complex, though they are known to be efficient radiators. Their properties are reviewed in Sec. 9.2.3.

Energy flows in an electron-beam excited rare gas as diagrammed in Fig. 9-26 for xenon. Argon and krypton show the same behavior. Atomic ions produced by high-energy primary and secondary electrons collapse rapidly to highly excited neutral atoms. These excited atoms relax to states of the $5p^56s$ first excited configuration (Xe^*) of the rare gas, which are the 3P_0

Table 9-7. "Auroral" and "transauroral" transitions of Group VI A

	O	S	Se	Te
<u>$^1S_0 \rightarrow ^1D_2$ auroral transition</u>				
λ (μm)	557.7	772.5	776.8	790.9
τ_r (S)	0.8	0.56	0.43	0.32
σ (10^{-20} cm^2) ^a	8.7	45	48	60
E_s ($\text{J}\cdot\text{cm}^{-2}$) ^a	4	0.57	0.53	0.42
<u>$^1S_0 \rightarrow ^3P_1$ transauroral transition</u>				
λ (μm)	297.2	458.9	488.7	541.9
τ_r (S)	16	2.9	0.13	0.027
σ (10^{-20} cm^2) ^a	0.052	3	40	230
E_s ($\text{J}\cdot\text{cm}^{-2}$) ^a	1300	14	1	0.16

^aThe peak cross section σ and saturation energy E_s are calculated for 300 K Doppler-broadened lines using calculated radiative lifetimes τ_r for sulfur, selenium, and tellurium and the experimental radiative lifetime for oxygen.⁵¹

and 3P_2 metastables and the 1P_1 and 3P_1 resonance states. Excimer molecules are then formed by three-body collisions in either a $^1\Sigma$ state of short radiative lifetime (about 5 ns) or a slightly lower lying $^3\Sigma$ state of somewhat longer radiative lifetime (from about 100 ns for Xe_2^* to perhaps 1-3 μs for Ar_2^*).

These states radiate to a repulsive $^1\Sigma^*$ ground state in continua centered at 127 nm, 146 nm, and 172 nm for Ar_2^* , Kr_2^* , and Xe_2^* , respectively. The bandwidth of the continuum is around 10% of the center wavelength in all three cases. The three-body formation process and the relaxation of highly excited atomic states to the first excited configuration proceed rapidly at pressures above about 1 atm, under which circumstances excimer formation and radiation completely dominate the channeling of energy in these systems.

Measured or calculated values of the electron energy deposited per atomic ion or highly excited atom formed in these gases can give an upper bound on the efficiency with which rare gas excimer fluorescence can be produced since each ion or excited molecule can, by the pathways in Fig. 9-26, lead to the emission of one excimer quantum if other loss processes do not first interfere. The calculated partitioning³³ of energy among various ions and neutral excited states in argon, excited by high energy electrons, predicts that 78% of the total number of atomic excitations result in ionization while the remaining 22% produce highly excited neutral atom states. The structural similarity of argon, krypton, and xenon suggests that the heavier rare gases will show similar behavior. We ignore here some small

effects of the approximately 1 eV background electron concentration.

The electron energy loss required to produce a single ion in these gases has been measured³⁴ and also calculated for argon.³⁵ Using argon as a nominal case, 26.2 eV are deposited to produce 1.3 excitations capable of forming excimers which then radiate photons of mean energy at 9.8 eV to give a maximum conversion efficiency from electron kinetic energy deposited to fluorescence energy radiated of about 50%.

Efficiencies of 10-50% have been measured for rare gas excimer fluorescence under conditions of low excitation. The most precise current measurements are discussed in Sec. 9.2.1. Several of the loss processes which reduce the fluorescence efficiency in a real system are discussed below.

Excited State Collisions. If the instantaneous rare gas excimer density is too large, a collision with a second excimer can occur in a time which is short compared to the radiative lifetime, particularly for triplet excimers. Such a collision causes Penning ionization, destroying one excimer and returning the other to an ionic step high in the kinetic chain. Minimizing this process favors short radiative lifetimes (xenon) and low densities of excitation.

Photoionization of Excimers by Excimer Radiation. The rare gas excimers are photoionized by absorption of their own radiation. These cross sections may be estimated to be a few times 10^{-18} cm^2 and are lowest for argon.³⁵ Minimizing this loss favors argon

and short propagation distances through excited regions.

High Gas Temperature. High gas temperature is thought to be particularly harmful for rare gas excimer lasers since it decreases gain by exciting high vibrational levels and thereby widening the emission band while leaving losses relatively unaffected. A large rise in gas temperature can also affect fluorescence efficiencies through its influence on kinetic rates, ground state absorption by colliding atoms with sufficient kinetic energy to ride up the repulsive ground state curve to an internuclear separation from which they can absorb an excimer photon, or perhaps other processes. If we arbitrarily restrict the gas temperature to no more than 1000 K, then the single-pulse energy out of a rare gas excimer cell initially at 300 K and radiating at 30% efficiency is restricted to no more than 2.4 kJ per mole of rare gas. The gas pressure is of secondary significance as long as it is sufficiently high to force efficient and rapid excimer formation.

In addition to these intrinsic loss mechanisms, there is an important practical efficiency loss from impurity

effects. An impurity may absorb the rare gas excimer radiation or may draw energy away from the kinetic chain of Fig. 9-26 by collisions with excimers or other energy carriers. Note, for example, the CO and Xe absorptions present in Kr_2^* laser spectra, as described in Ref. 46. These effects require minimizing the impurity concentrations of certain offensive species, such as H_2O , O_2 , CO, and rare gases heavier than that used in the fluorescer. This limit depends, in a complex way on pressure, optical depth, and the like, but it may be near 10 ppm for practical devices.

Limitations on optical coupling may also affect the usefulness of such devices. Mirrors of reflectivity 95% or more have been fabricated for Xe_2^* radiation, but reflectivities for Kr_2^* and Ar_2^* are at most about 70 - 80%. This is in contrast to the situation at longer wavelengths for which reflectivities greater than 99% are routine. This restricts the use of mirrors to collect vuv radiation and also limits the energy-flux-density which such mirrors can handle without damage since the losses are absorbed in the coatings. Optical windows, if used, will probably be made of MgF_2 . A study of the degradation of MgF_2 uv transmission in high radiation environments suggests that there will be little problem in using such a window at the Xe_2^* wavelength but that the window-service lifetime may be rather short at the Ar_2^* wavelength. All these optical considerations favor the use of Xe_2^* .

The simplest and probably most efficient light source which can be designed with these excimers is a superfluorescent laser oscillator with a cavity composed of one highly reflecting mirror and the small back reflections from an optical window separating the excimer source from a cell containing the material to be photolyzed (see Fig. 9-27.) This gives a collimated light source in which little light is lost to absorption in the walls of the device. It is not completely certain that the laser efficiency can be made as large as the spontaneous fluorescence efficiency, however, since the laser appears to operate only on the singlet transition and to be quenched by the presence of a large triplet concentration. Efficient energy extraction then depends on an electron concentration and temperature which is sufficiently high to cause rapid triplet-singlet conversion, and this may have other undesirable effects. Spontaneous radiators have the disadvantage of high divergence but may also be useful with careful design, as they have been in more conventional optical pumping arrangements.

Possible Lasers Using Rare Gas Excimer Photolysis of N_2O , OCS , OCSe , and CS_2

The preceding discussion has shown that photolytic energy transfer from Ar_2^* to N_2O and from Kr_2^* to

Fig. 9-26. Kinetic chain for the production of rare gas excimer radiation in e-beam-excited high-pressure rare gas.

OCS has interesting possibilities for production of $\text{O}^*(\text{S})$ and $\text{S}^*(\text{S})$ for use in lasers. There is sufficient information available on these processes that a reasonable analysis of the kinetics of potential lasers is possible. Production of $\text{Se}^*(\text{S})$ from OCSe with Xe_2^* and $\text{S}^*(\text{S})$ from CS_2 with ArF^* is much less well understood but will be mentioned briefly.

Absorption of excimer radiation by N_2O or OCS cannot be described accurately by a single cross section, though for practical purposes one may define an "effective cross section" which is an adequate model if the absorption does not vary too severely across the excimer continuum. For N_2O absorption of Ar_2^* emission gain-narrowed to about 5 nm, this condition is approximately satisfied, and we have measured an effective absorption cross section of σ_e of $3.5 \times 10^{-17} \text{ cm}^2$ giving a saturation energy flux for N_2O decomposition of about $0.036 \text{ J} \cdot \text{cm}^{-2}$. The saturation energy flux E_s is defined in the usual way as $h\nu/\sigma_e$. A molecule subjected to an energy flux E_s has an e^{-1} probability for survival. The absorption length for $\sim 1 \text{ Torr N}_2\text{O}$ is 0.4 cm.

The OCS absorption of Kr_2^* is another matter since there is a considerable variation in absorption coefficient across the Kr_2^* fluorescence band. We shall model OCS by assuming an average extinction coefficient of 400 cm^{-1} for a somewhat gain-narrowed Kr_2^* source. Our measurements of Kr_2^* absorption by OCS give transmissions less than this Beer's-law approximation until 90% of the incident flux has been absorbed. This gives an effective absorption cross section of $1.6 \times 10^{-17} \text{ cm}^2$, a saturation energy of about $0.1 \text{ J} \cdot \text{cm}^{-2}$, and an absorption length of about 0.1 cm for 30 Torr OCS. The variation in absorption coefficient is small enough that it is of no practical importance since we will be discussing OCS cells which those coefficients predict to be optically thick for any wavelength within the Kr_2^* continuum. The practical effect of a very low absorption coefficient at a given wavelength is to permit Kr_2^* radiation at that wavelength to escape from the cell, reducing the photolytic yield and the overall efficiency of the system. Strong absorption provides good coupling of the optical flux to the medium.

Photolysis of an Optically Thick Absorber. The short absorption lengths given above for modest reactant concentrations emphasize that any large laser using $\text{Ar}_2^* - \text{N}_2\text{O}$ or $\text{Kr}_2^* - \text{OCS}$ photolysis will operate with a pump-radiation absorption length much smaller than the dimensions of the laser volume. This situation has not been encountered previously in optically pumped lasers and leads to some interesting properties. We therefore consider some of the general features of such excitation before proceeding to specifics.

Penetration of saturable absorbers by intense light beams is by now a well studied phenomenon; we deal

Fig. 9-27. Representative optically pumped laser using a super-fluorescent rare-gas excimer source to pump N_2O or OCS.

here with a simplified case in which the absorbing molecule dissociates when excited and in which, therefore, recovery of the absorption may be neglected.

There is a limiting case of saturable absorption which displays the important features of the problem. Assume that the absorption cross section of the absorbers is so large that the absorption length approaches zero and that absorbers are present at a density ρ . Assume also a plane wave propagating through the absorber in one dimension with a photon flux $n(t)$ photons per unit area and time. To eliminate the confusion of retarded time, assume also that any disturbance in the system propagates at a velocity much less than c .

From $t = 0$ to $t = t_1$, the wave will bleach into the absorber a distance $X_0(t_1)$ given by

$$X_0(t_1) = \frac{1}{\rho} \int_0^{t_1} n(t) dt. \quad (1)$$

For this ideal case, the photon flux at a point X at time t is $n(t)$ for $0 \leq X \leq X_0(t_1)$ and is zero for $X \geq X_0(t_1)$. The velocity of propagation of the front which divides the opaque and transparent regions is given by

$$\frac{\partial X_0(t)}{\partial t} = \frac{n(t)}{\rho}. \quad (2)$$

A real saturable absorber will show similar behavior but with a finite transition region between opacity and transparency. The spatial extent of this region is about $1/\rho\sigma$, the absorption length in the medium. The velocity of propagation of the transition region is again $n(t)/\rho$, and the apparent risetime t_r of the transmitted wave seen by an observer at a position X_0 is the time required for the wave to bleach a distance of approximately one absorption length, or $1/\sigma n(t)$.

If $1/\tau_r$ is much larger than the rate of deactivation k_p of the products of photolysis by the parent molecule [e.g., $O(^1S)$ deactivation by N_2O], the bleaching front destroys the parent molecules so rapidly that such processes may be neglected. The principal deactivations are then reactions among the various decomposition products.

Turning now to a laser-active medium produced by high intensity photolysis of N_2O or OCS , we note that the photolytic decomposition of these molecules leaves fragments possessing several electron volts of kinetic energy. There will therefore be a sharp temperature change in the gas across the transition region of the photolytic decomposition. This temperature change can drive a hydrodynamic shock front which changes the gas density and causes very undesirable optical inhomogeneities. For a given temperature discontinuity, there is a maximum velocity of shock front propagation, and the formation and propagation of such a shock can be prevented if the transition region moves through the gas at a velocity $n(t)/\rho$ which is much greater than the maximum velocity shock which it can sustain. It happens that such velocities are not unreasonable, and we shall arbitrarily require that the velocity of the transition region exceed Mach 10 for the representative laser designs discussed below without attempting a detailed analysis of the hydrodynamics. Assuming a helium buffer in the amplifier with sonic velocity 10^5 cm/s, an amplifier in which the transition region propagates 10 cm is restricted to pump pulses less than 10^{-4} s. Other considerations will usually be more restrictive. The laser volume in these devices will then be excited in a time which is short compared to the hydrodynamic response time and cannot develop a density gradient during excitation.

The low saturation energy, or high absorption cross section, for N_2O and OCS has a considerable advantage for the preparation of a laser-active medium with a very uniform gain profile. The ultraviolet flux incident on a molecule is many times the saturation energy, causing nearly 100% decomposition of the parent molecules and a very uniform gain profile. Nonuniformities in the ultraviolet flux translate themselves into different penetration depths in the laser-active medium rather than variations in excited state density. Tolerances on turbulence and other optical disturbances in the fluorescence cell are therefore much reduced over the tight specifications required for propagating high quality, short, focusable pulses. These high quality pulses propagate in a more benign environment at lower particle density.

Ar_2^* - N_2O Transfer. An idealized laser amplifier using Ar_2^* photolysis of N_2O is shown in Fig. 9-27. An Ar_2^* lamp, preferably operating as a superfluorescent laser to provide better directionality, radiates

through a vuv window which forms one side wall of a cell containing N_2O . We assume this radiation has negligible divergence over the depth d_a of the N_2O cell and neglect the details of engineering design and optimization in favor of very general predictions concerning the characteristics of such an amplifier.

The N_2O cell will also contain an inert buffer such as helium or argon to reduce the temperature rise in the cell and to suppress hot atom reactions. The buffer might be present at the same high pressure as the gas in the Ar_2^* excimer cell, which reduces the pressure loading on the vuv window. In such a case, the laser transitions of interest in the N_2O cell are the induced-dipole transitions described in Sec. 9.2.2. We assume oscillation on the electric quadrupole line with a helium buffer at a few hundred Torr and collision- and temperature-broadening of the quadrupole line to twice its 300 K Doppler width. This gives a cross section of about 4.5×10^{-20} cm² and saturation energy flux of 8 J·cm⁻². Nitrogen gas may be added to quench $O(^1D)$ if required. The concentration of molecular species must be kept low for amplifiers operating at high peak powers, however, since stimulated Raman scattering from molecular vibrations could become an important parasitic loss process in these devices.

N_2O and $O(^1S)$ are simultaneously present in the laser gain medium only in the small transition region which separates the unexcited and completely decomposed sections of the gain medium. The N_2O deactivation rate on $O(^1S)$ does not, as noted earlier, significantly affect the $O(^1S)$ lifetime in the laser. That lifetime is determined by deactivation rates in collision with the products of other dissociative channels in N_2O photolysis. We assume a yield of 8% [$N_2(A^3\Sigma) + O(^3P)$] and 2% [$N(^2D) + NO(X)$]; furthermore, we assume that $N(^2D)$ interactions with $O(^1S)$ require a three-body collision and are negligible. The excited state interaction $N_2(A^3\Sigma) + O(^1S)$ has an unknown rate, but excitation to higher excited states of N_2 is allowed and we have observed some evidence of $N_2(B)$ production. We assume the reaction has the same rate as $N_2(A^3\Sigma) + O(^3P)$ ($\approx 10^{-10}$ cm³·s⁻¹). The effective deactivation rate for $O(^1S)$ after the N_2O decomposition, expressed in terms of the initial N_2O concentration, then becomes about 3×10^{-11} [N_2O] s⁻¹.

The effective rate which we use here is subject to considerable error. Product yields for decomposition by Ar_2^* radiation are difficult to measure precisely, and this rate contains only a crude estimate for the $N_2(A^3\Sigma)$ deactivation. In the absence of $N_2(A^3\Sigma)$ and NO , the effective rate for $O(^1S)$ deactivation is dominated by $O(^3P)$ and is about 6×10^{-13} [N_2O] which illustrates the importance of these species and the potential for improvement of the product of energy storage density and inversion lifetime which is determined by the

effective deactivation rate.

The critical parameters for the amplifier of Fig. 9-27 are Ar_2^* excimer flux per unit area of the vuv window, the pulse length of the Ar_2^* lamp, the pressure of N_2O in the cell, and the depth of penetration d_{ii} of the Ar_2^* radiation, all of which are interrelated. We choose an Ar_2^* pulse length of $0.05 \mu\text{s}$ as an estimate of the minimum practical pulse length for a large electron-beam pumped device. The N_2O pressure is set at 2 Torr to give an inversion lifetime of $0.5 \mu\text{s}$ which is long compared to the pump pulse and avoids collisional decay of $\text{O}(^1\text{S})$ during the excitation. With 90% $\text{O}(^1\text{S})$ yield for Ar_2^* photolysis, the $\text{O}(^1\text{S})$ concentration is $5.7 \times 10^{16} \text{ cm}^{-3}$ and the energy storage density for the auroral transition is $20 \text{ J} \cdot \text{liter}^{-1}$ when the N_2O in the cell has been completely decomposed. The small signal gain is 0.26% per cm.

The maximum penetration depth d_{ii} is determined by the Ar_2^* energy flux at the vuv window. Assuming that the window will tolerate $1 \text{ J} \cdot \text{cm}^{-2}$, or $2 \times 10^7 \text{ W} \cdot \text{cm}^{-2}$ peak intensity, d_{ii} is 10 cm. The penetration depth may also be limited by impurity absorption, though it is important to note that common impurities such as H_2O will be decomposed at the high ultraviolet flux present, and the limiting absorption will be the absorption of radicals such as OH. There are magnetic dipole absorption bands⁵⁶ (Lyman-Birge-Hopfield system) of N_2 in the region of the argon continuum, and the absorption of Ar_2^* radiation by these transitions in the N_2 fragment from N_2O decomposition will also determine an upper limit to d_{ii} . The oscillator strength⁵⁷ of these bands is approximately 10^{-3} , so the N_2 absorption is probably negligibly small. The $\text{O}(^1\text{S})$ atom itself can absorb at 121.8 nm, at which Ar_2^* radiation is still present in very clean systems. The Lyman α absorption of H at 121.6 nm from minor hydrogen impurities in the argon dominates this region completely in most cases, so the absorption of Ar_2^* radiation by $\text{O}(^1\text{S})$ need not be an important destruction mechanism for $\text{O}(^1\text{S})$.

If one assumes that 50% of the Ar_2^* radiation from a superfluorescent Ar_2^* cell enters the N_2O cell in the idealized laser of Fig. 9-27, with a $2 \times 10^6 \text{ W} \cdot \text{cm}^{-2}$ radiance from the Ar_2^* cell, the Ar_2^* cell must have a depth of 20 cm behind each cm^2 of the vuv window in this amplifier.

The efficiency of a possible $\text{Ar}_2^* - \text{N}_2\text{O}$ amplifier is of considerable practical interest since large, inefficient devices require an enormous investment in energy storage facilities. Any eventual application of laser fusion to power generation also requires an efficient laser. With 30% conversion of electron energy deposited in the argon to excimer radiation and 100% transfer of the radiation to N_2O , the maximum quantum efficiency [energy stored in the $\text{O}(^1\text{S}) - \text{O}(^1\text{D})$ transition divided by energy deposited] is about 6%. A real

device will have other energy losses. Assuming as nominal but fairly realistic estimates that 25% of the electrical energy used is actually deposited in the gas, 50% of the excimer fluorescence is absorbed in N_2O , and 50% of the stored energy is extracted, the practical or "real" efficiency (laser pulse energy out divided by total energy input) becomes about 0.3%. This projected efficiency does not meet the efficiency requirements of at least 5%, which some very tentative models demand for application of laser fusion to power generation. It is, however, at worst comparable to other current candidates.

$\text{Kr}_2^* - \text{OCS}$ Transfer. The idealized amplifier of Fig. 9-27 will now be discussed for $\text{Kr}_2^* - \text{OCS}$ transfer to produce $\text{S}(^1\text{S})$. We consider both the $\text{S}(^1\text{S}) - \text{S}(^1\text{D})$ quadrupole auroral line and the $\text{S}(^1\text{S}) - \text{S}(^3\text{P})$ magnetic-dipole transauroral line, assuming that the $\text{S}(^3\text{P}_1)$ and $\text{S}(^1\text{D})$ states are either not produced or have been quenched to $\text{S}(^3\text{P}_2)$ by addition of appropriate buffers. An optical cross section half of the 300 K, Doppler-broadened values of Table 9-5 is assumed as it was for oxygen. The resulting $30 \text{ J} \cdot \text{cm}^{-2}$ saturation flux for $\text{S}(^1\text{S}) - \text{S}(^3\text{P}_1)$ is near the upper limit of present optical technology.

The deactivation rate for $\text{S}(^1\text{S})$ will be determined by impurities or by reaction with other decomposition products of OCS rather than by collisions with OCS itself, as was the case for $\text{O}(^1\text{S})$ and N_2O . The variation in absorption coefficient across the Kr_2^* band will give a transition region thicker than the $\text{Ar}_2^* - \text{N}_2\text{O}$ transition region, however, so there may be some $\text{S}(^1\text{S})$ deactivation by OCS. The decomposition products of OCS are not well known. The less than 3.5×10^{-16} rate for collisions with CO is very small and will probably be insignificant compared to other processes.⁵⁸ We shall assume for the sake of discussion that the effective deactivation rate for $\text{S}(^1\text{S})$ is $10^{-13} \text{ cm}^3 \cdot \text{s}^{-1}$.

For this case, we shall design for a $1 \mu\text{s}$ Kr_2^* pump pulse with a $10 \mu\text{s}$ $\text{S}(^1\text{S})$ inversion lifetime since pulsed power technology may permit a much cheaper and more efficient power supply for a $1 \mu\text{s}$ pulse rather than a $0.1 \mu\text{m}$ pulse which requires elaborate pulse forming lines. The OCS filling pressure is therefore set at 30 Torr. Assuming 80% yield of $\text{S}(^1\text{S})$ in Kr_2^* photolysis, the $\text{S}(^1\text{S})$ density is $7.6 \times 10^{17} \text{ cm}^{-3}$, and the energy storage density is $190 \text{ J} \cdot \text{liter}^{-1}$ for the auroral and transauroral transitions, respectively.

The penetration of Kr_2^* radiation in OCS will be affected by CO absorption to a much greater degree than the N_2 absorption of Ar_2^* mentioned previously. The $\text{CO}(\text{A}^1\Sigma - \text{X}^1\Pi)$ (0,2) and (0,3) fourth positive bands^{57,59} extending about 1 nm to the red of band heads at 147.7 nm and 144.7 nm lie within the Kr_2^* fluorescence bandwidth. The $\text{A-X}(1,4)$ hot band and

the three forbidden bands ($a-X$), (a^1-X), and ($I-X$) are also present.³⁹ The effect of these forbidden bands will depend on collision broadening and possibly also on collision-induced effects and cannot be assessed accurately without experimental data. Gain-narrowing of the Kr_2^* source helps to avoid the allowed ($f=0.15$)³⁷ absorptions of the fourth positive system since these lie on the wings of the Kr_2^* continuum (and may be seen as impurity absorptions in Kr_2^* laser spectra).⁴⁰ Excited CO will probably also have a much larger deactivation rate with $S(^1S)$ than ground state CO, as discussed earlier for the comparable $N_2(A^3\Sigma) - O(^1S)$ interaction. We shall assume that the absorption in 10 cm at 30 Torr is not a serious limitation.

A 10 cm penetration of 30 Torr OCS with a 1- μ s Kr_2^* lamp requires an energy flux of $13 \text{ J}\cdot\text{cm}^{-2}$ at an intensity of $1.3 \times 10^7 \text{ W}\cdot\text{cm}^{-2}$. This may exceed the energy handling capability of reasonable vuv windows. With 50% collection of a $10^6 \text{ W}\cdot\text{cm}^{-3}$ radiance from the Kr_2^* lamp, assuming superfluorescent emission toward the vuv window, there must be a depth 26 cm of Kr_2^* lamp behind each cm^2 of window area.

The maximum quantum efficiencies for these potential lasers will be about 4% for the auroral and about 7% for the transauroral transitions, with practical efficiencies roughly an order of magnitude smaller, as was the case for $Ar_2^* - N_2O$.

$Xe_2^* - OCSe$ Transfer. There is insufficient information available on the properties of $Se(^1S)$ and $OCSe$ for a detailed discussion of this case at present. The yield of $^{78}Se(^1S)$ near the peak of the Xe_2^* continuum is high, as shown in Fig. 9-27. The $Se(^1S) + OCSe$ reaction rate is also fast ($1.6 \times 10^{-10} \text{ cm}^3\cdot\text{s}^{-1}$) so that rapid bleaching of $OCSe$ will be more important in such a device than for $N_2O - O(^1S)$ or $OCS - S(^1S)$ devices. Efficiency and energy storage will be comparable to the cases discussed above given that no rapid deactivators are produced in the $OCSe$ photolysis and that the yield

of $Se(^1S)$ is at least 80%. The CO deactivation rate is known¹⁸ to be no more than 1.6×10^{-10} . The transition of most interest here is the transauroral line at 488.7 nm which might have a cross section of about $2 \times 10^{-19} \text{ cm}^2$ and saturation flux of about $2 \text{ J}\cdot\text{cm}^{-2}$. Optical components for Xe_2^* radiation at 172 nm are far easier to develop than those for Kr_2^* and particularly Ar_2^* radiation.

$ArF^* - CS_2$ Transfer. The same theoretical arguments which successfully predict the position of the $^1\Sigma_u^+$ absorption yielding $O(^1S)$ from CO_2 , $O(^1S)$ from N_2O , $S(^1S)$ from OCS , and $Se(^1S)$ from $OCSe$, predicts⁴⁰ a high yield of $S(^1S)$ from CS_2 near 197 nm. Experiments on CS_2 photolysis in this region have not shown $S(^1S)$ production, but the CS_2 deactivation rate on $S(^1S)$ is about $8 \times 10^{-10} \text{ s}^{-1}$ which is so large that a measurement of $S(^1S)$ production is difficult, as in the case of $Se(^1S)$ produced from $OCSe$. The ArF^* emission at about 193 nm, which is known to be one of the more efficient rare gas-halide systems, couples well to this absorption. The large deactivation rate implies that an $ArF^* - CS_2$ laser must also operate at an ArF^* flux level high enough to bleach the CS_2 rapidly. The deactivation rate of $S(^1S)$ by CS is also unknown, as is the absorption spectrum of CS near 193 nm. Yield and deactivation measurements will be undertaken by G. Black at SRI under Livermore contract in the coming year.

The longer wavelength of the ArF^* emission makes optical components less of a problem than for the rare gas excimers; however, this advantage may be more than compensated by the extremely corrosive environment in a cell containing F_2 .

**J. Murray
H. Powell
C. Rhodes**

9.3.2 ATOMIC IODINE LASER EXPERIMENTS

We have structured techniques for high energy laser media into three different categories:

- direct pumping by electrons,
- photolytic or optical pumping,
- pumping due to chemical reactions.

The choice of pumping technique for a particular system hinges on the details of the energy channeling processes existing in the medium. So, for example, the pumping of vuv rare gas excimer laser proceeds efficiently under electron bombardment due to the very fast and highly selective energy channeling associated with the electron and heavy particle kinetics. A dye laser

may not work under these conditions at all but may prefer photons as its energy input. Finally, the pumping of electronic transitions by chemical reactions has recently received intense scrutiny, having made significant contributions in the infrared in the past.

From a kinetics viewpoint, pumping a laser medium with photons offers attractive avenues for selective energy transfer, assuming that appropriate excited states are available. The medium is then free of large electron densities which can open up additional energy branching paths or directly excite unwanted levels. From a systems standpoint, however, this decoupling of the medium from the pump source places the output

Fig. 9-28. Overlap of the emission from 1 Torr Br₂, 25 Torr Xe, 2 atm Ar with C₃F₇I absorption band.

stage one more step removed from the wall plug. Therefore, development of efficient photolytic sources, either coherent or incoherent, determines the utility of photon-pumped high energy laser media.

The rare gases have demonstrated efficient conversion (25-50%) of electron beam energy to vuv fluorescence and have been matched up conceptually with various compounds containing Group VI elements as photolytic lasers. From a systems standpoint, these schemes face the usual difficulties involved with the transport of high vuv fluxes through optical materials.

Recently, various mixtures of rare gases and halogens have produced intense emission in the near-uv (200-400 nm),^{37, 38} a much less hostile portion of the spectrum. The emission spectrum of the XeBr molecule, as measured in our laboratory, is shown in Fig. 9-28 compared to the absorption spectrum of C₃F₇I, the alkyl iodide compound most commonly used in the well-known 1.3-μm iodine photodissociation laser. The iodine laser has been constrained to low efficiency operation due to the broad-banded nature of the xenon flashlamp spectra used to drive it.

Energy is channeled into formation of the XeBr* due to interruption at near gas kinetic rates of the rare gas excimer formation channel.

On the basis of measurements indicating approximately 25% conversion of electron-beam energy to vuv-

excimer fluorescence on one of our 235-keV, 1-μs electron beam systems, we have measured the fluorescence efficiency for XeBr* and demonstrated the photolytic pumping of the 1.3-μm iodine laser using narrowband excimer fluorescence.

The apparatus is shown in Fig. 9-29. The 1 × 100 cm² electron beam is emitted from a blade cathode driven by a two-stage Marx generator charged to 1.20 keV. The resultant beam, considering inductive losses in the transfer line, has a nominal energy of 235 keV and a current density at the anode of about 3.5 A/cm².

The gas cell was a polyethylene-coated, stainless steel chamber fitted with Monel-flanged parts and plumbing lines. These materials are known to resist corrosive attack by bromine. The 0.025-mm-thick titanium anode foil was protected by a 0.013-mm-thick Kapton polyimide film.

It was found that the optimum fluorescence was achieved for partial pressures of 1 Torr Br₂, 25 Torr Xe, and 2 atm Ar. Argon was used as the principal constituent because of the expense involved in filling our 100-liter cell with xenon. Very fast energy transfer processes deliver excitation energy from the argon excimer to xenon metastable atoms in mixtures of this type. Therefore, for every 9.8-eV excitation of the argon excimer, a 4.5-eV photon should be produced from the XeBr* molecule if significant loss channels are absent.

We obtained fluorescence measurements on our apparatus without the quartz tube present, as shown in

Fig. 9-29. An apertured ITT 4018 (S-20 UVG) photodiode was aligned to view a well-defined emitting volume transverse to the electron beam and 3 cm from the anode foil. The photodiode viewed the fluorescence through a re-entrant quartz window and a bandpass filter of transmission centered at 281.2 nm. In this way, effects due to optical absorption were avoided.

Electron-beam energy deposition was inferred to be 44 mJ/cm² from recent experimental data generated in 2 atm of Ar on this device. These experiments are discussed in Sec. 9.2.1, where fluorescence efficiencies from the argon excimer are reported to be about 25%.

The partial pressures of xenon and bromine were varied parametrically to arrive at the optimum condition stated above. The bromine partial pressure was controlled by a re-entrant double-walled concentric-tube cold finger. A bromine pool was held at vapor temperature in the inner tube whose wall temperature was controlled by methyl alcohol circulating in the outer jacket. Mixing due to free convection and firing of the electron beam assisted in maintaining liquid-vapor equilibrium.⁴⁶ The fluorescence remained constant over several shots into the same gas mixture.

Fig. 9-29. End view of apparatus showing fluorescence detector for efficiency measurements and laser tube for iodine laser experiments.

The fluorescence, as shown in Fig. 9-28, was produced in three spectral features. The most prominent feature, peaked at 281.8 nm, is attributed to transitions from the excited XeBr ($\Sigma_{1/2}^+$) state of ionic character at large internuclear separation⁴⁷ to the relatively flat ground state. This band exhibited vibrational fine structure at high resolution as measured on a 0.3-m McPherson 218 spectrograph which viewed the emitting volume through a re-entrant quartz light pipe positioned at the edge of the source, viewing its long axis. A broad-banded diffuse continuum originating from the same excited state and ending on the repulsive 2π states of the ground manifold was also observed. A third feature, attributed to $\text{Br}_2(D^1\Sigma_u \rightarrow 3\pi_g)$, was observed to be intense under these conditions. The production mechanism for this species for our system is not understood at this time, but we have made this transition oscillate on our apparatus (see Sec. 9.2.3).

The fluorescence intensity was determined with the photodiode within the 12.2-nm FWHM bandpass of the filter and corrected with spectrographic data to include the wholeband fluorescence. The intensity per unit volume was 5 mJ/cm³. This indicates a fluorescence efficiency of $11 \pm 5\%$ in the 220-340 nm spectral region. The error bars are derived for this absolute intensity measurement on the basis of conservative estimates of systematic errors. According to the estimates given above, a value of 11% would indicate near unity transfer from the argon excimers to xenon metastables and, thence, to the XeBr excited state (neglecting the contribution due to Br_2).

On the basis of the intensity observed at the photodiode window, we determined that a demonstration experiment could be constructed on our device to show iodine laser operation when pumped by narrowband excimer fluorescence. As shown in Fig. 9-29, a 9-mm-i.d. quartz tube was inserted through the cell at a position centered 3 cm from the anode foil and supported at two locations by Teflon rods. The tube was filled with 100 Torr of $\text{C}_3\text{F}_7\text{I}$, and an optical cavity was established with two dielectric mirrors of reflectivity at least 99% at 1.315 μm , spaced 2.2 m apart. Without attempting to optimally couple the XeBr* fluorescence into the laser tube, estimates showed that gain of about 10^{-1} cm^{-1} could be achieved on the iodine transition, a value large enough to exceed the optical losses.

Laser oscillation was observed at 1.3 μm as detected on a 7102 photomultiplier tube. The temporal shape of the pulse was typical of a gain-switched oscillator, lasting approximately 500 ns (see Fig. 9-30). The integrated pulse energy was determined to be about 0.12 mJ on a thermopile calorimeter.

Possible techniques for configuring the various elements of the above experiment to produce an efficient device are discussed elsewhere in this report. From a

Fig. 9-30. Temporal evolution of the iodine laser pulse.

systems standpoint, a fluorescence-driven system requires substantial effort in optical coupling. Concentric geometries seem to offer the most promising possibilities. From an electron beam standpoint, significant effort would be required in the development of cylindrical electron beams for a system based on this

concept. For high repetition rate systems (about 100 Hz) the utility of the electron beam must be carefully examined in light of the foil survival problem. Since rare gas-halide systems have been efficiently pumped by electric discharge techniques, attention must be given to those devices as a way to circumvent the above difficulties. Perhaps new flashlamp systems based on the kinetics encountered on our apparatus are a possibility.

Finally, coherent pumping techniques can be investigated for these systems. Since XeBr has been proven ineffective as a laser material, its use must be limited to fluorescence. However, KrF systems have produced impressive laser results during the last year, and the 249-nm output could be useful for pumping the alkyl iodides as well as other materials.

J. Swingle
C. Turner, Jr.

9.3.3 RARE EARTH (RE^{3+}) MOLECULAR VAPOR LASERS

Intensive R&D of Nd:glass lasers at LLL during the past few years has placed in sharp relief the advantages and disadvantages of this laser medium for generating multiterawatt, subnanosecond pulses for fusion research. The disadvantages are simply summarized:

- 1) Small ratio of self-focusing fluence (approximately 1 J/cm^2 at 100 ps) to saturation energy fluence (5 J/cm^2), necessitating operation in the small signal-gain region and resulting in inefficient use of stored energy.

- 2) Requirement for large surface area transverse to the beam axis.

- 3) Relatively high unit volume and maintenance costs.

- 4) Only very low average power capability due to low thermal conductivity and low efficiency operation.

Analysis shows, however, that these disadvantages result primarily from the dielectric properties of the glass host and not the active rare earth ion (RE^{3+}) which has many desirable properties. The nonlinear refractive index of a dielectric substance n_2 is proportional to the product of number density and hyperpolarizability of the contributing atomic and molecular species. The RE^{3+} laser ion is present in the glass as an impurity ($2 \times 10^{20}/\text{cm}^3$) and does not contribute significantly to n_2 . The electronic charge associated with glass constituent atoms is present at a density of about $2 \times 10^{22}/\text{cm}^3$ and dominates the observed values of n_2 . A several-fold reduction in n_2 of laser glass is anticipated by carefully selecting glass composition, but a much lower density medium must be used to achieve more than an order of magnitude

reduction in n_2 . Rare earth liquid lasers, such as Nd:POCl₃, possess some potential for high average power by flowing the medium, but these fairly dense liquids exhibit n_2 -values⁶¹ comparable to those of glass, manifest other significant optical nonlinearities^{62,63} and tend to possess rather large stimulated emission cross sections (approximately equal to 10^{-19} cm^2); these qualities preclude high energy storage density in large amplifiers.

In view of these observations, we were prompted to consider the suitability of rare earth (RE^{3+}) molecular vapors as a class of lasers for advanced fusion applications. Under ideal conditions, we might expect a relatively low nonlinear refractive index, operation at high energy fluence (about 10 J/cm^2) and in the saturated (efficient) gain regime, low unit volume cost, and attainment of high average power through flow of the laser medium.

Because of the peculiar electronic structure of the lanthanide and actinide trivalent ions (equivalent $4f^n$ and $5f^n$ ground electronic configurations), it is possible to estimate the radiative and unimolecular nonradiative transition probabilities using simple phenomenological models. These calculations have been carried out and reported for several classes of relatively volatile rare earth molecular vapors.⁶⁴⁻⁶⁶ The results of these studies are summarized below.

The calculations indicated that at least several rare earth molecular vapor systems should be viable candidates for high energy storage lasers for fusion applications. Experimental confirmation of the basic phenomenological models is expected to provide an

excellent theoretical and computational tool to permit an efficient assessment of this generic class of laser media.

In the following material, we discuss 1) basic molecular requirements, 2) properties of three different molecular systems: rare earth trihalides, rare earth chelates, and rare earth trihalides complexed with transition-metal trihalides, and 3) work planned on the spectroscopy and kinetics of these molecular systems and pumping techniques to be employed on the most promising candidate systems. Recent experiments⁶⁷ sponsored by LLL, on the radiative and collisional stability of a rare earth/transition-metal trihalide complex have generally confirmed the more critical aspects of the analysis put forward⁶⁴⁻⁶⁶ providing a substantial stimulus to verify laser action in such molecular systems. These experiments are in progress.

Basic Molecular Considerations

The electronic configurations of the lanthanide rare earth atoms consist of the xenon core ($1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^6$) plus $6s^2$ or $5d^1 6s^2$ valence electrons and a number of 4f electrons. The 4f electrons are spatially buried within the closed $5s^2 5p^6$ electron shells of the core and are well shielded from the external environment. The three $5d^1 6s^2$ electrons are chemically active and permit formation of simple molecules containing triply ionized rare earth ions, RE^{3+} , such as $(RE)X_3$, where $X = Cl, F, I, Br$ or a singly charged radical. More complex molecular species are also of interest for a gas phase rare earth RE laser. In molecules of the form $(RE)X_3$, the RE^{3+} ion is necessarily coordinated in a position lacking inversion symmetry. The ligand fields of the cations will thus induce electric dipole transitions among the electronic levels of the ground $4f^n$ electronic configurations. In solid state hosts successfully used for lasers, the RE ions are also situated in lattice sites lacking inversion symmetry, suggesting that $(RE)X_3$ molecules might indeed be suitable for gaseous RE lasers.

To assess RE lasers for short-pulse laser action, a number of kinetic rates will have to be known. These can be identified through reference to Fig. 9-31 which shows the energy levels of the Nd^{3+} ion in a molecule (schematic). The comments made here for Nd^{3+} generally apply to all RE^{3+} ions. Because of 4f shielding, the centers-of-gravity of the electronic energy levels will not be shifted significantly from those of the free ion. These levels are labeled in the conventional Russell-Saunders notation $||[SL]J\rangle$ and are also designated by level number. As in solids, each electronic J-manifold will be split into a number of Stark components by the ligand fields of the other atoms in the molecule (not

shown). Energy may also be taken up by the molecule in the form of vibrations. Vibrational energy levels, associated with a single vibrational mode of the molecule, are designated by the vibrational quantum number ν , for each electronic level. The molecule may also rotate, providing additional energy level structure as shown for the $\nu = 1$ vibrational level of the ground electronic state. (As in solids, we anticipate that electronic-vibrational interaction will be very small and that optical spectra of RE vapors will be due to purely electronic transitions.)

From the point of view of using these systems for lasers, and in particular for short pulse lasers, we need to know the characteristic rotational and vibrational equilibration times since energy will be stored in these degrees of freedom. For Nd^{3+} lasers, pumping of the $^4F_{3/2}$ upper laser level generally occurs via the transition from the $^1I_{9/2}$ ground level to the levels lying above $11,000\text{ cm}^{-1}$. In solids these manifolds relax rapidly via excitation of lattice vibrations to the $^4F_{3/2}$ manifold; the $^4F_{3/2}$ manifold generally decays radiatively. In an RE vapor laser, we require relaxation of the pumped transitions to the $^4F_{3/2}$ manifold in a time which is short compared to the radiative lifetime of the $^4F_{3/2}$ level. At the same time the $^4F_{3/2}$ manifold must be stable against nonradiative de-excitation over the same interval. Energy stored in vibrational and rotational modes of excited molecules must also be available to the $^4F_{3/2}$ electronic level in a time which is short compared to the width of the pulse to be amplified. A necessary, although not sufficient, condition to achieve such a dynamic response is that the fundamental vibrational modes of the molecule are relatively low in energy (say no greater than 300 cm^{-1} , as shown in Fig. 9-31). Vibrational relaxation of the $^4F_{3/2}$ manifold then requires an unlikely excitation of high order overtones (while relaxation of the pump levels requires more probable excitation of relatively low order overtones).

The rotational level spacing of the $(RE^{3+})X_3$, and more complex, heavy element molecules will in general be quite small. For example, we estimate for NdI_3 that the rotational constant B is approximately 0.01 cm^{-1} (compared to B at approximately 0.4 cm^{-1} in CO_2). This suggests that the rotational level density will be quite high and that the thermalization probability will be at least gas kinetic.

Finally, the viable RE molecular vapors must have sufficient volatility and stability at workable temperatures. A search of the literature has identified at least three potentially useful RE molecular vapor systems for initial study:

- RE - chelates,
- RE - trihalides,
- RE - transition-metal trihalide complexes.

Fig. 9-31. Schematic representation of the energy level structure of Nd^{3+} in a molecular vapor.

Each type of molecular vapor has advantages and disadvantages with respect to the radiative, kinetic, and volatility requirements set out above. Highlights of the available data on these vapors are given next, followed

by more specific comments on each system. The interested reader should consult Refs. 64, 65, and 66 for assumptions used in the calculational model and calculated radiative and nonradiative transition probabilities.

Three Classes of Rare Earth Molecular Vapors

A considerable amount of information is available on vapor pressures and absorption properties for the molecular systems cited. However, almost no experiments have been performed on the fluorescence properties of these systems. The absorption spectra for the rare-earths, when combined with the Judd-Ofelt model^{68, 69} of ligand-induced electric dipole moments, are invaluable in predicting various radiative properties of the rare-earths. The Judd-Ofelt model of induced electric dipole transitions in the $4f^n$ ground configurations of the RE^{3+} ions, which has been successfully applied to crystals,⁷⁰ liquids,⁷¹ and glasses,⁷² is applicable to gas phase spectra as well. In this analysis, the absorption intensities of the rare earth vapors are characterized in terms of three phenomenological intensity parameters, Ω_i (Judd-Ofelt parameters), which are used to calculate the four radiative $^4F_{3/2} \rightarrow ^4I_j$ transition probabilities (see Fig. 9-31), the $^4F_{3/2}$ radiative lifetime, and the cross section for stimulated emission near $1.06 \mu\text{m}$ —all properties for the exemplative case of Nd^{3+} . The absorption intensities of Pr^{3+} , Nd^{3+} , Er^{3+} , and Tm^{3+} bromides and iodides have been measured by Gruen, DeKock, and McBeth⁷³ and by Gruen.⁷⁴ A number of studies on high vapor pressure lanthanide chelates were performed⁷⁵ in the mid-1960's. The absorption spectra of trivalent Pr, Nd, Sm, Eu, Dy, Ho, Er, and Tm were recorded⁷³ in the vapor phase chelate 2,2,6,6-tetramethyl-3,5-heptanedione. The spectral absorbance of the Nd-Al-C1 complex has been measured by Øye and Gruen.⁷⁶ Without going into the details of the Judd-Ofelt predictions for these vapor hosts, suffice it to indicate here that the projected laser performance of the rare earth vapors appears as attractive as the rare earth properties in glass; i.e., $\text{Nd}^{3+}:\text{ED2}$ glass. For example, the peak stimulated-emission cross section of $\text{Nd}^{3+}:\text{ED2}$ glass at $1.06 \mu\text{m}$ (see Fig. 9-31) is $\sigma(\text{Nd}^{3+}:\text{ED2}) = 2.9 \times 10^{-20} \text{ cm}^2$, whereas the Judd-Ofelt predictions for the vapors are $\sigma(\text{NdI}_3) \cong 3.1 \times 10^{-20} \text{ cm}^2$ and $\sigma_p(\text{Nd-Al-C1}) \cong 1.7 \times 10^{-20} \text{ cm}^2$.

Rare Earth Chelates

The first detailed fluorescence study on any rare earth vapor was reported by LLL in 1975⁷⁷ for the 3D_1 state of Tb^{3+} in the vapor phase chelate 2,2,6,6-tetramethyl-3,5-heptanedione, i.e., $\text{Tb}(\text{thd})_3$. In this investigation, measurements of the fluorescence decay as a function of temperature and pressure demonstrated that intermolecular collisional deactivation is unimportant whereas nonradiative deactivation by intramolecular processes dominates the fluorescence

lifetime at temperatures of 230–300°C. The rate for the latter process is well described by an Arrhenius equation and suggests that the Tb^{3+} relaxation occurs through transfer to low-lying excited states of the chelate.

A schematic diagram of the experimental apparatus is given in Fig. 9-32. The $\text{Tb}(\text{thd})_3$ vapor was excited by approximately 1-mJ, 10-ns pulses from a nitrogen laser operating at a repetition rate of about 25 Hz. The 337-nm pump radiation entered the oven through a uv-pass filter which attenuated discharge light from the nitrogen laser and served as a thermal cap on one end of the 33-cm-long main oven. The transmission of the 337-nm laser light through the vapor cell was monitored by a fast photodiode.

Fluorescence from the Tb chelate vapor was observed at right angles to the excitation axis through a quartz window in the oven. Scattered 337-nm excitation light was rejected by a dielectric-coated filter. The fluorescence was focused into a 0.25-m, $f/3.5$ grating monochromator equipped with an S-20 photomultiplier having a few nanoseconds risetime. Typical spectral resolution was about 3 nm. The detector output was displayed on an oscilloscope (Tektronix 7704) and recorded using a gated boxcar integrator (PAR 160). All fluorescence decays exhibited a simple exponential temporal dependence over more than two e-folding times.

Transient fluorescence from $\text{Tb}(\text{thd})_3$ was readily observable at pressures of a few Torr and temperatures greater than 200°C. The emission consisted of a series of bands in the 490–650 nm region corresponding to transitions from the 3D_1 level of Tb^{3+} at about 20,500 cm^{-1} to levels of the 7F ground multiplet. As is typical of Tb^{3+} fluorescence, the strongest band was at about 550 nm and had a width about 20 nm. Direct 337 nm excitation of fluorescence by absorption into higher-lying levels of Tb^{3+} is weak because of the small oscillator strengths for $f-f$ transitions. Therefore, excitation is attributed to singlet absorption of the chelate followed by ligand-to-rare-earth energy transfer. This transfer may proceed directly from the lowest excited singlet level or by triplet levels.⁷⁸ Fast intersystem crossing rates have been observed in liquid chelate systems, and the triplet levels typically are found at energies above and favorably situated for transfer to the 3D_1 level. The observed risetime of the 3D_1 fluorescence was no slower than the pump pulse duration; thus, the implied transfer time from the chelate to Tb^{3+} must be less than several nanoseconds.

The $\text{Tb}(\text{thd})_3$ fluorescence decay times in the gas phase are very much shorter than in the solid or liquid phases. Whereas at room temperature the Tb^{3+} fluorescence lifetime was around 500 μs in solid $\text{Tb}(\text{thd})_3$ and around 1 ms and 600 μs , respectively, for 4×10^{-4}

molar solutions in EPA and 96% ethanol, the vapor phase lifetimes were less than 1 μ s for temperatures greater than 200°C. These short lifetimes are due to nonradiative deactivation of the 5D_4 state. This relaxation can occur through intermolecular or intramolecular processes. To investigate the first possibility, T_{SA} (see Fig. 9-32) was varied to generate vapor pressures from 1.6 to 5.8 Torr while T_B was kept fixed at 300°C. If biomolecular collisions were important for relaxation, the fluorescence lifetime would be inversely proportional to pressure. The measured $Tb(thd)_3$ lifetimes, however, were independent of pressure over an 1 above range to within the experimental uncertainty of $\pm 10\%$.

To examine the role of intramolecular deactivation, T_{SA} was kept fixed at 200°C, corresponding to a chelate vapor pressure of 3.5 Torr, and T_B was varied from 230 to 300°C. The effect of temperature on lifetime is dramatic—a 70°C increase in temperature causes a factor of six decrease in lifetime. In Fig. 9-33, the fluorescence decay rates ($1/\tau_f$) are plotted versus $1/T_B$ and are seen to support an Arrhenius description of the 5D_4 deactivation of the form

$$1/\tau_f = W_0 \exp(-E_0/kT_f), \quad (1)$$

where W_0 and E_0 are determined to be about $4 \times 10^{12} \text{ s}^{-1}$ and 5400 cm^{-1} , respectively. These magnitudes for the activation energy E_0 and relaxation rate W_0 suggest a model for deactivation involving rapid intramolecular transfer from the rare earth to the chelate followed by chelate relaxation. For a given chelate, the rare earth decay scheme could be by either the lowest triplet or excited singlet levels depending upon their decay rates and locations with respect to the excited rare earth level. Based upon the present evidence for $Tb(thd)_3$,⁷⁹ relaxation via the lowest triplet level appears possible.

Nonradiative deactivation of 5D_4 , wherein the approximately $14,700 \text{ cm}^{-1}$, $^5D_4 \rightarrow ^7F_0$ energy is taken up by exciting multiple vibrations of the chelate molecule, was also considered. Since the vibrational spectrum of a molecule of an approximate weight of 709 is necessarily complex, we concentrate on the highest frequency vibrations which are generally most important for relaxation since they can conserve energy in the

Fig. 9-32. Experimental arrangement used in measuring fluorescence lifetimes of the $Tb(thd)_3$ chelate as a function of pressure and temperature.

Fig. 9-33. Semilog plot of the measured fluorescence decay rate from the Tb^{3+} , $^5\text{D}_4$ level (at 550 nm) vs the inverse of the body temperature.

lowest order process. Assuming a single frequency model and a vibrational frequency ν_v , the predicted temperature dependence for an n -quanta deactivation is⁸⁰

$$\frac{1}{\tau_f} = W'_0 \left[\frac{\exp(h\nu_v/kT)}{\exp(h\nu_v/kT) - 1} \right]^n \quad (2)$$

When high frequency vibrations such as C-H, $\nu \approx 2800 \text{ cm}^{-1}$ ($n = 6$) or O-H, $\nu \approx 3500 \text{ cm}^{-1}$ ($n = 4$) are used in Eq. (2), the predicted temperature variation of $1/\tau_f$ over the range shown in Fig. 9-33 is negligible. The use of a large number of lower frequency vibrations yields a greater temperature dependence. This is illustrated for a 1000 cm^{-1} , 15-quanta process in Fig. 9-33; however, the temperature dependence is still inadequate. Furthermore, the resultant probability W'_0 for this case is much too large compared with measured rare earth multiphoton relaxation rates in crystals.⁸⁰ The interplay between different combinations of ν_v and n in Eq. (2) has been extensively discussed for multiphoton deactivations in crystals.^{80,81} As mentioned above, similar considerations on the expected nonradiative relaxation processes in the rare earth trihalides and the rare earth trihalides complexed with transition-metal trihalides have been undertaken.⁶⁴⁻⁶⁶

The prospect of laser action in $\text{Tb}(\text{thd})_3$ is not encouraging. The present results indicate that, in the case of $\text{Tb}(\text{thd})_3$, at the temperature required to obtain a reasonable density of rare earth ions, the radiative quantum efficiency will be low. While short lifetimes and low efficiencies do not preclude lasing, they are

generally unfavorable conditions especially in the context of a laser fusion igniter. Other ions which have fluorescing levels farther removed from the lowest excited chelate levels, such as Eu^{3+} , may make better candidates for vapor phase rare earth lasers. The energy gap between the fluorescing level and the lower-lying vibrational frequencies of the carrier molecule should, however, be kept as large as possible to avoid deactivation by the multiquanta vibrational quenching process discussed above and in Refs. 64-66. In cases where this process is significant, the rare earth should be attached to molecules containing no light atoms so as to reduce the available vibrational frequencies and therein the probability for deactivation. Certainly, many potential combinations exist between all the available rare earths and chelates such that certain matches may indeed yield attractive vapor phase, rare earth fusion laser gain media.

Rare Earth Trihalides

The biggest drawbacks of the trihalogen carrier vapors are: 1) the high temperatures required to obtain reasonable vapor pressures, i.e., 1200 K (900°C) produces only 1 Torr vapor pressure at about 10^{16} molecules/ cm^3 , and 2) the chemical reactivity of the vapors. However, these adverse features are surmountable. The vapor pressure information and stored energy density for NdI_3 and NdBr_3 are shown in Fig. 9-34. The

Fig. 9-34. Number density and stored energy density in the $^5\text{F}_{5/2}$ J-manifold of NdI_3 and NdBr_3 vapors as functions of temperature.

depicted available stored energy density at $1.06\ \mu\text{m}$ assumed an excitation of one-half the vapor molecules to the ${}^4\text{F}_{3/2}$ upper J-manifold of Nd^{3+} . As seen in Fig. 9-34, temperatures at about 1400 K are required to attain 10 J/liter, a storage comparable to present CO_2 short-pulse lasers. As the temperature is raised to increase the gas number density, the thermal population in the lower laser manifold ${}^4\text{I}_{11/2}$ increases exponentially. This effect has been included in calculating the stored energy density curves of Fig. 9-34.

Rare Earth Trihalides Complexed With Transition Metal Trihalides

This class of trivalent rare earth molecular vapors may be the most attractive, combining both the attributes of reasonable vapor pressures and negligible propensity for radiationless deactivation. The remarkable physiochemical properties of the rare earth/metal-chloride vapor complexes discovered by Øye and Gruen appear to overcome the high temperature constraint of the pure RE-trihalides while exhibiting comparable spectral properties.⁷⁶ By providing a vapor of Al_2Cl_6 molecules over solid NdCl_3 , the vapor pressure of Nd-bearing molecules is increased by 7 to 13 orders of magnitude in the temperature range from 600 to 800 K. The studies of Øye and Gruen⁷⁶ suggest that the Nd^{3+} ions appear as monomers in the vapor with two possible stoichiometries, $\text{Nd}(\text{AlCl}_4)_3$ and $\text{Nd}(\text{AlCl}_4)_2(\text{Al}_2\text{Cl}_7)$. In these molecules, the $(\text{AlCl}_4)^-$ and $(\text{Al}_2\text{Cl}_7)^-$ radicals replace the single halide atom in the RE trihalides, resulting in similar $4f \rightarrow 4f$ optical spectra. The lower molar absorptivity of the Nd-Al-Cl complex compared to the pure trihalides suggests a more ionic bonding in the complex.

From the known pressure and temperature data,⁷⁶ one can estimate the energy storage for the complex. This is shown in Fig. 9-35 as a function of temperature and can be readily compared with the pure trihalogen case represented in the figure. Again, one assumes one-half the molecules are excited to the ${}^4\text{F}_{3/2}$ level and also corrects for the thermal ${}^4\text{I}_{11/2}$ population. Obviously, much lower temperatures are required for the Nd-Al-Cl complex to achieve a given energy storage, i.e., at $T = 762\ \text{K}$, the vapor pressure of the RE complex is about 70 Torr. Figure 9-35 also illustrates another aspect of the problem. It shows the Al_2Cl_6 background pressure and the ${}^4\text{F}_{3/2}$ energy storage as a function of temperature. Note the relatively high background pressure of 6 to 7 atm which might have profound (good and/or bad) effects on the energy dynamics of the molecular complex. If pressures as high as 8 atm and temperatures as high as 800 K can be tolerated, stored energies in excess of 100 J/liter may

be attainable. Also, it turns out that high temperatures T greater than 800 K will be required not only for energy storage, but to provide a reasonable optical thickness for medium pumping and a useful small signal gain coefficient. For example, at $T = 762\ \text{K}$, the peak absorption coefficient for the strong $5870\ \text{\AA}$ band is only $0.06\ \text{cm}^{-1}$ with the near infrared bands approximately five times weaker. For half the molecules in the ${}^4\text{F}_{3/2}$ manifold at $T = 762\ \text{K}$, the small signal gain coefficient at $1.06\ \mu\text{m}$ is estimated to be $1.5\%/ \text{cm}$ or well below that of ED-2 glass which is about $7\%/ \text{cm}$.

Biomolecular Nonradiative Deactivation Processes

In the initial analyses of the RE molecular vapors as fusion lasers⁶⁴⁻⁶⁶ emphasis was placed on providing estimates of the radiative and unimolecular nonradiative (multiquantum vibrational deactivation) transition rates. It was shown that in the simple and complexed trihalides, that the unimolecular nonradiative relaxation process could not compete with radiative relaxation processes by several orders of magnitude in specific systems of interest. Further analysis suggests that metastable f-electronic states will ultimately be quenched by biomolecular collisions as the vapor pressure is increased.

In the case of simple trihalogen vapors, an excited RE molecule can collide with a ground state RE

Fig. 9-35. Stored energy density in ${}^4\text{F}_{3/2}$ J-manifold of Nd-Al-Cl vapor complex and pressure of Al_2Cl_6 vapor as a function of temperature.

Fig. 9-36. Dipole-dipole quenching of the ${}^4F_{3/2}$ J-level of the Nd^{3+} ion.

molecule resulting in two RE molecules in excited states lying below the metastable level. This nonradiative deactivation processes is analogous to concentration quenching in RE-doped solids.⁸² The process is illustrated in Fig. 9-36 which shows an NdX_3 molecule excited in the ${}^4F_{3/2}$ J-level and a ground state NdX_3 molecule. Because of a near energy match between the ${}^4I_{9/2} \rightarrow {}^4I_{15/2}$ and ${}^4F_{3/2} \rightarrow {}^4I_{15/2}$ electronic transition, a collision between these two molecules may result in two NdX_3 molecules in the ${}^4I_{15/2}$ J-level. Assuming an exact energy match, we can estimate the probability per collision of forming the doubly excited collision pair. If $\langle \mu_1 \rangle^2$ and $\langle \mu_2 \rangle^2$ are the transition moments indicated in Fig. 9-36, then the quenching probability per collision for a dipole-dipole interaction potential is⁸³

$$P(v, b) = \frac{4 \langle \mu_1 \rangle^2 \langle \mu_2 \rangle^2}{9 \hbar^2 b^4 v^2}, \quad (3)$$

where b is the impact parameter and v is the relative velocity of the collision partners. We now estimate this probability for the Nd-Al-Cl_3 complex. Taking the values⁶⁴ $\langle \mu_1 \rangle^2 = 4.1 \times 10^{-40}$ esu, $\langle \mu_2 \rangle^2 = 2.3 \times 10^{10}$ esu, $b \approx 5 \times 10^{-8}$ cm (hard sphere), and $v = 1 \times 10^4$ cm/s (Maxwellian distribution; $T = 800$ K), we calculate $P = 6 \times 10^{-5}$ per collision or a cross section $\sigma \sim 2 \times 10^{-19}$ cm². At a partial RE-vapor molecule density of 10 Torr, the collisional lifetime of the ${}^4F_{3/2}$ J-level is estimated as $\tau_c \sim 5$ ms. This value is orders of magnitude longer than the unimolecular relaxation time, but approaches the calculated radiative lifetime $\tau_r = 1.4$ ms. The estimate just given is not offered as rigorous, but it does indicate that bimolecular quenching via dipole-dipole interactions may be important in limiting the lifetime of excited RE electronic states. In the case of the transition metal complexes, relaxation of excited RE molecules via collisions with uncomplexed Al_2Cl_6

molecules may also limit RE excited state lifetimes. Although molecular excitation of high-order overtone vibrational transitions (with very weak dipole transition moments) will be required to conserve energy in such a collision, the high number density of uncomplexed Al_2Cl_6 molecules may render a relatively short deactivation time.

A number of projections outlined in this discussion have recently received supporting experimental confirmation. Hessler and Carnall⁶⁷ have recently measured the characteristic emission spectra of TbCl_3 complexed with AlCl_3 at a vapor pressure of about 2 atm (perhaps 10 Torr of Tb-containing molecules). The measured fluorescence lifetime of the 5D_4 level of 1.6 ms agreed well with the estimated radiative lifetime for this level of 0.7–1.4 ms.^{65,66} This result shows that unimolecular deactivation across the $14,800 \text{ cm}^{-1}$ gap appropriate to this system is small (as calculated). In this case there is no energy conserving Tb-Tb collisional deactivation matrix element. Furthermore, $\text{Tb-Al}_2\text{Cl}_6$ collisions at a frequency of $2 \times 10^{11} \text{ s}^{-1}$ also failed to quench the metastable state, consistent with a near-vanishing multiquantum vibrational dipole moment. We speculate that the 5D_4 level is populated across a 5800 cm^{-1} gap from the higher lying $\{{}^3D_3, {}^5G_6\}$ levels by way of a resonant Tb-Tb collision involving $\{{}^3D_3, {}^5G_6\} \rightarrow {}^5D_4$ and ${}^7F_6 \rightarrow {}^7F_0$ electric dipole transition, and not by way of unimolecular nonradiative processes which are estimated to be small.^{65,66} The reason for the efficient Tb-Tb quenching is the large dipole transition moment of 4.6×10^{-38} esu for the $\{{}^3D_3, {}^5G_6\} \rightarrow {}^5D_4$ transition. In fact, the collisional time to populate the 5D_4 level is estimated to be about 20 μs for a partial Tb vapor pressure of 10 Torr. This estimate appears to be consistent with the limited studies made to date.

Future Work on Rare-Earth Molecular Vapors

Work in the immediate future will concentrate on the rare-earth-metal-halogen complexes and their basic absorption spectra under anticipated laser medium pressures and temperatures as well as the fluorescence lifetimes under the same conditions. Similarly, studies will be continued on certain attractive rare-earth chelate systems. Of course, the practical problems of materials compatibility also will be addressed for any attractive RE-vapors. For the most promising candidates, a variety of laser demonstration experiments are envisioned. To illustrate the possible laser pumping techniques the energy level diagram of Fig. 9-37 is useful. The optical spectrum of Tb-Al-Cl complex has not been measured but based on absorption spectra recorded for Tb³⁺:CaF₂ crystals, the lowest lying 5d level of Tb³⁺ is placed near 44,000 cm⁻¹ as shown in Fig. 9-37. (We would also expect the lowest lying 5d

state of Pr³⁺ to lie at the same energy; remarks made for Tb³⁺ pumping apply directly to Pr³⁺ pumping.) The absorption spectrum of AlCl₃⁸⁴ exhibits a moderately strong and fairly narrow absorption band at 42,000 cm⁻¹ as well as a very broad, intense band above 45,000 cm⁻¹. The latter band is interpreted as a charge transfer band. The lowest lying 5d band for Nd³⁺ is expected to lie above 50,000 cm⁻¹.⁸⁵

We can describe four generic types of laser pumping, based on the energy level diagrams of Fig. 9-37: 1) optical pumping by way of the relatively weak 4fⁿ → 4fⁿ ligand-induced absorption bands; 2) optical pumping of strong 4fⁿ → 5d bands; 3) optical pumping of the lowest lying electronic states of AlCl₃ (or the complex) followed by energy transfer to RE 5d levels, and finally, transfer to 4fⁿ metastable levels; and 4) direct electrical excitation of excited electronic levels of either the RE ion (5d levels) or complex.

The laser design problems associated with method (1) above have been discussed. For typical RE partial

Fig. 9-37. Electronic level structure of Nd³⁺, Tb³⁺, and AlCl₃.

vapor pressures of, say 10 Torr, the largest Nd pump band (5850 Å) absorption coefficient is only $\alpha = 0.06 \text{ cm}^{-1}$. Aside from axial laser pumping at 5870 Å, efficiently pumping such a single, weak (and relatively narrow) band presents a difficult if not impossible task.

In the cases where the parity-allowed $4f^{n-1}5d$ bands lie below the excited electronic states of the complex, direct optical pumping of the RE^{3+} ion should be greatly improved. Peak optical cross sections for these strong bands should be approximately $5 \times 10^{-18} \text{ cm}^2$ with transition bandwidths⁸³ of about 1500 cm^{-1} . For a 10-Torr RE partial pressure, we would expect an absorption coefficient of about 0.5 cm^{-1} for 5d bands. This is a reasonable value for efficient transverse pumping of a cylindrical tube of vapor. The use of 5d bands of Tb^{3+} ($44,000 \text{ cm}^{-1}$), Pr^{3+} ($44,000 \text{ cm}^{-1}$) and Ce^{3+} ($32,000 \text{ cm}^{-1}$) for transverse optical pumping becomes particularly interesting in view of recent fluorescence studies of the rare gas-halogen vapors.^{37,38} It has been shown³⁸ that the rare-gas halogens, such as XeBr , can be efficiently pumped with electron beams to produce intense, narrow band fluorescence. This radiation, in turn, can be efficiently used to pump energy-storing laser media for fusion applications. The three krypton halogens (KrCl , KrF , KrBr) and XeI are of interest for 5d pumping of Tb^{3+} and Pr^{3+} in the vapor complexes. XeCl appears to have a useful spectral match with Ce^{3+} although the Ce^{3+} ion would not be very energy storing. We note that under less extreme collisional environments, i.e., chelate lasers, operating in the vapor phase on $\text{RE}^{3+} 4f^{n-1}5d \rightarrow 4f^n$ -allowed transitions, could provide attractive sources for use in a variety of laser isotope separation schemes.

It is conceivable that optical energy pumped into the excited electronic states of the molecular complex might be efficiently transferred to the RE $4f^n$ metastable levels, possibly via the $4f^{n-1}5d$ levels. This

phenomenon has been observed in the fluorescence of PrI_3 molecules in Ar and Xe matrices at low temperatures.⁸⁶ Since the vast majority of AlCl_3 molecules in the vapor complex do not contain RE ions, electronic excitation energy must be transferred rapidly by collisions to RE-containing molecules, if the mechanism is to be efficient. Internal conversion of electronic energy in AlCl_3 molecules into nonradiative channels appears to be rapid⁸⁴ since fluorescence of AlCl_3 is not observed when optically pumped above $40,000 \text{ cm}^{-1}$.

Finally, it would be highly advantageous if the RE vapor complexes could be directly pumped with electron beams. Since there are not strong optical transitions below about $40,000 \text{ cm}^{-1}$, inelastic scattering of electrons will pump only high lying electronic levels—either 5d levels of the RE^{3+} ions or electronic states of the complex. If electron energy largely pumps the molecules not containing RE ions, the efficient transfer process to RE-containing molecules will again be required. In this connection, buffering with several atmospheres of Xe gas may be effective in channeling electronic energy into the RE ions. One might anticipate efficient collisional transfer between Xe_2^+ excimers and the RE-Al-Cl complexes. Clearly, with regard to direct electronic excitation, there are many more unknowns and uncertainties than knowns. Most of these questions can best be answered by experimental studies which are now in progress. During the next year we hope to improve the phenomenological dynamics models, establish a good working kinetics data base, demonstrate laser action in several RE-molecular vapors, and initiate a systematic investigation of this generic class of lasers for fusion applications.

W. F. Krupke

R. R. Jacobs

9.4 Gaseous Electronics

The program element is devoted to theoretical and experimental studies on the interaction of low energy ($\leq 10 \text{ eV}$) electrons with gaseous media. In addition, we are studying many aspects of the generation and propagation of relativistic electron beams, including

such topics as pulse power technology, beam pinch in several diode geometries, and the collective and non-collective energy loss processes of electrons in gaseous media.

9.4.1 RELATIVISTIC ELECTRON BEAM PHYSICS

Areas of Investigation

Interest in the use of relativistic electron beams for pumping gas laser media results from their ability to deposit large amounts of energy in large volumes with

high efficiency and reasonable spatial uniformity. We have undertaken a general study of electron beam technology as applied to the requirements of the laser fusion program to determine in a "semiquantitative"

manner the degree of overlap between existing technology and our requirements, the factors which limit the performance of the electron beam system, and the areas of physics or technology which require further investigation.⁸⁷ We conclude that there is significant parameter space accessible to existing technology and of interest to the laser fusion program. However, there are several broad areas which need further work to verify scaling relationships, implement conceptual solutions to anticipated problems, and extend the boundaries of existing technology. These areas are described briefly below.

Beam Pinch in Space Charge Limited Diodes.

Exciting large volumes of gas to satisfy the high energy storage requirement of laser fusion requires us to generate electron beams with large cross sections. The formation of large area beams is impeded by the deflection of the beam electrons in the self-magnetic field of the beam referred to as beam pinch. In extreme cases this deflection disrupts the uniform flow of current in the diode and produces a highly constricted beam which is not suitable for pumping large scale lasers. Since the magnetic field increases with increasing beam area at constant current density, beam pinch imposes an upper limit on the area of an electron beam generated from a single cathode. Electron beam sources of larger area can be constructed from arrays of individual beams if each diode segment is shielded from the magnetic fields produced in adjacent segments. Two geometries of particular interest are shown in Fig. 9-38. The required magnetic isolation can be accomplished by driving each cathode from a separate source.

Current Flow in Diode Strucutes. An alternative means of obtaining magnetic isolation of diode segments while driving several cathodes from a common source involves managing the current flow in the diode structure so that the necessarily unsymmetric current flow produces a negligible magnetic field in the beam-formation region. A possible scheme for achieving this in a rectangular geometry is shown in Fig. 9-39 where electron current flow is indicated by the arrows.

Formation of Plasma Cathodes at Low Fields.

The cathodes in diode structures are at room temperature, and the applied electric fields are not sufficiently large to obtain field emission over macroscopic regions of the cathode surface. The accepted explanation of their operation is that field enhancement caused by microscopic projections from the cathode surface leads to a field emission current which ohmically heats the projection until it explodes, producing a dense plasma which covers the cathode surface. This plasma provides the electrons necessary to sustain space-charge limited current flow. This process works well in average fields exceeding about 250 kV/cm. At lower fields blades are

Fig. 9-38. Electron beam geometries. (a) Rectangular. (b) Cylindrical.

frequently used to provide macroscopic field enhancement. However, blade cathodes operated at high current densities suffer from erosion, nonuniform emission, and a lack of repeatability.

Plasma Closure in Diodes. The plasma which forms the emitting surface in the diode expands leading to a decrease in diode impedance which will ultimately short the diode if the applied voltage pulse is sufficiently long.

Suppression of Emission in Intense Electric Fields.

A cross sectional view of a typical diode segment is shown in Fig. 9-40. This geometry has been chosen for several reasons: (1) to maximize beam area, (2) to provide uniform current density at the anode plane, (3) to provide some field enhancement at the cathode tip to assist emission from this region, (4) to minimize space between adjacent diode segments, and (5) to minimize the strength of the electric field at the cathode shank, since emission from this region to the diode side walls wastes energy. Although the fields in this region have been minimized, this is not sufficient to prevent emission in general, and an effective means of suppressing emission must be used. Thin dielectric coatings have been used to suppress emission, but optimal materials and fabrication techniques have not been determined and the effective lifetime of such coatings is not known.

Fig. 9-39. Current-flow patterns in a rectangular diode structure.

Insulator Flashover in Vacuum. The diode insulator which forms the interface between the diode itself and the energy source which drives it is a critical component of the overall system. Its voltage standoff capabilities strongly impact system performance, and the relative merits of insulator configurations will influence the choice of the electron beam geometry.

Laser Cell Foils and Mechanical Support Structures. 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. Extensive use has been made of beryllium and titanium foils for this purpose. However, the performance of high-strength composite materials in this application warrants investigation. Unsupported foils may suffice in cylindrical geometries at modest pressures, but in rectangular geometries a mechanical support structure for the foil will be required. The optimum geometry for this structure involves a trade-off between mechanical strength and electron beam transmission.

Energy Deposition Processes in Gases. At high pressures (greater than 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 energy distribution is controlled by the scattering of beam electrons by screened atomic nuclei. This scattering provides smoothing of local beam nonuniformities and some control over deposition (and hence gain) profiles. At low pressures, particularly in gas mixtures involving attaching species, the deposition of energy by ohmic currents associated with space charge and inductive electric fields can be important.

Present Status

Beam Pinch. In connection with the study described above an analytical description of beam pinch in planar, rectangular, and radially converging cylindrical geometries was formulated. Relativistic mechanics and magnetostatics were combined with

Fig. 9-40. Electron-beam diode module.

expressions for space charge limited current flow to obtain a general scaling relationship describing beam pinch in the form

$$\frac{w}{d} V^{1/2} = \alpha \sin \theta, \quad (1)$$

where w is the width of the 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. Empirical observations indicate that the appropriate width w to be used in the treatment of diodes as pictured in Fig. 9-40 is the beam width at the anode rather than the cathode width. The details of the calcu-

Fig. 9-41. Geometry scaling of beam pinch, 1.0 MV. (a) $d = 1$ cm, 4030 A/cm. (b) $d = 10$ cm, 408 A/cm.

lation as well as expressions for the functional forms for α are presented in Ref. 88. For voltages of the order of 1 MV, angles of 60° , and reasonable geometries, the maximum value of w/d is approximately 3.

Numerical Simulations. In preparation for an experimental investigation of beam pinch, numerical simulations of complex two-dimensional diode geometries have been performed using the code EGUN.⁸⁹ The emphasis in these calculations was to investigate the validity of the analytic scaling relationship listed above. To test the geometry scaling, simulations were made with identical diode shapes and constant voltage, but with different anode-cathode spacings. The result was the generation of identically shaped beams presented in Fig. 9-41. The voltage scaling was checked by holding all other variables constant and calculating the quantity $w/d \times V^{1/2}$ with w measured at the anode plane. The constancy of this quantity is demonstrated in Fig. 9-42. In addition, a systematic variation of cathode width and shape was performed. In no case simulated so far have conditions have been found which exceed the limitations predicted by the analytical calculation.

EGUN has been modified to permit the simulation of radially converging electron beams in cylindrical geometries. Comparison of EGUN simulations with the calculations of Langmuir and Compton⁹⁰ in an idealized geometry is presented in Fig. 9-43 and indicates that the modification is working correctly. Simulations of complex, realistic geometries will be performed in the near future.

Energy Deposition in Gases. Use of the three-dimensional, Monte Carlo, electron-photon transport code SANDYL¹¹ continues to provide the major source of information concerning the magnitude and spatial distribution of energy deposited in the laser medium by beam electrons through collisional processes. It has provided general relationships between electron energy and the stopping power and size of the laser medium used in the study described above and detailed informa-

Fig. 9-42. Voltage scaling of beam pinch.

Fig. 9-43. Current characteristics of a cylindrical diode. $V = 1$ MV, $w = 3$ cm, $R_c = 2.5$ cm.

tion used in the interpretation of experimental measurements (see Sec. 9.2.1).

The injection of charged particle beams into gases generates electromagnetic fields and produces a fractionally ionized plasma. Ohmic currents flow in this conducting medium in response to these fields, and the resulting energy dissipation can heat the plasma electrons to the point where they influence the kinetic processes occurring in the gas. There are three means by which the beam produces an electric field. First, there is a space charge field associated with the charged beam particles themselves. Second, typically the gas is sufficiently dense that a significant fraction of the beam electrons are stopped in the gas, and the resulting charge accumulation produces an electric field. Third, there is a magnetic field associated with the beam current, and its temporal variation induces an electric field.

A one dimensional numerical model has been developed to describe this problem. Maxwell's equations are combined with an equation describing the evolution of plasma density. The electric field and hence, plasma currents, are assumed to be parallel to the beam current, and the spatial derivatives are replaced by a transverse scale length. The results of calculations in xenon gas at pressures greater than 1 atm under conditions typical of laboratory experiments support the conclusion that the energy dissipated by ohmic processes is a negligible fraction of the energy deposited directly by the beam. At lower pressures ohmic cur-

rents become more significant, but the kinetics included in the model are not sufficiently sophisticated to treat this region. The results of two calculations for different transverse scale lengths are presented in Fig. 9-44 and show that little plasma current flows for scale lengths such that magnetic effects are important. This is in direct contrast with the situation normally encountered in electron beam transport problems where beams are injected into geometries whose transverse dimensions are small compared with axial dimensions. Consequently space charge fields are predominantly transverse, and axial currents are driven by inductive fields. In the one-dimensional model, space charge fields are assumed to be axial implying that the transverse dimensions of the system must be large compared with the depth of penetration of the beam into the gas. Unfortunately, geometries typically encountered possess comparable transverse and axial dimensions, thus

Fig. 9-44. Ohmic currents (σE) in xenon. (a) $L = 100$ cm, (b) $L = 2$ cm, $P = 10$ atm; $E = 1$ MeV.

necessitating a two-dimensional treatment. Such a numerical model is being developed and will incorporate a more sophisticated kinetics package which will permit its application to a wider range of problems.

Near-Term Experimental Programs

We have designed a modification to the PI422 machine located in Building 169 which will make that machine suitable for pursuing many of the areas described above. The output characteristics of the modified machine are presented in Table 9-8. The high voltage configuration is illustrated in Fig. 9-45. It consists of a water dielectric coaxial pulse-forming line, a high pressure SF_6 output switch, a tapered transmission line transformer, flat diode insulator, and a large vacuum chamber ($\sim 1 \text{ m}^3$) to permit the construction and testing of complex extended diodes in both rectangular and cylindrical geometries.

Our first major application of the PI422 machine will be directed toward a systematic study of the voltage-current characteristics and electron trajectories in relativistic diodes in both rectangular and cylindrical geometries. We will emphasize the evolution or verification of scaling relationships to predict the performance of such diodes and to permit the design of large scale systems.

The study of beam pinch and the construction of complex diode structures requires techniques for suppressing unwanted emission. Dielectric coatings presently in use are adequate for the initial phases of this work. However, more durable coatings capable of withstanding higher fields will be required before the beam pinch studies can be completed. A parallel program to develop this technology will be pursued.

L. G. Schlitt
J. Taska

Table 9-8. PI422 machine characteristics

Mode	Voltage	Current	Impedance	Pulse length	Rise-time	Energy
High voltage	2.0 MV	150 kA	13 Ω	55 ns FWHM	18 ns	15 kJ
Low voltage	1.4 MV	230 kA	6 Ω	55 ns FWHM	22 ns	15 kJ

Fig. 9-45. Schematic of PI422 pulse-forming line.

The use of intense electron beams has provided sources with sufficient electrical pump energy to enable the discovery of new classes of uv visible gas lasers. Such lasers are the vuv rare gas (RG) excimer lasers, the RG halide excimer lasers, and the RG-atomic oxygen and the RG-atomic iodine transfer lasers. These particular lasers may be categorized according to their ability to store energy in the excited state of the laser gas. The excimer systems typically store energy for about 50 μ s while the atomic systems store energy for much longer periods. Additionally, these systems have efficiencies of approximately 1-30% based on the electron energy deposition in the gas with the excimer systems having the higher efficiency; the atomic systems require an additional step of energy transfer from an intermediate excimer and thus have lower efficiency.

The high efficiency and desirable wavelength of these lasers makes them attractive for ERDA applications. Their ability to store energy distinguishes their applicability to LIS or LF.

LIS requires relatively low energy per pulse (≤ 1 J) at a high repetition rate (≥ 1 kHz), while LF requires $\geq$ pulses at low repetition rates.

Basically, electrical energy can be delivered through power conditioning equipment at a rate required for LIS; i.e., using lasers such as RGH and

delivering pump energy in about 50-ns pulses. It does not appear at present that power conditioning equipment can deliver electrical energy to a laser at the rate required for LF. Therefore, this application must rely on energy storage in the excited states of the laser gas.

All laser systems of interest involve the conversion of electrical energy to either fluorescent or laser optical energy. The electrical energy may be supplied either by a direct electron beam injected through a thin foil into the laser gas or by a discharge. In both cases, the directed electron energy is transverse to the optical axis to minimize source voltage as shown in Fig. 9-46. All the aforementioned lasers excluding iodine were discovered using electron beam pumps. Both RGH (KrF and XeF) and iodine have been made to lase using discharges although not as efficiently as with direct e-beam pump.

To contrast the pump techniques, we consider the electron energy deposited per unit volume which is given approximately by

$$E_{ve} = \int \frac{V}{W} J dt \quad \text{for direct e-beam} \quad (1)$$

and

$$E_{ve} = (E/P)(PJ)dt \quad \text{for discharge.} \quad (2)$$

Fig. 9-46. Electron pump configuration.

In the direct e-beam case, the acceleration voltage must be high enough that the electron beam efficiently penetrates the foil, generally no less than 200 kV. The value of the voltage is of little kinetic importance and is selected such that the electron range is comparable to the cell width.^{88, 91} The current density is constrained to be low enough that the excited state density and, hence, excited state-excited state collisional losses are minimized.

In the discharge case, the applied voltage is adjusted such that the E/p is proper to selectively pump particular states.

From a source viewpoint, the major difference is that the e-beam requires a high voltage while the discharge requires a high current, assuming the same deposited energy and pump time. The e-beam can pump uniformly because of the scattering of high energy electrons (but at the price of back- and sidescatter losses) and the use of a fragile foil. The discharge has the incipient problems of nonuniformity and arcing at the high E/P required to pump the visible-uv transitions, and it requires a lower source inductance because of the higher currents.

Because of the inherent discharge instability problems, discharges require auxiliary means of electron production to produce uniform electron deposition, to provide initial electron density, and perhaps to replace electron losses to recombination or attachment. Such auxiliary electron production may be from an e-beam, a plasma, photoionization, controlled predischarges, or a combination thereof.

In an effort to assess the applicability of various source techniques to laser requirements, we have developed source models based, in some cases, on very preliminary data concerning detailed pump physics and system kinetics. The following two examples relevant to LF and LIS typify the evaluations of source technology that have been conducted during the past year.

To consider the scalability of the O(¹S) laser for LF, we have used relevant data obtained on MEG I and evaluated the construction of a hypothetical 250-J power amplifier. The application of these data to a 250-J power amplifier is a vast extrapolation from the existing experiment, but the extrapolation has been made to permit an assessment of the related e-beam and source technology. Such modeling is necessary to evaluate the feasibility of possible use of the O(¹S) laser to fusion.

Using MEG I, we have determined the following parameters for KrO:

$$\sigma = 1 \times 10^{-20} \text{ P cm}^2, \quad (3)$$

$$\epsilon_{\text{sat}} = 35 \text{ P/J cm}^2, \quad (4)$$

$$\epsilon_{\text{vL}} = 5 \times 10^{-3} \text{ J/cm}^2, \quad (5)$$

$$n_0 = 1\%, \quad (6)$$

where P is the rare gas pressure in atmospheres.

We consider a 250-J power amplifier with a stage gain of 5 and assume that energy can be uniformly extracted by using apodized apertures. A 10-cm-diam cylindrical-laser cell would have an output optical flux of 3.5 J/cm², near the state of the art for optical components.

Selecting an operating pressure of 20 atm, the saturation flux is 1.75 J/cm². The gain is determined by

$$g = \frac{\epsilon_{\text{vL}}}{\epsilon_{\text{sat}}} = 0.29\%/\text{cm}. \quad (7)$$

The amplifier length to achieve these conditions is given by

$$L = \frac{1}{2g} \ln \frac{e^2 \epsilon_0 / \epsilon_{\text{sat}} - 1}{e^2 \epsilon_0 / (G \epsilon_{\text{sat}}) - 1}, \quad (8)$$

where ϵ_0 is the amplifier output flux and G is the stage gain. Since the input pulse is below saturation, the optical extraction efficiency is

$$\eta = \frac{\epsilon_0}{\epsilon_s} \frac{(1 - 1/G)}{g_0 L} = 0.85. \quad (9)$$

The basic source parameters are determined as described in Sec. 9.4.1, and Refs. 87 and 91. The e-gun voltage to uniformly pump a cylindrical cell is given by

$$V = \xi W \text{ (MV)}, \quad (10)$$

where

$$\xi = 2.510^{-4} \text{ Mp (MV/cm)}; \quad (11)$$

W is the cell width in centimeters, M is the atomic buffer gas in amu, p is the gas pressure in atm, ξ may be treated as an effective stopping field for the e-beam.

The current pulsewidth product necessary to obtain a given energy density E_{ve} in the gas, assuming a rectangular pulse for expediency of modeling, is given by

$$J \Delta t = \frac{E_{\text{ve}}}{\xi} \text{ (A-}\mu\text{s/cm}^2\text{)}, \quad (12)$$

where J is the current density in A/cm² and Δt is the pulsewidth in microseconds. Using these relations, the voltage necessary to uniformly pump a 10-cm-diameter cell with 20 atm of Kr buffer gas for KrO is 2.1 MV where $\xi \approx 0.42 \text{ MV/cm}$.

The current density pulsewidth product necessary to obtain the desired electron-energy density is 1.2. The

Fig. 9-47. Block diagram of electron pump elements.

pump time is limited by the $O(1S)$ lifetime, which in the MEG I experiments was about $0.7 \mu s$. For maximum efficiency, we select a pump time of 50 ns . The current, therefore is 24 A/cm^2 .

The total gun energy is around 60 kJ with efficiencies of about 50% of electron energy deposited in the cell, 1% pump efficiency, and about 85% extraction efficiency. The stored energy in the stage would be extracted by a subnanosecond optical pulse generated in previous stages.

For pumping this geometry a modularized diode of the hoop geometry is required. With an anode-cathode gap of 20 cm , a module length of between 40 and 70 cm can be electromagnetically graded to deliver the electrons orthogonally to the cell. We select 10 modules of 65 cm each that are contiguously connected along the cell.

The total source current of 500 kA requires a $4.2\text{-}\Omega$ /pulse-forming line. Even 10 separate pulse-forming networks (PEN's) each connected to a diode would be too inductive to produce a 50-ns pulse. We, therefore, are compelled to select a distributed pulse-forming line (PFL) using water for compactness. By employing two parallel coaxial $8.4\text{-}\Omega$ PFL's, the energy is better distributed to the laser cell. (See Fig. 9-47.)

Five diode segments are grouped and connected to each line. The 100-kJ , 4.4-MV Marx required is well within the state of the art. A final amplifier might appear as shown in Fig. 9-48.

On the whole, the pulse-power technology for this illustration and even larger amplifiers is within the state of the art. However, the e-beam diode configuration is rather new, and specific problems such as current feed to the cathodes and its magnetic field influence on trajectories and diode grading are presently being parametrically studied as described in Sec. 9.4.1.

To assess the applicability of direct e-beam pumping to LIS early during this reporting period, we had evaluated the use of $\text{He}_2^+ - \text{N}_2^+$ for a hypothetical high average power amplifier. Such modeling elucidated the problems of direct e-beam pumping for high average power systems and provided a framework for assessing the more recently discovered and more efficient RGH lasers.

The $\text{He}^+ - \text{N}_2^+$ laser system is far from being fully characterized. However, it might be attractive for a high average-power system (defined here as about 1 kHz). Thus, we make certain assumptions concerning the rather limited kinetic data and develop a hypothetical source to pump the laser at modest efficiencies.

We assume, based on the Collins' data, that an efficiency from electrons to laser ($n\ell$) of 2% is reasonable.⁹² Concerning the source, we expect that with proper charging, etc., a plug-to-electron deposition efficiency of 30% can be achieved in a well designed source cell. We further assume that the energy is uniformly extracted by the amplifier by a saturating flux from an oscillator.

Since helium is a low Z gas, we desire a low voltage gun, and the lowest reasonable voltage for which electrons can penetrate the foil is 200 kV . Recalling that $\xi = 2.5 \times 10^{-4} \text{ Mp}$, we obtain a cell width [according to Eq. (10)] of $w = V/\xi = 5 \text{ cm}$.

The pump pulsewidth may be estimated from the experimental lifetime, with the upper-state lifetime placing a probably longer bound on the pulsewidth. The upper-state fluorescent lifetime⁹² for N_2^+ ($B^2\Sigma_u^+$) is 66 ns .

Assume that we desire a pump-energy density E_{cl} of 0.02 J/cm^3 and that we selected $\approx 0.014 \text{ J/cm}^3$ from Collins since its parametric variation is unknown. Since $J\Delta t = E_{cl}/\xi$, we obtain $J = 10 \text{ A/cm}^2$ for a 50-ns pump pulse. The anode-cathode gap is therefore about $d = 4 \text{ cm}$.

Somewhat arbitrarily, we assume a $5 \times 5 \times 100$ amplifier. At 0.02 J/cm^3 the pump energy required is 50 J . Roughly half the e-beam energy might be deposited in the cavity by using the centrally directed e-beam as described earlier. Thus, the source must be about 160 J .

At 1 kHz , such an amplifier might provide around 900 W at 0.6% net efficiency. We now ask what might preclude repetition-rate operation. Of particular concern are parasitic losses and source design, i.e., switching and foil survival.

Parasitic losses are probably not a problem according to a study of high-gain amplifiers⁹³ since the bias fluence saturates the transition. Recent advances in high-voltage repetition-rate switch technology indicate that the switching problem is tractable using gas or vacuum switches. However, some further engineering and optimization will be required.

We have concerned ourselves with window-heating problems. Calculations of foil temperatures using a quasi-steady-state approximation show that the foil may be adequately cooled by radiative and helium convective losses.⁹⁴ We note that the average current loading is about 1 mA/cm^2 , a value comparable to the upper operating regime for the foil operation of cw CO_2

lasers containing large fractions of helium, which is important for cooling. There is no question that foil lifetime will be one of the most critical engineering tasks in developing high average-power direct e-beam pumped laser systems. These initial calculations show that control of foil temperature appears tractable.

This modeling has illustrated that one might construct direct e-beam pumped lasers of reasonable average power. Where we have assumed a laser efficiency based on electron energy deposition of 2%, the RGH lasers are more efficient (perhaps to 30%), and thus the power output and total efficiency could be much higher.

Based on the example we note that an efficient laser at about 1 kW (or higher for RGH) might be developed. Based on existing systems studies, however, one might require a much lower average power for LIS applications. Oddly enough, the e-beam laser as envisioned can not run efficiently at reduced powers. This is essentially because the range of the electrons determines the transverse cavity dimensions, and the aperture of the cavity then determines the laser energy required to saturate the transition. If the cavity cross section is reduced relative to the electron range, the electrons impact the walls and are lost. We noted

earlier that no less than 200 keV is required for transmission through the foil isolating the cavity from the e-gun and, hence, this determines a minimum cavity cross section as given in the example. Alternate schemes employing differentially pumped apertures⁹⁵ in place of the foil or diode plasmas⁹⁶ have not yet proved practical and efficient. Axial pumping in an intense magnetic field would permit smaller dimensions but increase the foil heating problem enormously. Thus, direct e-beam pumping is not intrinsically suited to low average power, high repetition-rate lasers.

We are currently examining discharge pumping for LIS application as described in Secs. 9.1.1 and 9.4.3 in the quest for more efficient systems.

L. Bradley

Pulsed Power

Currently energy for high repetition-rate systems is delivered from capacitor store on the time scale of 0.05 to 5 μ s. We have investigated alternative pulse tech-

Fig. 9-48. Meg III visible power amplifier.

nology. One such alternative to high voltage capacitive pulse forming lies in a transformer.

For electron-beam pumped lasers, the high electron voltage of 150 kV to about 2 MV determines many of the characteristics of the pulsed power system. In its simplest form, this system is a capacitor charged to the output voltage and then switched out through a vacuum diode. The output capacitor and diode are relatively efficient. However, the standard techniques of resistively charging an array of capacitors are inefficient.

To date, there has been little need for and little experience in building the current required repetitively pulsed system. Radar technology back to the 1940's has demonstrated that repetitively pulsed systems can be made to operate efficiently and reliably up to the 100 kV range.⁹⁷ However, this technology is based on the use of pulsed transformers to step up a voltage to the required value from that generated by a motor generator. Limitations occur at high voltages as insulation requirements drop the coupling factor of the step-up transformer. The resulting inefficiency generates heat which limits the transformer's average power capability. However, the stray induction of the poor coupling also increases the pulselength to an unacceptable time period for many systems.

One obvious solution is to use the long pulse to charge an output capacitor, then switch the capacitor to the load. This solves the stray inductance time limit but not the heat limitation on the transformer.

An alternate approach is the Tesla transformer. Unlike standard cw transformers that strive for a coupling coefficient of one, the Tesla transformer works with a coupling coefficient of 0.6 and less. The key to the Tesla transformer is that it works in a pulsed mode. Figure 9-49 is a schematic of the transformer circuit. The primary capacitor is charged to the initial voltage. Then the primary switch, S_p , is closed. Circuits $C_p - L_p$ and $C_s - L_s$ become two oscillators coupled by the transformer. For

$$\frac{1}{(L_p C_p)} \equiv W_p^2 = W_s^2 \equiv \frac{1}{(L_s C_s)}$$

and for a coupling coefficient of 0.6, the full system energy will be transferred to C_2 on the second voltage swing of C_s .⁹⁸ At this point, the output switch, S_o , is closed and energy is delivered to load, R_L , with a time constant of $(R_L)(C_s)$.

Provided the charge time for C_p is long compared to circuit ring time, and the circuit ring time is long compared to the energy delivery time, $(R_L)(C_s)$, each phase can be regarded as independent of the previous phase. Therefore, the Tesla transformer can also operate with a pulse rate comparable to standard transformers.

The low coupling coefficient allows the construction of an "air" (either oil or water) core transformer that has an "ideal" coupling coefficient and easy cooling for average power in the 100 kW to megawatt range.

Tesla transformers have been recently constructed to provide kilojoule pulsers in the megavolt range.^{98,99} Step-up values of about 100-140 are typical. Also, pulse rate limitations are typically the size of the charging supply.

For a power plant system, the minimum expected available voltage can be assumed to be 15 kV. Inductive charging of the primary capacitor will provide a voltage doubling to 30 kV. To obtain the above stated range at 150 kV to 2 MV, the step-up range is only 5 to 66. The lower step-up values allow for shorter secondary winding and, therefore, less resistive loss in the secondary. The prime energy loss then becomes the residual resistance of the switches.

For the primary switch, the relatively low voltage may allow the use of thyristor arrays in place of more common thyratrons or sparkgaps. Actual switch configurations will depend on pulse requirements.

The output switch will almost certainly be a spark

Fig. 9-49. Tesla pulsed transformer and associated input and output.

gap. This is probably the weakest component with a lifetime range of 10^4 to 10^5 shots before maintenance. However, the output switch is a requirement of the short pumping times for pulsed lasers. Therefore, the Tesla transformer could also be regarded as an engineering test bed for switch development.

In conclusion, in order to provide the joules/liter of

electrical energy in a short time on a repetitive basis, the Tesla transformer circuit promises to provide a family of pulsed systems more efficient and flexible than current designs.

C. Duncan

9.4.3 RARE GAS-HALIDE DISCHARGE LASERS

We are investigating rare gas-halide (RGH) lasers as potential tunable lasers and as pumps for dye lasers for LIS applications. RGH pulsed-discharge lasers may be capable of efficient (greater than 1%), high average power (greater than 1 W at several kHz) operation essential for an economically feasible LIS plant. The relative ease of scaling these devices to meet plant requirements over electron beam excitation techniques has prompted feasibility exploration of this laser concept.

Feasibility of the RGH discharge laser was first demonstrated by Burnham, Harris, and Djieu¹⁰⁰ who lased XeF at 351.1 nm and 353.1 nm with 0.1% electrical-to-optical efficiency using a modified nitrogen laser with multipin-to-plane discharge. Subsequently, Wang *et al.*^{101,102} demonstrated XeF and KrF (251 nm and 254 nm) with 0.2% nonoptimized efficiency. Other workers have indicated similar unpublished results.^{103,104}

We are exploring laser emissions from discharge-initiated chemical reaction to XeF* and KrF* using a modified N₂ laser (AVCO model C-950) in the configuration shown in Fig. 9-50. Two 5-m-radius concave mirrors with 99% reflectivity form the optical resonator with BaF₂ pellicle output coupling to a monochromator and a fast photodiode (total output coupling) of about 10%. Photodiode response and discharge current and voltage were monitored by display on a Tektronix 7904 scope. The discharge geometry was modified to $0.3 \times 2 \times 100$ cm by insertion of a stainless steel anode. Brewster's-angle windows (BaF₂) were added to permit external optics, and silastic sea-

lant was replaced with low vapor-pressure epoxy to slow fluorine attack. Fluorine was introduced as NF₃ from premixed gas cylinders (typically 1/3/290:NF₃/Xe/He). Gas mixtures were convectively mixed for at least 24 h before use.

We measured laser output pulse shape, and preliminary results are shown in Fig. 9-51. Figure 9-51a shows the discharge current pulse with about 30 kV of applied voltage and the super fluorescent XeF laser pulse at 351 and 353 nm. The 20-ns (FWHM) current pulse precedes the 30-ns laser pulse by about 30 ns. The time difference between current and laser pulses appears to be consistent with chemical kinetic rates for XeF* production. A 20-ns laser pulse without the 100-ns-long laser pulse tail (see Fig. 9-51b) has been observed and may be attributed to incomplete fluorine passivation and/or contamination in the system. Laser pulse-to-pulse jitter was observed and is believed to be due to free fluorine loss by chemical reaction with the laser housing.

We have not measured energy out and efficiency. Qualitatively, the peak laser intensity observed by the photodiode is about the same as when observing a 1-mJ nitrogen laser at 337.1 nm with pulse lasting 10 ns. This implies 1-2 mJ of XeF laser output with 0.1-0.2% efficiency.

The preliminary results with XeF discharge lasers and the potential for high average power output tunability and high efficiency at uv wavelengths makes these lasers candidates for future LIS applications.

J. Dzakowic

Fig. 9-50. XeF laser experimental arrangement and electrical circuit.

Fig. 9-51. (a) Upper trace: current waveform in discharge. Vertical: 7500 A/div. Horizontal: 20 ns/div. Lower trace: XeF laser output with 415 Torr (NF/Xe/He:1/3/290). (b) XeF laser output waveform at 400 Torr (NF/Xe/He:1/3/290).

9.5 Theoretical Atomic and Molecular Physics

Early in 1975 it became clear that considerably more effort in theoretical atomic and molecular physics was required in the laser program. That is, there was no laser program element responsible for understanding and modeling complex photon/electron/atom/molecule collision processes—issues of great importance in the development of advanced lasers, laser isotope separation, and laser photochemistry. A decision was therefore made to create a Theoretical Atomic and Molecular Physics effort in Y Program. The goal was to assemble a "critical mass" of relevant disciplines that could, with a balanced experimental effort, develop analytical and computational techniques to assist in gaining a basic understanding of collisional processes and ultimately permit study of more complex systems. Thus, the Theoretical Atomic and Molecular Physics (TAMP) Group was created in October 1975.

From inception, the TAMP group was to (1) provide timely theoretical support, (2) maintain a complete awareness of advances in the field, and (3) be at the forefront of developing and applying theoretical and computational methods. The TAMP effort is organized around three functions: projects, disciplines, and facilities.

Projects entail the application of theoretical expertise to a well defined problem of limited scope requiring a timely response to maintain project development. Often a project will require expertise on a range of subjects—as in the evaluation of a candidate gas laser.

To address issues raised in projects, TAMP expertise must embrace a range of disciplines. These include the physical science areas of atomic and molecular

structure, electron scattering and photoionization, heavy particle scattering, and photon physics. They also include empirical modeling, data management, and computer utilization. To support project work and to enhance discipline development, members of TAMP are developing both software and hardware facilities. The software comprises data bases and computer codes; the hardware permits more effective utilization of LLL computers.

Besides defining the basic Y-Program needs and a realistic approach for addressing them, there have been a number of significant activities this year. First, a near-critical mass of theorists has been assembled. Second, many of the necessary computer codes have been collected and are operational on the LLL computer system. In addition, a remote data-processing center has been assembled and a number of large data bases acquired. Finally, a number of projects have been initiated: rare gas-halide laser, copper/copper-halide vapor laser, and atomic actinides.

Plans for the next year include development of semiempirical models describing multiphoton effects, electron attachment, and molecular spectra. Method and code development will continue, with particular interest in the area of utilizing minicomputer networks for solving scientific problems. Increased activities are expected in chemical kinetics and dynamics, multiphoton effects, and spectral interpretation.

C. Bender

9.5.1 TAMP PROJECTS

The various theoretical and atomic physics projects involve direct theoretical support of a new gas laser concept or laser isotope separation issue. Five projects were well under way by the end of 1975: atomic actinide spectroscopy support, copper-vapor laser, rare gas-halide laser, electron scattering by F_2 , and the systematics of potential-energy surfaces.

Atomic Actinide Spectroscopy

Continuing efforts are under way at LLL to interpret the observed energy-level structure of the neutral uranium atom. Laser spectroscopy experiments yield assignments of parity and total angular momentum J and in addition distinguish between Rydberg levels (those for which a single active electron moves in a large orbit well outside the remaining core) and valence

levels (those for which the six valence electrons are combined in 5f, 6d, 6p, and 7s orbitals).

The classification of valence levels is made difficult by the large number of levels observed (presently some 300 of odd parity and 1300 of even parity), the large number expected to arise from combinations of six valence electrons, and the extensive mixing of spectroscopic terms and configurations, which hinders attempts to label levels by traditional quantum numbers.

Work on valence levels combines a twofold *ab initio* and semiempirical theoretical attack. In the semiempirical approach, theory expresses energy values in terms of a few radial-wavefunction integrals (describing electrostatic and spin-dependent interactions) whose values are adjusted for best least-squares fit to observations. By trial and error, one confirms hypothesized energy-level assignments and obtains

values for integrals as parameters. Previous workers have analyzed the lowest-lying odd parity levels, including the nominally $5f^9(4f)6d7s^2L_g^o$ ground state. Work at LLL has concentrated particularly on the even-parity levels of the low-lying configurations $5f^96d^2s^2 + 5f^97s^26p + 5f^97s^2$.

As a guide to physically acceptable parameter space for least-squares fits, extensive numerical studies of Hartree-Fock predictions for electro-static and spin-orbit integrals have been carried out. These configuration-averaged parameters have been computed for 30 of the important low-lying electronic configurations of the form $5f^k6p^l6d^m7s^n$ with integers $k + l + m + n = 6$. The computations provide estimates of the importance of configuration mixing and permit systematic study of the relationship between various radial integrals for different configurations of the same atom. Observed regularities, understandable in terms of electrostatic screening, guide the semiempirical approach in fitting and predicting energy levels and isotope shifts and in incorporating experience with other elements. More than 30 electron configurations have been studied for the uranium atom. In addition, isotope shifts have been computed for Hartree-Slater wavefunctions of U(I), U(II), Pu(I), Pu(II), Am(I), Am(II), Cm(I), Cm(II), Cf(I), and Cf(II).

K. Rajnak
B. Shore

Copper and Copper-Halide Lasers

Because of the high degree of selectivity in exciting the upper laser level and because the quantum energy for the laser transition is a substantial fraction of the upper-level excitation energy, the copper-vapor laser has an unusually high potential efficiency. A major drawback to metal-vapor lasers in general is the extremely high temperatures required to maintain a sufficient metal-atom density (about 1500°C for copper). The recent use of metal-halide compounds, such as $CuCl$ and CuI , has lowered the operating temperatures to 400°-650°. In these systems, the copper halide molecule is first dissociated by a discharge pulse and then the free copper atoms are excited by a second, carefully timed pulse. Scaling has not been entirely successful because of the lack of understanding of the basic mechanisms involved in achieving laser action in these systems. A careful modeling effort is needed to identify the major loss processes and inefficiencies. Before such a task can be attempted, electron excitation cross sections for the atom, electron dissociation cross sections for the molecule, and deactivation rates for the metastable lower laser level must be measured or computed.

The elastic and inelastic electron-impact cross sections for the Cu atom have been theoretically determined at two levels of sophistication. The calculated elastic integral cross sections in the Born and static-exchange models are compared in Fig. 9-52. The elastic differential cross section calculated in the static-exchange model is compared to the experimental cross section in Fig. 9-53. Because the results are in disagreement with the recent measurements by Williams and Trajmar at the Jet Propulsion Laboratory,¹⁰⁵ further higher-order calculations are in progress. Even with the availability of experimental cross sections, the theoretical results are needed to provide an absolute normalization.

There is essentially no experimental information on the dissociation processes of copper halogen compounds. To assign the excited electronic states of the molecule accessible by electron impact, accurate *ab initio* calculations of the potential surfaces for the states deriving from the $Cu(^2S, ^2D, ^2P)$ and $Cl(^2P)$ separated atom limits are being carried out. These curves will also allow the prediction of dissociation products and give information on the chemical recombination of Cu and Cl. Initially, a substantial fraction of the $CuCl$ vapor probably exists as a trimer Cu_3Cl_3 , and this will have to be taken into account in understanding the dissociation by the first discharge pulse to produce Cu atoms. We anticipate that a close interaction between

Fig. 9-52. Comparison of the elastic integral cross section for electron scattering by the Cu atom as a function of incident energy.

Fig. 9-53. Comparison of the experimental and static-exchange differential cross section for elastic electron scattering by the Cu atom at 20-eV incident energy.

theory and experiment is required to advance the state of the art in copper-vapor lasers.

N. Winter

Rare Gas Halides

The past year has witnessed the appearance of an important new class of moderately efficient, potentially tunable, gas excimer systems that operate in the visible and near-ultraviolet frequency range. A number of theoretical studies are planned to support the Laboratory's vigorous experimental effort in this area.

The basic mechanism by which laser action can be achieved in these systems is only partially understood. Emission is thought to correspond to a radiative transition from a bound, ionic upper state to a repulsive (bound-free) lower state. Population of the upper state is, in some cases, thought to involve a crossing of ionic and valence potential-energy curves. Careful modeling of these systems will be needed to identify the important excitation and loss mechanisms.

The first effort will be to understand the spectroscopy of these systems. Approximate potential energy curves for the NeF system have already been calculated. We are planning to obtain potential curves for other systems and from these to calculate the relevant bound-free and free-free Franck-Condon factors to investigate the possibility of broadband tuning in these systems.

Transition moments will be needed to calculate the radiative cross sections. These transition moments can also be used to estimate photoionization cross sections. The ratio of the photoionization cross section to the cross section for stimulated emission determines the extent to which these systems can be scaled. Finally,

the generalized oscillator strengths will be determined in an effort to understand the relative importance of direct electron impact excitation of various excited electronic states.

T. Rescigno

Electron Scattering by Fluorine

A theoretical investigation of low-energy electron scattering by fluorine was initiated.¹⁰⁶ This study was undertaken as part of the effort to develop new methods for studying low-energy electron-molecule scattering and attachment processes and to gain some insight into the behavior of molecular fluorine in the presence of low-energy electrons. At the time this work was begun, there were no other studies of electron-F₂ scattering available, either experimental or theoretical.

Phase shifts for elastic scattering of 0-13.6 eV electrons by F₂ were calculated in the static-exchange approximation. These phase shifts were "extracted" from the results of an extensive-basis-set self-consistent-field calculation. We define an effective phase shift, $\delta_{\ell m}^E(R)$, by the relation

$$\tan \delta_{\ell m}^E(R) = - \frac{W(R_{\ell m}^E j_{\ell})}{W(R_{\ell m}^E n_{\ell})},$$

where $R_{\ell m}$ is a radial function obtained by projecting a spherical harmonic onto a virtual Hartree-Fock orbital, j_{ℓ} and n_{ℓ} are spherical Bessel and Neumann functions, respectively, and W denotes the Wronskian. The phase shift is obtained from the region of coordinate space where $\delta_{\ell m}^E(R)$ has reached a constant value. This approximation scheme is based on the validity of the so-called "low l -spoiling" approximation that had previously been shown¹⁰⁷ to yield satisfactory results in the case of electron scattering by H₂ and N₂.

The elastic cross section depicted in Fig. 9-54 is seen to be dominated by a broad resonance at about 2.2 eV. This shape resonance corresponds to the formation of a quasi-bound state of $^2\Sigma_u^+$ symmetry, which then leads to a large enhancement in the elastic cross section. The exact position and width of this resonance will doubtlessly be sensitive to polarization and correlation effects that were ignored in the initial investigation. There is also the interesting possibility that this shape resonance can serve as a channel for dissociative attachment to produce F + F⁻. A further investigation of this system as well as accurate potential-energy curves for F₂ and F₂⁻ will hopefully allow us to shed some light on the electron attachment process.

T. Rescigno

Fig. 9-54. Electron- F_2 total elastic cross sections obtained from interpolated phase shifts. Cross sections are in units of a_0 , and the electron momentum is given in atomic units.

Potential-Energy Surfaces

Potential-energy curves and surfaces form the foundation for many theoretical studies. Examples range from determining detailed spectra to predicting the rate of chemical reactions. Therefore, it is important to produce such surfaces. Over the past five years, a surface-computation technology has developed at L.I.L. One of the most important observations from these studies is that not all surfaces can be determined. The first *ab initio* surface for greater than three electrons (Fig. 9-55) involved only three atoms

yet required the calculation of potential energy at some five hundred points.^{108, 109} The results of that first study were very encouraging in that agreement with experiment was most impressive. The study also pointed out the need for including electron correlation effects, particularly near the saddle point where bonds are being formed and broken. Studies have continued on the $H_2 + F_2$ system with consideration of

The results on the last two reactions were most enlightening. The exchange barriers were predicted to be high

(20 kcal for HF_2 and 40 kcal for H_2F) which was in disagreement with semiempirical surfaces. Because of these disagreements and the fact that, because of economics, not all potential surfaces can be generated, a systematic study of types of potential energy surfaces was initiated. To date, the study has covered

Of the above reactions, only the ion-molecule and model organic chemistry studies are not yet complete.

C. Bender

Fig. 9-55. *Ab initio* potential energy surface for the $H_2 + F \rightarrow H + HF$ reaction.

The theoretical questions encountered in the laser program require experts from a variety of disciplines. Currently, these disciplines include: atomic and molecular structure, electron scattering and photoionization, heavy particle scattering, photon physics, and empirical modeling. The TAMP personnel have experience in most of these disciplines, as demonstrated via scientific presentations and publications. Besides their involvement in various TAMP projects, scientists must initiate, follow, understand and/or implement new computational methods or theories as they become available. Finally, members of the discipline must maintain high scientific visibility.

Atomic and Molecular Structure

Atomic and molecular structure studies provide many essential ingredients required to model and understand atomic and molecular collision processes. Transition moments, energy levels, potential energy curves and hypersurfaces are properties used by other disciplines within TAMP. The methods for determining such properties are dramatically different for atoms and molecules, hence the subdivision into atomic structure and molecular structure.

Early in development of the laser isotope separation program, it became clear that an effective means for developing the necessary data bases involved the simultaneous use of theory and experiment. Indeed, theoretical estimates¹²⁰ of the cross section and line width of autoionization states in the uranium atom preceded experimental observation by approximately one year. Additionally, theoretical predictions using Hartree-Fock calculations guided early atomic spectroscopy studies. Current studies involve determining energy levels, isotope shifts, transition moments and autoionization cross sections for many of the actinide atoms.

Molecular structure studies include geometry determinations, generation of potential energy curves and surfaces, prediction of molecular spectra (including vibrational and rotational), and methods development. Theoretical methods range from empirical to full *ab initio*,¹²¹ the type of method being determined largely by the accuracy required and the urgency for response. Empirical techniques have been very useful in predicting thermodynamic properties. Semiempirical techniques, such as Huckel theory, are useful for aromatic organic chemistry. Model-potential methods, which approximate the interaction of core electrons with valence electrons, are becoming increasingly useful and will be applied to molecules containing lanthanide and actinide atoms in the future.

Finally, *ab initio* techniques¹²² can be used to treat

all electrons or just the valence electrons (pseudopotential). With recently developed computer codes, calculations are now possible for systems involving first through fourth-row atoms. Depending on the accuracy required, systems with as many as two hundred electrons can be considered.

Having determined the potential-energy hypersurface, other characteristic features of the system can be determined. For example, the vibrational and rotational eigenvalues and eigenvectors can be determined and used to predict or interpret spectra. Such surfaces are also an important input for chemical dynamics analyses. Transition moments between electronic states (or surfaces) are used to predict spectral intensities and photoionization cross sections.

C. Bender

N. Winter

Electron Scattering and Photoionization

The understanding and modeling of gaseous laser systems, as well as the ability to assess the merit of many proposed isotope separation schemes, depends critically on the availability of cross sections for various electron-impact and photoionization processes. Low-energy electron impact is utilized at some stage of the inversion mechanism in most gaseous systems. In addition to electron-impact excitation, there are a number of molecular collision processes, characterized by the presence of a free electron in either the initial or final state, that constitute significant loss mechanisms in e-beam generated and gaseous discharge systems. These include such processes as Penning and collisional ionization,¹²³ photoionization, dissociative attachment, and electron-ion recombination. A major thrust of the theoretical effort will be toward the development of practical techniques for studying these processes.

Electron scattering cross sections depend directly on matrix elements of the electronic interaction potential between continuum electronic wavefunctions. The computation of these wavefunctions then constitutes the major effort in a theoretical study of electron scattering processes. The formulation of the problem and the numerical method of choice depend critically on the energy of the incident (or ejected) electron and the complexity of the atomic or molecular target.¹²⁴ Efforts in this area will emphasize development of those techniques which are applicable to *molecular* systems. Specifically, the intent is to develop methods which make use of an expansion in a discrete set of Gaussian basis-functions.

Our approach to the low-energy electron-molecule scattering problem is based on an integral-equation formulation of the scattering equations (the Lippmann-Schwinger equation) and its reduction to a finite matrix problem through the use of a square-integrable expansion basis.¹²⁵ Molecular continuum wavefunctions so obtained can then be used to predict cross sections for the excitation of molecular electronic states. This approach was used to calculate cross sections for the low-energy excitation of the first two triplet states ($b^3\Sigma_u^-$, $a^3\Sigma_u^-$) of molecular hydrogen and represented the first attempt to obtain an electronically inelastic electron-molecule scattering cross section at a level beyond the Born approximation.¹²⁶

In the course of studies on electronically elastic electron-molecule scattering, an approximate method for obtaining elastic e^- -molecule cross sections solely from the results of a matrix Hartree-Fock calculation on the ground-state molecular target was devised.¹²⁷ This method was based on the observation that the virtual Hartree-Fock orbitals obtained by diagonalization in a sufficiently complete basis set are, apart from an overall normalization, good approximations to the true continuum solutions. This observation, coupled with an assumption of asymptotic angular-momentum decoupling, allows analysis of the elastic cross section in terms of "low l -spoiled" phase shifts. Elastic cross sections for e^- -H₂ obtained in this way were found to agree well with results obtained using the more rigorous Lippmann-Schwinger approach. Elastic cross sections for e^- -N₂ and e^- -F₂ were also obtained,¹²⁸ and a preliminary study of low-energy e^- -CO₂ scattering was initiated.

The ability to characterize e^- -molecule scattering resonances as a function of molecular geometry is an important step in understanding processes such as Penning ionization or dissociative attachment. These processes are thought¹²⁹ to proceed through the excitation of a quasi-bound state imbedded in a continuum of electronic states which has a finite lifetime for decay. The position and width of this state, together with accurate molecular and ionic potential energy curves, can then be used to model these processes. We are currently investigating a number of schemes for obtaining the necessary resonance parameters.

In the area of atomic and molecular photoionization, we have taken an approach in which the cross sections are computed directly, rather than through the appropriate continuum wavefunctions. The fact that the photoionization cross section depends on a matrix element of the dipole operator between a continuum state and a bound electronic state allows one to investigate a number of different possible computational schemes. Among the methods under study are analytic continuation of the frequency dependent polarizability¹³⁰ and

the Stieljes imaging technique based on the method of moments.¹³¹ The input for both these procedures is a finite set of transition frequencies and oscillator strengths. Also under investigation is a new technique based on the theory of dilation analytic potentials through the use of complex coordinates.¹³² All of these methods share the property of being directly applicable to molecular systems.

T. Resigno

Electron Attachment

We have begun to give serious attention to the theoretical description of dissociative attachment of electrons to small molecules. Reactions of the form

are generally considered to proceed in two steps, the first being a resonant electronic excitation of the system to a quasi-bound state AB^* which may then either autodetach or dissociate:

The potential energy curves for the neutral state AB and the state which dissociates to $A^- + B$ may cross at some value of the internuclear separation; for smaller values of R , then, the AB^* state becomes embedded in a continuum of electronic states and is thus characterized by an R -dependent autoionization width, $\Gamma(R)$. Theoretical expressions have been derived that express the dissociative attachment cross section in terms of the potential energy curves for AB and AB^* and the width $\Gamma(R)$.¹³³ The significant point (from the standpoint of isotope separation) is that, depending on the position of the crossing point and the magnitude of $\Gamma(R)$ over the Franck-Condon region, dissociative attachment may proceed with a significant energy barrier and that a selective vibrational excitation might lower this barrier (Fig. 9-56).

For sufficiently simple molecules, we may hope to calculate the potential curves and resonance widths *ab initio*. We have already initiated such a study for the fluorine molecule.³⁴ For more complicated polyatomics, we can still hope to model the process through a semiempirical parameterization of the cross section.

T. Resigno

Fig. 9-56. Potential energy curves for dissociative attachment. For distances smaller than R_c , the AB curve becomes autoionizing. For the situation pictured here, dissociative attachment will not proceed for electron energies less than E_b .

Heavy Particle Scattering

The kinetics modeling of laser systems and LIS processes relies on a large data base of rate coefficients for energy transfer processes, chemical reaction, photodissociation, and ionization. A major part of input to the modeling effort requires the calculation of reactive and nonreactive scattering of atoms and molecules. The single-surface collision phenomena can be adequately described by classical mechanics. The dynamics of multichannel (several electronic states) atom-atom scattering can be readily treated quantum mechanically. Collinear atom-diatom reactive and nonreactive scattering is also routinely calculated using quantum theory.

The molecular dynamics effort can be broken down into the following areas:

- energy transfer and multichannel curve-crossing processes
- reactive scattering
- photodissociation and unimolecular decomposition

Energy transfer includes the deactivation of internally excited states of an atom or molecule during a collision and can occur on a single potential energy surface or involve several electronic states. Examples of two energy-transfer reactions presently under study are:

The first reaction involves the quenching of electronically excited atomic oxygen by molecular nitrogen and involves two electronic potential energy surfaces coupled by spin orbit interactions. A fraction of the electronic energy is channeled into vibrational energy of the nitrogen molecule. Previous theoretical treatments of reaction (1a) have used classical, semiclassical, and statistical methods and approximate potential energy surfaces. The present treatment is quantum mechanical and utilizes accurate *ab initio* surfaces for the $N_2 + O$ collision. Reaction (1b) is closely related and involves the deactivation of vibrationally excited nitrogen molecules by atomic oxygen. At present, it is not certain if the deactivation occurs on a single potential surface or involves several electronic states. These two reactions are prototypes of nonreactive multichannel scattering and are made more interesting by the availability of accurate potential energy surfaces.

Another class of energy transfer reactions that is being studied involves atom exchange. The prototype reactions in this case are:

where vibrational deactivation has previously been thought to occur by fluorine exchange (2a). Recent *ab initio* calculations^{11b} have shown that the reaction barrier for fluorine exchange is greater than 40 kcal/mole. Also, W. R. Wadt has demonstrated that the potential energy surface for the $HF + H$ collision is not strongly angular-dependent and has a minimum energy path for fluorine exchange near 90° . This invalidates the theoretical studies which employed various LEPS potential surfaces with low barriers for reaction (2a) and a linear transition state. A three-dimensional classical trajectory calculation using an accurate potential surface is being carried out to determine the relative importance of reactions (2a) and (2b) for deactivating the $v = 1, 2$, and 3 vibrational states of HF .

The concept of laser-driven chemistry is the basis for several isotope separation schemes. Since it is possible to use lasers to selectively increase the internal energy of the reactants, it is important to understand the effect of excitation on the cross section for reaction and the internal energy distribution of the products. In collaboration with B. R. Johnson of the Aerospace Corporation, we have investigated the dependence of the reaction cross section and the product branching ratios on the vibrational state of the reaction

where the initial vibrational state of H_2 was $\nu = 0$ or $\nu = 1$. Only the $\nu' = 0$ and $\nu' = 1$ states of OH were energetically accessible. The rate constants were determined as a function of temperature and fitted to the Arrhenius formula, $K(T) = A(T)^{1/2} \exp(-E_a/RT)$ (molecule⁻¹ s⁻¹). The dependence of $\ln K$ on T is shown in Fig. 9-57 for the two cases. The experimental rate for the ground state reaction is given by the dashed curve and indicates the excellent agreement between theory and experiment. At 300 K the rate for the $H_2(\nu = 1)$ reaction is enhanced by 7×10^3 relative to the $H_2(\nu = 0)$ rate. While more work is required to understand fully the utilization of internal energy to overcome a reaction barrier, the implication of these results is that the reaction rates for selected isotopic species of infrared active molecules can be controlled by laser radiation.

N. Winter

Photon Physics

Photon physics involves studying interaction of intense laser beams with atoms and molecules. Numerical and analytic studies are exploring possible schemes

for more effectively ionizing atoms and are examining mechanisms by which lasers excite and dissociate molecules. Demonstrated uranium isotope separation at Livermore has been based upon schemes in which a succession of single photons, tuned to atomic resonances, excite and then ionize uranium atoms. These multistage processes have been successfully modeled using traditional chemical-kinetic rate equations. The use of lasers as the excitation source permits processes in which intermediate atomic levels retain phase coherence (multiphoton processes), possibly enhancing the ionization efficiency. The ionization rate and population coherence are strongly influenced by laser frequency, polarization, and intensities, as related to atomic energy levels and degeneracies.

By contrast to processes in atomic vapor, laser-induced molecular excitation and dissociation remains imperfectly understood. The great abundance of molecular energy levels resonantly accessible to infrared radiation makes possible a wide range of near-resonant excitation mechanisms. It is important to develop both analytic and numerical models appropriate to various regimes of collisional frequency and to various degrees of molecular complexity.

B. Shore

Fig. 9-57. Comparison of rate coefficients vs temperature for the $O + H_2 \rightarrow OH + H$ reactions.

Empirical Modeling

An important element of the theoretical effort is empirical modeling and data analysis. Empirical modeling in this context simply means adjusting a theoretical model to better agree with results of "normalization" experiments. A good example of this modeling is the analysis of the uranium energy levels; theory provides expressions for energies in terms of interaction parameters. Hypothesized parameter values, constrained in part by experience with other elements and by *ab initio* calculations of relativistically corrected Hartree-Fock properties, are steadily refined together with energy-level assignments so as to optimize agreement between theory and experiment. Other modeling efforts include use of optimization techniques for developing parametric models describing experimental results. The most recent such study involved determining lifetimes and cross sections from atomic spectroscopic data.¹³¹

Over the past five years a unique approach has been developed for solving problems involving the interpretation of large amounts of experimental or theoretical data. The methods of pattern recognition have provided the foundation for solution of a general class of problems defined as follows:

"... given a set of objects characterized by measurements made on the objects, is it possible

to find and/or predict a property of these objects which is not directly measurable but is known to be related by some unknown relationship

Solution of such problems is often possible using non-parametric pattern recognition techniques. If the probability density functions, etc., are known, the optimum approach would be the use of parametric techniques (normal statistics). Because of experimental design, this is often not possible with real-world (real-time) problems. Non-parametric techniques can be subdivided into three areas: preprocessing, display, and learning. Preprocessing seeks to answer the question of what is the best representation or use of the measurements. Here the number of variables may be reduced and/or useful information about the property to be predicted may be discovered. Preprocessing can take the form of functional operations (e.g., logarithm, square root, raising to a power, etc.), and transformational (e.g., sums, differences, cross products, Fourier, Hadamard, Karhunen-Loeve, etc.). Display techniques are used to represent the measurement space with a more viewable two- or three-dimensional plot. This ability to "see" the data has often proven valuable to the analyst. Dimension-reduction techniques are used to generate such plots. Learning techniques are separated into supervised and unsupervised techniques. Unsupervised learning (or cluster analysis) seeks point

densities or clusters of points which may reflect meaningful interobject relationships. Supervised learning extracts from a training set of data a rule which can be used to make predictions. This general approach is very interactive and requires considerable "human" pattern recognition. First, data is collected and prepared for computer analysis. Preprocessing is followed by display so the scientist can "see" the effect of the preprocessing step. Next, learning techniques are used to better understand the measurements and/or to construct learning rules. The results of display and learning determine whether or not further preprocessing or collection of additional data (new measurements) is required.

Recent or current studies include modeling economic processes, chemical spectral analysis, modeling analytical chemistry processes,¹³⁶ improved uranium exploration, studying the connection between air pollution and health, aging of multicomponent systems, compound (chemical) design, studying production-related materials problem,¹³⁷ relating chemical structure information to biological activity,¹³⁸ and studying the systematics of atomic structure calculations.

C. F. Bender
K. Rajnak

9.5.3 FACILITIES

The ability to respond quickly to the various theoretical questions raised requires a unique "theoretical facility." The answer to the questions usually requires some degree of interaction with a computer; the theoretical facility therefore includes LLL's Octopus system, a remote processing station, and all the necessary computer codes and data bases.

Remote Processing Facility

The remote processing facility is designed to investigate the effects of distributed, semiparallel, computer networks and the man-machine interfacing properties of such systems. Trends in usage of the LLL Octopus network have yielded some interesting statistics. In 1966, some 60% of all computer time at LLL was spent repeating loop calculations. This type of calculation typified large numeric codes performing scientific calculations. Today the Octopus network, much expanded, only spends 10% of its major processor time in such detailed calculations.

This shift in processor effort is partially explained by the increased concern in computer graphics and

"on-line" researcher interaction with simulation routines. It is also partially explained by a gradual shift from what is commonly thought of as large scientific calculations to more generalized data management and problems, for which Octopus was not designed. Simultaneous with these changes in utilization, the time lag associated with development and packaging of large scale scientific computers virtually guarantees that the computer hardware when delivered contains components which are already out of date.

Microprocessors, not plagued with the long time lag from inception to delivery, have typical delivery times of less than one year. In fact, during the current "microprocessor revolution" computer speeds are increasing by factors of four to five per year. Typical of the large scale integrated (LSI) microprocessors is the INTEL MCS80, an eight bit processor on a chip which is the heart of the remote data processing facility. This particular device, its basic circuits and associated interface logic, has been subjected to LLL engineering standardization; these are now available as store-stock items.

The remote data-processing facility shown in Fig. 9-58, contains two central processing units, 16,000 words of random access memory, 1000 words of read-only memory, a CRT display unit, a keyboard high speed paper tape unit, a line printer, and a dual floppy-disk data storage unit. A card reader and add-on peripherals are planned. The data processing facility interacts with Octopus as a terminal, as a smart terminal, and off-line. In the "smart" mode evening and weekend batch-production computer runs are executed and monitored. Off-line operation will allow interactive review of Octopus-generated output using interactive graphics.

Planned is the use of specialized hardware for solving specific computational problems. Special-purpose hardware devices (e.g., array processor, specialized

LSI, etc.) will be interconnected to create a micro-processor network system which should run at the speed of a CDC 6600.

**L. Cox, Jr.
C. Bender**

Computer Codes

Computer codes provide TAMP scientists the means to quickly develop insight into a given problem. Each discipline is responsible for collecting, implementing, and developing the necessary codes.

Atomic structure codes are used mainly for studies involving lanthanides and actinides. The codes are:

- RCN—Computes numerical nonrelativistic Hartree-Fock (or Hartree-Slater) wavefunctions, rel-

Fig. 9-58. Control console of the remote computational facility.

ativistic corrections, continuum functions, and configuration interaction wavefunctions.¹³⁹

- **RCG**—Produces synthetic spectra, position and intensities of spectral lines, given radial integrals (either empirical or *ab initio*).¹⁴⁰

- **THI**—Least-squares fitting routine for semiempirical modeling of energy levels.

- **DCLO**—Numerical relativistic multiconfiguration self-consistent field (MCSCF) for atoms.¹⁴¹

- **CLEM**—Expansion function techniques for determining nonrelativistic Hartree-Fock wavefunctions used primarily for determining basis sets for molecular calculations.¹⁴²

Codes which calculate molecular geometries by energy minimization, potential energy surfaces, and molecular properties are:

- **SEMI**—A collection of semiempirical codes, simple Hückel theory, extended Hückel theory, complete neglect of differential overlap (CNDO) and incomplete neglect of differential overlap (INDO). Codes can be used to determine geometries and in some cases their dynamic properties.¹⁴³

- **MODPOT**—Model potential calculation for polyatomic molecules, replaces effect of core electrons with empirical model.¹⁴⁴

- **POLYATOM/GVB**—Cartesian-Gaussian basis functions are used to compute self-consistent (SCF) and generalized valence bond (GVB) wavefunctions.^{145, 146}

- **SYMMOL**—Similar to above but for highly symmetric molecules.¹⁴⁶

- **SCREEPER**—General purpose SCF, multiconfiguration SCF, configuration interaction wavefunctions calculated using Cartesian-Gaussian expansion functions.

- **PROPTS**—Molecular properties (one electron) for Cartesian-Gaussian basis functions.¹⁴⁷

Model-potential calculations for spherically symmetric potentials are done with the code:

- **BSCHROD**—Produces bound-state eigenvalues and eigenfunctions for some 30 analytically expressible spherically symmetric potentials using B-spline basis functions. Produces scattering solutions and obtains cross section and phase shift at fixed energy or, using variable boundary condition technique, at a mesh of energies. Calculates Slater integrals (including autoionization). Calculates and plots oscillator strengths and photoionization. Calculates positions and widths of shape resonances.¹⁴⁸

The electron scattering and photoionization codes were developed primarily for molecules. The codes are:

- **DIATOM**—Solves the Lippmann-Schwinger equation for electron scattering by homonuclear diatomic molecules.

- **XTRACT**—Finds e⁻-diatomic phase shifts by the "low l-spoiling" approximation.

- **CROSS**—Finds photoionization cross section from a set of transition frequencies and oscillator strengths by the method of analytic continuation.

- **IMAGE**—Stieljes' imaging code for determining cross sections using the method of moments.¹⁴⁹

- **ROTCORD**—A modified atomic configuration interaction program. Used to determine autoionizing states and photoabsorption cross sections using the method of rotated coordinates.

- **BATES/CRSEC**—Obtain numerical atomic scattering solutions for partial waves with $\ell \leq 10$ for both neutral and ionic Hartree-Fock potential. Computes and plots total and differential cross sections.

The heavy particle scattering codes are:

- **CLASTR**—Program which computes the classical trajectory for an atom-diatom molecule collision. Modified to select the impact parameter according to quantum mechanically allowed angular momentum values. Produces the cross section for both reactive and nonreactive scattering processes.¹⁵⁰

- **ABC**—A program which also computes the classical trajectories for an atom-diatom collision, but is not constrained to use the LEPS form of the potential surface.¹⁵¹

- **REAPTH**—Reaction path close-coupling program which solves the Schrödinger equation for collinear reactive and nonreactive atom-diatom molecule collisions. This program accepts a general potential energy surface.¹⁵²

- **MULCH**—Multichannel log-derivative quantum mechanical program which includes the possibility of the collision occurring along several electronic potential energy curves.¹⁵³

Currently only two codes exist for empirical model and data analysis. They are:

- **NCOPT**—A general nonlinear optimization code.

- **PATTER**—Interactive pattern recognition techniques are used for interpretation of large collection of information.¹⁵⁴

C. Bender
L. Cox, Jr.
K. Rajnak
T. Rescigno
B. Shore
N. Winter

Data Bases

Data bases are another important part of the "theoretical facility." If properly used, the systematics of a system can be determined. Three data bases exist at present:

• ULEVEL—Contains information on approximately 1500 uranium electronic configurations, parity, etc.

• ULINE—Contains information on approximately 80,000 observed uranium atom spectral lines; includes

relative intensities, parent energy levels, and some level information, etc.

• DIATOM—Spectroscopic constants for selected diatomic molecules.¹³³

C. F. Bender

9.6 Laser Isotope Séparation Laser Projects

The Advanced Lasers Group has a program element that addresses the technological aspects of lasers for laser isotope separation applications. These studies, presently directed toward coherently pumped dye lasers, examine both the dye medium and its possible

oscillator/amplifier configurations as well as the coherent pump source. [See *Laser Isotope Separation Annual Report-1975*, Lawrence Livermore Laboratory, Rept. UCRL-50040-75 (1975).]

9.7 Laser Fusion Laser Projects

A laser fusion power reactor must be viewed as a system in which the laser, laser-radiation transport, and fusion pellet can be regarded as major subsystems. At present we can only offer some nominal laser-subsystem performance requirements based on a rapidly evolving experimental, analytical, and computational effort in fusion pellet evaluation.¹ For purposes of discussion here, a "reasonable" set of performance characteristics for a laser system of interest is listed in Table 9-9. Worth noting is that nominal pulse widths of a few nanoseconds only are required for lasers delivering several hundred kilojoules of energy per pulse (e.g., pulse peak power of about 100 TW or more) and that pulse repetition rates of 5-50 Hz appear useful.

A laser system satisfying these gross requirements is envisioned to be a multichain master-oscillator power amplifier (MOPA), consisting of a well-controlled master oscillator that drives N equivalent power amplifier chains. The number of chains N appropriate for the laser depends on a large number of issues including the

required symmetry and uniformity of illumination of the pellet,¹ laser constraints in scaling the transverse dimension of the largest power amplifiers, limits set by damage of optical components, unit cost of large optical elements, and unit cost of alignment and control instrumentation for each laser chain. A detailed system optimization of this sort has been reported¹ for the Shiva Nd:glass laser currently under construction at LLL. For a system delivering 100-200 kJ, a reasonable working number for N is 32, requiring each MOPA chain to deliver about 3-6 kJ of energy. The optimum staging of the chain power amplifiers will not be considered here, nor the design characteristics of the master oscillator. We consider below the general characteristics of the larger power-amplifier modules capable of delivering 3-6 kJ at the output aperture. Postulating optical components that can withstand a peak energy density of, say, 10 J/cm² for 1-ns pulses, typical output aperture sizes must range from 30 to 40 cm in diameter.

Table 9-9. Laser performance requirements for early laser-fusion applications¹

Average power (MW)	0.5 - 10
Pulse energy (kJ)	100 - 200
Pulse widths (ns)	1 - 2
Peak power (TW)	100
Pulse repetition rate (Hz)	5 - 50
Number of chains	~32

The atomic-iodine photodissociation laser, discovered by Kasper and Pimental¹⁵⁵ in 1964, has recently been the object of intensive development in Germany^{156,157} and the Soviet Union^{158,159} as a single-pulse, high-energy, high-peak-power laser source for scientific fusion research. The utility of the iodine laser medium for this purpose rests in part on the following three basic properties: 1) a relatively short operating wavelength of 1.315 μm , 2) an adequate (if marginal) stored energy density of several joules per liter, and 3) nominal freedom from nonlinear optical processes that can seriously degrade beam quality. The best performance for a single MOPA iodine laser chain was recently reported¹⁶⁰ as 260 J in a 0.7-ns pulse (0.4 TW) with an overall system efficiency of about 0.1%. Output beam quality with respect to focusability on small targets has not yet been discussed in the literature.

The ERDA laser fusion program, which grew rapidly in the late 60's and early 70's, emphasized the development of high-peak-power, single-pulse Nd:glass lasers to carry out basic scientific research experiments in laser fusion. As a result of fundamental, technological, and engineering advances attained during the development of Nd:glass laser sources,¹ it is anticipated that the Nd:glass laser MOPA can be scaled sufficiently to address the critical scientific milestones of the ERDA laser fusion program.¹⁶¹ In view of this historical fact, interest at our laboratory in the atomic-iodine laser medium centers primarily on its potential use as high-average-power pulsed laser in the context of laser fusion applications.¹ In addition to the useful basic properties cited above, the iodine laser medium is gaseous in form, allowing the possibility of flowing the spent, optically inhomogeneous laser gas out of the laser cavity in order to achieve high average output power with acceptable output beam quality. To assess the atomic-iodine laser medium for use in high-average-power laser-fusion applications, one must evaluate a large number of basic, technological, engineering, and economic issues in a systems context. A very simple analysis of these issues indicates that the presently used pumping techniques and technologies comprise one of the least efficient subsystems for average power scaling. We have recently proposed and demonstrated¹⁶² alternative pumping sources that provide additional scaling options for relatively efficient, high-average-power iodine and other¹⁶³ optically pumped laser media for fusion applications.

The atomic-iodine photodissociation laser generally utilizes a mixture of fluoroalkyl iodide (CF_3I , $\text{C}_2\text{F}_5\text{I}$) and buffer (He , Ar , CO_2) gases as the working medium. The photodissociation spectra of CF_3I and

$\text{C}_2\text{F}_5\text{I}$ shown in Fig. 9-59 exhibit a peak centered near 2700 Å with a maximum cross section of about $6 \times 10^{-19} \text{ cm}^2$ and a spectral halfwidth of about 400 Å. In conventional iodine lasers, the ultraviolet continuum and line radiation from a pulsed xenon flashlamp¹⁶⁴ is used to photolyze the iodine-bearing molecules and produce a population inversion between $^2\text{P}_{1/2}$ and $^2\text{P}_{3/2}$ electronic states of the ground electronic configuration of atomic iodine. Recent experimental studies¹⁶⁴ have shown that approximately 4.5% of the capacitor bank energy appears as radiant energy in the 2500-2900 Å spectral band using a 20-Torr xenon-fill flashlamp and a 30- μs discharge pulse, typical for iodine laser experiments. The use of simmer currents¹⁶⁴ to increase the spectral brightness of xenon lamps has also been observed. Enhancement of spectral brightness in the region of the iodine photodissociation bands has also been demonstrated in xenon lamps doped with heavy metals such as Zn and Cd,¹⁶⁵ but with a substantial reduction in lamp life. In using xenon or doped xenon flashlamps for scaling an average-power iodine laser, detailed tradeoffs must be made in terms of flashlamp geometry, cooling, pump radiation transport, lamp failure modes, lamp lifetime, and other factors.

Other pumping techniques have been used in atomic-iodine laser devices. These include pumping with uv radiation generated in a CO_2 -laser-produced plasma¹⁶⁶ and with uv radiation emitted from an exploding wire/gas discharge.¹⁶⁷ Neither of these techniques offer an intrinsic high energy, high average power scalability with good prospects for conserving high optical homogeneity of the laser medium. Recently, Pleasance, and Weaver¹⁶⁸ have demonstrated laser action in atomic iodine by direct electrical excitation of $\text{CF}_3\text{I}/\text{N}_2$ gas mixtures. Although more ground-state iodine atoms than excited ($^2\text{P}_{3/2}$) atoms are produced in the discharge, favorable kinetics of the gas discharge result in a population inversion in the afterglow.

Although the prospect of direct electrical excitation of the laser gas is conceptually attractive, it is doubtful that stable, volumetric discharges can be attained at the pressures required for useful energy storage density and gain bandwidth. We have, therefore, continued to search for efficient, relatively narrowband spectral radiators that can be excited using scalable prime energy sources. Recent experiments have shown that the rare-gas-halogen exciplexes¹⁶⁹ and the diatomic halogen molecules¹⁷⁰ are efficient, relatively narrowband¹⁶⁹ radiators in the spectral region between 1900 and 4000 Å. These molecular vapors are readily pumped using subrelativistic electron beams of moderate current densities ($<100 \text{ A/cm}^2$) and several of these

Fig. 9-59. Spectral absorption curves for the photodissociation bands of C_3F_7I and CF_3I . Superimposed are the stimulated emission spectra of the KrF laser¹⁰ and the Br_2 laser¹¹ and the spontaneous emission spectrum of XeBr and Br_2 molecules.¹⁰²

molecular systems have been used to produce coherent emission^{30-33,40-41} in the ultraviolet spectral region. Although these molecular laser systems do not store energy (because of the short radiative lifetimes of the exciplex or diatomic molecules), they can be used to efficiently pump an energy-integrating laser medium such as atomic iodine. In this respect, we have concentrated our experimental and computational efforts on three specific molecular systems whose emission spectra correlate with the photodissociation spectrum of the fluoroalkyl iodides shown in Fig. 9-59. The molecular systems of immediate interest are XeBr, KrF, and Br_2 , all of which are relatively efficient fluorescers and have been operated as lasers.^{30-33,41}

In applying these emitting gases to the iodine-laser pump problem, we have two generic options¹⁰² to consider: 1) "incoherent pumping" using spontaneous emission of the fluorescing gas, much like a low-density flashlamp, and 2) "coherent pumping" using stimulated emission from the excited gas, permitting iodine pumping through a small solid angle because of the brightness of the pump source. These generic-pumping techniques offer a wide range of options in the design of large-power amplifiers consistent with volumetric flow of the iodine laser medium and the achievement of acceptable output-beam quality. The choice between incoherent and coherent pumping with a specific pump gas is dictated in part by the microscopic kinetic and collisional processes that dominate each molecular system. To differentiate these two pumping techniques, we show in Fig. 9-59 the spontaneous emission spectrum of the XeBr exciplex¹⁰² (2-atm Ar buffer, 25-Torr Xe, 1:1 rr Br_2) and the

stimulated emission spectrum of the KrF laser¹⁰ and the Br_2 laser.¹¹ We have recently demonstrated the pumping of an atomic iodine laser using "incoherent" pumping with XeBr exciplex fluorescence radiation.¹⁰³ We have also measured the fluorescence efficiency (11%) for the conversion of e-beam energy deposited in the pump gas to uv emission in the spectral band shown in Fig. 9-59. Experiments to demonstrate "coherent" pumping of iodine using KrF (and possibly Br_2) are currently in progress.

The purpose of this study was not to present an optimized point design of a high-average-power atomic-iodine laser system or amplifier—a task that is impossible based on currently available data. Our intent, rather, was to outline a number of the systems issues that must be considered very early in the design of average-power laser systems and to scope operating parameter ranges for some of the principal subsystems where possible.

Working Gas Medium

Stimulated emission in the atomic-iodine laser occurs on one or more hyperfine components of the $^2P_{1/2} \rightarrow ^2P_{3/2}$ magnetic dipole transition, characterized by a total spontaneous emission rate of 5.4 s^{-1} . At low pressure, this leads to peak stimulated-emission cross sections in excess of $5 \times 10^{-16} \text{ cm}^2$, a value too large to allow for a useful stored energy density and adequate gain bandwidth to amplify nanosecond laser pulses. The introduction of foreign gases into the laser mixture has been used to sufficiently broaden the iodine laser transitions to store several joules per liter of

working gas and to amplify nanosecond (and shorter) pulses. The collisional broadening and upper laser level deactivation rates have been measured for He,¹⁷⁰ Ar, CO₂,¹⁷¹ and others.^{172, 173} In selecting a buffer gas for use in an average-power iodine amplifier, consideration must be given to additional properties, such as specific heat, nonlinear index of refraction, commercial purity, influence in driving or moderating adverse chemical reactions in the photolyzed working gas, sensitivity to shock wave formation under pump source illumination (wavelength sensitive), and cost. Without exhaustive study, it appears that argon is a viable candidate buffer gas meeting these criteria, although CO₂ and N₂ cannot be ruled out at present. A buffer pressure of 1-atm argon¹⁷² provides for an adequate bandwidth to amplify nanosecond-long pulses, but generally higher pressures of argon will be required (up to 5 atm) to increase the energy storage density and avoid superfluorescence and parasitic oscillation losses^{173, 174, 175} in laser amplifiers as large as those contemplated here. A counterforce to limit the total working pressure of the flowing-gas laser medium is provided by the increased energy required to transport the higher-pressure gas and more importantly by the increased difficulty in controlling gas-density fluctuations to an acceptable level to ensure good output-beam quality.

The minimum partial pressure of the fluoroalkyl iodide gas corresponds to that molecular density that physically can store the desired energy per unit volume (usually 50 to 10 J/liter, corresponding to a minimum pressure of 2-4 Torr). A greater partial pressure than this (generally 10 to 40 Torr¹⁷⁶ of C₃F₇I) is used in flashlamp-pumped MOPA's to provide adequate optical absorption in the photolytic pump bands in amplifiers ranging from 6 to 20 cm in diameter. In the case of "coherent" pumping, where the spectral emission of the pump is narrow and the pump flux is relatively high, the C₃F₇I partial pressure may be determined on the basis of the degree of "bleaching" of the working medium (see Sec. 9.3.1) and the geometry of the amplifier. This phenomenon may provide for lowering the partial pressure of the C₃F₇I vapor and for a better utilization of the vapor in the optical cavity for any single pulse of the laser. This in turn will tend to minimize problems of separating "unused" C₃F₇I material from fragmented material in the gas flow loop. For purposes of this discussion, we can take the working-gas laser medium as consisting of, say, 20-Torr C₃F₇I or CF₃I and, say, 5-atm Ar buffer. Such a working laser medium will have an inversion storage time¹⁷³ of approximately 10 μ s.

The maximum size of a power amplifier will be limited by superfluorescent or parasitic depumping of the laser gas¹⁷³ (if other technical constraints do not preempt this limit). Assuming that the 1.3- μ m radi-

ation leaving the laser volume does not return into the volume, superfluorescent depumping limits the maximum straight-line dimension of the amplifier, L_m , to a value¹⁷⁴ such that $\alpha_1 L_m \leq 5$, where α_1 is the small-signal gain coefficient, $\alpha_1 \leq \sigma_1 \Delta N$, where σ_1 is the collision-broadened cross section for stimulated emission and ΔN is the population inversion density. At 5 atm of Ar, $\sigma_1^* \approx 0.8 \times 10^{-19}$ cm²; so that, for $\Delta N = 2 \times 10^{17}$ cm⁻³ (or 20 J/liter stored), $\alpha_1 = 0.016$ cm⁻¹ and $L_m \approx 300$ cm, which can be taken as the length of the amplifier. To store 2 kJ of energy at 1.3 μ m and at an inversion density of 2×10^{17} /cm³, the transverse amplifier dimension must be 30 cm.

Rare-Gas-Halogen Pump-Source Kinetics

Examination of the alkali-iodide photodissociative spectra (see Fig. 9-59) shows that there are several choices of rare gas-halogen or dihalogen fluorescers that will efficiently couple into this band. The judicious choice of which of these radiators to use is primarily based on whether coherent or incoherent pumping of the alkyl iodide is desired. The fact that a choice exists has to do with the detailed kinetic processes operative in these radiators; for example, XeBr operates poorly as a laser¹¹ but is a bright and efficient fluorescer,¹⁶² whereas just the opposite is true for optimum laser conditions in KrF.¹⁷⁷ Before proceeding further it is important to discuss the major kinetic processes that are responsible for the population in the upper radiative state in the pump systems. However, one must bear in mind that at this time there does not exist a great deal of data and analysis; what is presented here is a best estimate of the important processes. We concentrate our discussion on the rare-gas-halogen systems and in particular on XeBr. (For further discussion on these kinetic processes see Sec. 9.2.3).

One potentially major production mechanism for the upper $\Sigma_{1/2}^+$ state involves the metastable rare-gas atom:

The rate coefficient for this processes has been measured by Velazco and Setser¹⁸ and a $\langle Qv \rangle = 4.6 \times 10^{-10}$ cm³/s found. Once formed, this state will radiate to the various lower states with a branching ratio that depends on the spontaneous emission rate (assuming the absence of stimulated processes).

Of importance in this work is the following radiative channel:

The emission rate for this reaction is thought to be $\tau \approx 18$ ns.¹⁶² There are several collisional processes that

compete either for XeBr^* or for Xe^* . At sufficiently high gas densities the three-body xenon-excimer formation will compete with the reaction given in Eq. (1); namely,

where M represents either xenon or, as discussed below, Ar. This represents a major loss for the Xe^* state at high densities because the Xe_2^* state subsequently radiatively decays at the rate of $2 \times 10^8 \text{ s}^{-1}$.

Two other important collisional loss processes for Xe^* are worth noting:

The first of these—Eq. (4)—is a Penning ionization process and cross sections of about 10^{-14} cm^2 are probable. The second loss process—Eq. (5)—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 latter reaction is of utmost importance in determining the performance characteristics of electron-beam sustainers or simple electrical-discharge excitation schemes. It has been shown both experimentally and theoretically to substantially limit the effective use of a sustainer discharge to augment the e-beam-pump xenon-excimer system. Roughly speaking, these two reactions indicate that to produce Xe^* at high efficiencies, the Xe^* population must be no larger than about 10^{15} cm^{-3} . These processes will be important for XeBr^* as well and with probably similarly large cross-section values. This result is of prime importance in the context of using rare gas-halogen molecular systems as pump sources for iodine lasers because such sources will necessarily involve a low density of radiating molecules (whether spontaneous or stimulated) at any instant of time. To provide the required total pump energy, such sources, therefore, will be spatially extended and must be driven to radiate for times much longer than the natural (spontaneous) radiative lifetime of the active molecules.

There is an additional collisional loss process that appears to be energetically possible; namely, the collisional deactivation of XeBr^* by bromine. In their work on XeF^* , Ewing and Brau²⁰ postulated the following deactivation scheme; namely,

From their data they infer a rate coefficient $\cdot \text{Qv} \cdot$ of about $8 \times 10^{-30} \text{ cm}^3/\text{s}$. Because this process effectively

competes with the radiative channel, one must work at a sufficiently low halogen concentration that this reaction does not dominate that given in Eq. (2). Making the assumption that this process is as important for XeBr^* , one finds that the bromine concentration, for efficient operation, is limited (2 Torr or lower). Upon detailed study one sees that, if the radiation can be extracted from the medium on a time scale faster than the spontaneous decay rate, then the deleterious effect of reaction (6) can be reduced. This is one possible reason why several of the rare gas-halogen systems are more efficient as a laser¹⁷⁷ than as a fluorescer.^{31,161} For the case of XeBr^* its operation as a laser is poor, probably because of an excited-state absorption transition that spectrally overlaps the laser transition. This represents a stimulated loss process raising the pumping requirements and therefore obviates its use as a laser in the context of the present application.

Let us briefly discuss one of the pumping schemes. If one desires to use an electron beam or e-beam sustainer configuration, then for the efficient utilization of the electron energy either the device must be large or the pressures high. For several reasons, both economic and physical, argon is used as the main energy reservoir for the conversion of electron beam energy into the atomic and molecular systems. This particular choice is dictated by its high Z as well as the following favorable energy-transfer process:

For sufficiently high argon pressures this reaction represents a major pumping process for the excited xenon atom. For a 100-200 keV electron beam, argon pressures of several atmospheres are generally used.

At the low average electron energies typically found in electron-beam pumping of high-pressure gases, processes involving the dissociative electron attachment of the halogen molecule could also provide an effective kinetic channel for producing the upper $^2\Sigma^+_{1/2}$ state. This kinetic scheme could proceed as follows:

followed by

where X represents the rare gas atom, R_2 the halogen molecule, and M a heavy third body (generally another rare gas atom). Both of these reactions have, in general, large rate coefficients. One major competing process involves the rapid three-body conversion of X^+ into molecular ions X_2^+ , followed by the rapid dissociative recombination of X_2^+ with the background elec-

trons. Another kinetic scheme involving charge-transfer collisions also is probable.

Obviously these systems are quite complicated and certainly warrant further theoretical study. Let us estimate, however, the maximum intrinsic efficiency for the production of XeBr* for the kinetic processes Eqs. (1)-(7). From Eq. (7) we have

$$\eta_{\text{XeBr}^*} = \eta_{\text{Ar}_2^*} \frac{E_{\text{XeBr}^*}}{E_{\text{Ar}_2^*}}, \quad (10)$$

where η and E are the appropriate production efficiencies and photon (or state) energies. Theoretically $\eta_{\text{Ar}_2^*}$ can be shown to have a value of about 50% if the argon excited-state densities are held below approximately 10^{15} cm^{-3} . This implies a maximum intrinsic efficiency η_{XeBr^*} of less than 23%.

Values approaching this (11%) have been observed experimentally in our Laboratory,¹⁶² along with a general agreement with partial-pressure predictions. Similar efficiencies are predicted for the KrF laser¹⁶³ for comparable partial pressures of Ar, Kr, and F₂. Taking into account reasonable inefficiencies associated with power conditioning and electron-beam transport losses, the rare gas-halogen radiators are essentially as efficient as flashlamps—possibly more efficient. As a minimum, they provide a valid alternative to flashlamps for the scaling of high-average-power iodine laser systems. The technological and design constraints will differ substantially, providing a considerably wider range of design options.

Amplifier Design Options—

Rare Gas-Halogen Pumps

Electron-beam excited rare-gas-halogen pumping sources are intrinsically low density (about 10^{15} cm^{-3}) radiating sources. This imposes a rather different set of amplifier design constraints than encountered using conventional flashlamps, which are relatively compact radiators. In particular, the volume of the rare gas-halogen pumping source (either spontaneous or stimulated) will tend to be roughly the same as that of the laser amplifier. To see that this is reasonable, assume equal volumes of pump source and laser gas. Each unit volume of pump gas will radiate about 10^{15} quanta in the fluorescence lifetime of the exci¹⁶⁴ex, τ_f —about 20 ns. If each pump-gas volume is pumped for a time equal to the iodine storage time (τ , about 5 μm), the total number of quanta produced per cubic centimeter is $10^{15} \tau/\tau_f$ or approximately 2.5×10^{17} photons/cm³. If these photons are deposited in a cubic centimeter of laser gas, the available stored energy density would be about 20 J/liter. The total volume of a pump source radiating coherently (laser or superfluorescent) could be smaller than one radiating incoherently by the ratio

of the stimulated emission lifetime τ_s to the spontaneous lifetime, τ_f .

As discussed previously, there exist basically two generic schemes for pumping photolytic laser systems: namely, incoherent and coherent. Figure 9-60 illustrates schematically these two approaches. As can be seen, the radial incoherent pumping can result in a spatial distribution of the gain medium that possesses a minimum value on axis. Alterations in the optical depth to ameliorate this problem are possible; however, such measures are usually accompanied with a lower coupling efficiency. This situation can be alleviated by using axial coherent pumping, wherein the shape of the spatial distribution of the pump beam can be tailored to match the spatial requirements imposed upon the gain media. The particular pump scheme employed, for a given system application, depends on many factors, several of which are discussed below.

"Incoherent" Pumping. Because an incoherent or spontaneous emitting rare gas-halogen pump source such as XeBr radiates into 4π steradians, the radiating gas must be coupled optically as tightly as possible to the laser gas volume consistent with gas flow requirements. A cross-sectional view of one possible configuration is shown in Fig. 9-61. The amplifier consists of two opposing e-beam-driven XeBr pump channels in which a mixture of Ar, Xe, and Br₂ flows. A portion of the XeBr emission is coupled by direct propagation or reflection through a uv-transmitting window into the central rectangular area forming the laser amplifier cavity. A mixture of C₃F₃I and Ar flows through the central channel at a subsonic rate, which replaces the gas in the lower cavity between successive laser pulses. The pulse to be amplified propagates in a direction normal to the plane of the page. To make this an attractive concept, considerable design innovation must be applied to the problem of maximizing the collection of uv pump radiation emitted away from the working laser volume and its redirection into the laser volume, consistent with e-beam-foil and fluorescer-gas-flow constraints.

Detailed sizing of a pair of electron guns that could supply the required pump energy to drive a 2-kJ iodine amplifier channel is difficult on the basis of available data. The least-well-understood aspect of such a gun involves the processes that short out the diode, particularly on a time scale as long as several to ten microseconds. We can make an estimate of nominal parameters by extrapolating from the results of Schlitt and Bradley.¹⁶⁵ A cursory analysis indicates that approximately 7000 J of XeBr fluorescence could be produced from a gun with 30- $\times$ -300-cm area in a 15-cm-wide channel containing 10 atm of Ar and appropriate partial pressures of Xe and Br₂. The required gun parameters are: voltage 1.5 MeV, current density 10 A/cm²,

Fig. 9-60. Schematic representation illustrating the comparisons between radial incoherent and spatially tailored axial pumping of the gain medium.

anode-cathode spacing 20 cm, and pulse length 2 μ s. This estimate attempts to take into account a lower efficiency in the production of XeBr fluorescence at the higher Ar buffer pressure. The estimate of gun parameters and fluorescence yield is given here only to indicate nominal parameters and considerable optimization can no doubt be attained with detailed modeling of both gas kinetics and e-beam generation and transport.

“Coherent” Pumping. The main advantage of using superfluorescent or laser radiation from the rare gas-halogen pump source is the conceptual (and practical) ease with which pump radiation can be coupled to the amplifier cavity. One optical coupling configuration for such a pump source is illustrated in Fig. 9-62. The pump source, shown in plan view, consists of a

rare gas-halogen (RGH) laser channel pumped by opposing electron-beam guns. Radiation is extracted from the pump laser on both ends of the channel and directed by a pair of reflecting mirrors R_1 and R_2 and a pair of dichroic mirrors D_1 and D_2 into the two ends of the iodine amplifier channel. A cross-sectional view of the pump laser and amplifier is shown in Fig. 9-63. The pump-laser loop consists of the laser cavity, expanded exit channel, compressor, heat exchanger, and an acoustic damping element. For optical cavity dimensions of 50 cm or smaller and pulse repetition rates of 5 to 50 Hz, the flow of the Ar, Kr, F_2 working-gas mixture will be subsonic—perhaps 0.1 Mach number. Provision is also made for gas makeup and removal of contaminants introduced into the laser gas during electron-beam pumping and gas circulation. Aside

Fig. 9-61. Cross-sectional view of an atomic-iodine power amplifier pumped "incoherently" with XeBr exciplex fluorescence excited by an electron beam. The optical (propagation) axis of the iodine laser beam is normal to the cross-sectional plane.

from production of contaminants, the Ar, Kr, F₂ gas mixture should be relatively stable because of the inertness of the rare gases and the dissociative nature of the ground state of the KrF molecule. Other fluorine fuels could be used, but deleterious chemical by-products would be produced in the excitation region,

greatly complicating the conditioning of laser gas within the loop; and, in addition, the yields of rare gas halides in reactions such as

are also greater^{17a} than for reactions wherein other fluorine fuels are substituted for F₂ (e.g., NF₃).

A similar flow loop is indicated for the iodine amplifier, with the addition that provision must be made for removal of deleterious chemical products formed upon photodissociation of the alkyl iodide fuel. Solution of this problem in a cost-effective manner promises to be one of the most formidable issues that would have to be addressed in a high-average-power iodine-laser system.

The use of axial pumping of the iodine amplifier cavity has both significant advantages and some notable disadvantages. By shaping the spatial distribution of the pump beam and taking into account effects resulting from bleaching of the alkyl iodide fuel, a wide variation in spatial distribution of iodine gain can be produced and used as a design tool to optimize the output beam quality of the iodine amplifier. The high spatial brightness of the KrF pump source allows for high transport efficiency to the iodine amplifier. One of the major drawbacks of this configuration is that the area of irradiation of the iodine amplifier is limited to the aperture area of the amplifier. This implies large uv optical fluences on the transport and window optics. Transverse pumping of the iodine amplifier cavity over a much larger area alleviates this problem but greatly complicates beam generation and handling of the KrF pump radiation

Fig. 9-62. Optical configuration for axial pumping of an iodine power amplifier using coherent radiation from a KrF-pump laser.

Fig. 9-63. Cross-sectional view of iodine power amplifier and KrF-pump-laser gas-flow systems.

Amplifier Efficiency

The electrical efficiency of the laser amplifier can be expressed as a product of the energy efficiencies of the amplifier subsystems and the laser energy extraction efficiency:

$$\eta_T = \eta_{pc} \eta_{eb} \eta_p \eta_t \eta_{ph} \eta_{ext}, \quad (11)$$

where

- η_{pc} = power conditioning efficiency to generate e-beam,
- η_{eb} = e-beam transport and deposition efficiency,
- η_p = ratio of pump-laser energy to e-beam deposited energy,
- η_t = efficiency of pump-laser energy transport and deposition,
- η_{ph} = ratio of iodine and rare-gas-halogen photon energies,
- η_{ext} = energy extraction efficiency from I^*

In general the maximum efficiency of individual subsystems will be moderated when a fully optimized amplifier system is designed. However, it is useful to estimate a nominally high overall efficiency for an iodine amplifier by assigning fairly generous efficiencies to the major subsystems:

$$\begin{aligned} \eta_{pc} &= 0.8 \\ \eta_{eb} &= 0.6 \\ \eta_p &= 0.2 \\ \eta_t &= 0.8 \\ \eta_{ph} &= 0.25/1.32 = 0.18 \\ \eta_{ext} &= 0.66 \end{aligned}$$

Inserting these values into Eq. (11), we obtain $\eta_T \leq 8 \times 10^{-3}$, a rather unattractive efficiency for even optimistic performance of a fusion target. This low projected efficiency is dominated by the two low subsystem efficiencies: $\eta_p = 0.20$, and $\eta_{ph} = 0.18$. The energy efficiency of the rare-gas-halogen pump source ($\eta_p = 0.2$) is the maximum value projected for this class of systems and is likely to somewhat lower in practice. The low ratio of iodine to photolyzing photon

energies is an intrinsic property of the photolytic iodine laser and arises because of the relatively strong bonding of the iodine atom to the C_3F_7 radical. This low intrinsic ratio is the basis of our continuing search for other, slightly bound molecules that can be photolyzed by radiation from relatively efficient rare gas-halogen laser pump sources and yield energetic, metastable atoms or radicals.

In estimating η_T values, the maximum value of 0.66 has been assumed for the laser extraction efficiency η_{ext} . In a laser system meeting a specific application requirement, η_{ext} must be interpreted as the efficiency of extracting stored energy in a laser beam that has a spatial intensity and phase distribution that allows it to be properly focused on the fusion target. Meeting focusing requirements generally implies a beam/amplifier filling factor less than unity and imposes a limitation on the beam intensity to avoid optically induced phase and intensity variations on the laser beam and its reduction of focusability. In practice, these constraints can seriously reduce the useful extraction efficiency well below the maximum theoretical value. Furthermore, one must take into account that the energy must be inputted to the laser system to replenish the dissociated C_3F_7I fuel which does not spontaneously recombine. A preliminary definition of a reprocessing cycle for C_3F_7I fuel supply suggests that the laser subsystem efficiency may be reduced below the value cited above by a factor of 2 or more.

A more meaningful projection of iodine-laser systems efficiency can only be generated on the basis of a detailed design; however, these general considerations indicate that real iodine laser systems will operate at an overall efficiency below 1%.

Nonlinear Optical Laser-Beam Distortion

As discussed above in the context of system efficiency, the quality (focusability) of the output laser energy is a critical aspect of laser system design. There are, of course, many sources of laser beam distortion that can render the beam useless. In the case of the Nd:glass laser, the nonlinear index of refraction dominates the limitation on achieving useful beam quality in the energy-density regime above a few gigawatts per square centimeter. Being a dielectric medium, a $C_3F_7I + Ar$ gas laser mixture is also subject to optically induced changes in its index of refraction, which can lead to phase and intensity distortions of the optical beam. We consider here some simple estimates of the importance of these processes in the iodine laser.

There are two primary sources of beam-induced

distortion. The first is a time-integrating change of refractive index that accompanies the transfer of excited iodine atoms ($^2P_{1/2}$) into the ground atomic state ($^2P_{3/2}$) by simulated emission. This phenomenon can be of significance only when the laser gain medium is operated in saturation, a necessary condition for any fusion laser that is to be efficient. The second mechanism is instantaneous on the time scale of the pulse of interest (nanoseconds); it arises from a distortion of the electron cloud of the constituent molecules or atoms in the gas mixture. This is the direct analog of the dominant optical nonlinearity in Nd:glass lasers.

A theoretical analysis of the time-integrating optically induced change in refractive index has been performed under contract to LLL by R. Hellwarth¹⁷⁹ and has been applied to several laser media (iodine, CO_2 , and oxygen atom lasers). The key results of Hellwarth's analysis applied to the iodine laser are presented here. It was shown that intensity-dependent refractive-index changes contributed by the laser atom (I) can be expressed in terms of resonant and nonresonant susceptibilities, X_R and X_{nr} , respectively. The imaginary part of the resonant susceptibility, X_R gives rise to the small-signal gain coefficient, g , for the inverted iodine atom system. Saturation of the gain by stimulated emission gives rise to a corresponding reduction of the real part of the resonant susceptibility, X_R which in turn changes the index of refraction of medium. Hellwarth has shown that the change in phase $\Delta\phi$ of a ray propagating through a gain medium of length L is simply given by

$$\Delta\phi_R = (X_R^1/X_R^0) g L (U/U_s), \quad (12)$$

where U_s is the usual saturation energy density

$$U_s = h\nu/\sigma(\nu) (1 + g_u/g_l), \quad (13)$$

where $\sigma(\nu)$ is the stimulated emission cross section at frequency ν and g_u , g_l are the total degeneracies of upper and lower laser levels, respectively. In Eq. (12), U is the time-integrated pulse energy density:

$$U(t) = \int_0^T \Pi(s) ds. \quad (14)$$

Hellwarth has calculated the susceptibility of the complex atomic-iodine transition, taking into account collisional broadening by argon buffer gas of the transition hyperfine structure. Susceptibility curves are shown in Fig. 9-64 for argon buffer pressures of 0.4, 1, and 3 atm. The spectral widths of 100 ps and 1-ns time-bandwidth-limited pulses centered at the peak of the gain (X_R) curve are indicated in the figure as well. The ratio X_R^1/X_R^0 is seen to vary strongly with frequency. These data show that for the higher buffer pressures

Fig. 9-64. Real (X') and imaginary (X'') susceptibility of the $^2P_{1/2}$ - $^2P_{3/2}$ transition of atomic iodine buffered by (a) 0.4, (b) 1.0, and (c) 3.0 atm of argon. Ordinate is in frequency in wave numbers minus 7600 cm^{-1} . Abscissa gives susceptibilities per atom multiplied by 3.4×10^{25} . (After Hellwarth.¹⁷⁶)

required for energy-storing iodine amplifiers and for nanosecond-long pulses, the ratio X_0/X_0 is small at the gain peak and within a gigahertz of peak gain. For example, for the amplifier considered here ($L = 300\text{ cm}$, $g = 0.016$, exit flux of 10 J/cm^2) the on-axis phase change resulting from anomalous dispersion is less than 1 rad. The phase-shift near the edges of the beam will approach zero, resulting in about one-third wave of phase variation across the aperture. The effect is relatively small here, but it should be considered in detail in any design of an iodine power-amplifier chain. The situation is noticeably worse at lower buffer pressures, particularly for 100-ps pulses, which will badly chirp. Operation slightly off the gain maximum may be necessary to minimize phase shifts across the amplifier aperture.

Hellwarth has shown that the nonresonant contribution to the phase delay upon gain saturation is expressed as

$$\Delta\phi_{nr} = (U/U_{nr}) gL, \quad (15)$$

where

$$U_{nr} = \frac{1}{2} AC/2H(\alpha_+ - \alpha_-), \quad (16)$$

and where α_+ and α_- are the polarizabilities of the upper ($^2P_{1/2}$) and lower ($^2P_{3/2}$) laser levels.

Hellwarth¹⁷⁹ has estimated the difference in level polarizabilities as $\Delta\alpha = 0.1\alpha_+$ and has taken $\alpha_+ = 4 \times 10^{-24}\text{ cm}^3$.¹⁸⁰ These values lead to a nonresonant saturation energy density of $U_{nr} = 1.3\text{ J/cm}^2$, which is smaller than the corresponding coefficient $U_s X_0/X_0$ for argon pressures greater than about 0.5 atm. Hellwarth concluded, therefore, that the nonresonant phase shift would dominate the resonant contribution in the atomic iodine laser.

However, Padrick and Palmer¹⁷² have experimentally measured the polarizability difference $\Delta\alpha = 0.023 \pm 0.007$, which increases the value of U_{nr} to about 5 J/cm^2 . This saturation energy density value exceeds that of the resonant scale parameter $U_s X_0/X_0$ for pressures below 1 atm but not below 3 atm. Thus, the resonant effect may be more important under some conditions, and both effects should be treated in detailed amplifier chain designs, particularly for pulses shorter than 1 ns. For pulses of 1 ns or greater, the nonresonant effect is expected to dominate under all practical conditions.

We now turn to the instantaneous nonlinear refractive index arising from electronic distortion of the atoms and molecules of the working laser medium. The familiar nonlinear index of refraction, n_2 , is related to the hyperpolarizability, γ , by the expression

$$n_2 = \frac{\pi}{2n} \left(\frac{n^2 + 2}{3} \right)^4 N\gamma, \quad (17)$$

where n is the linear index of refraction and N is the number density of atoms or molecules. The hyperpolarizabilities of the rare gases have been measured¹⁸¹: He (0.03), Ne (0.05), Ar (0.59), Kr (1.4), and Xe (3.9)—all in 10^{-36} esu . A comparative value for laser glass is 2.0. Since N for, say, 5 atm of Ar is about 1/100 that of glass, the effective n_2 for an Ar-buffer iodine laser is about 1/100 that of Nd:glass. Molecules similar to the alkyl iodides manifest hyperpolarizabilities comparable to that of Ar (e.g., $0.1\text{--}0.6 \times 10^{-36}\text{ esu}$ ¹⁸²), but the low partial pressure of these species in the laser mixture renders them unimportant in considering optically induced refractive index changes.

In summary, the estimates given above suggest that, in general, laser-beam-induced refractive index changes will be of little, if any, importance in the design of high-energy storage iodine amplifiers producing nanosecond-long pulses. The effects of any small whole-beam index gradients can be minimized by proper design using the analysis outlined here. The results presented here suggest that beam quality in practical iodine amplifiers will be determined by mac-

roscopic density variations in the laser medium. At the relatively short wavelength of $1.3\ \mu\text{m}$ and the moderately high gas pressures required for energy storage (about 5 atm), achievement of acceptable beam quality (even tens of times the diffraction limit) appears to be a very difficult problem. This general problem is currently being analyzed and will be the subject of a future report.

Conclusions

In summary, pumping atomic iodine photodissociation lasers using radiation from rare-gas-halogen excimeres has been described. Two basic pumping methods (incoherent and coherent) have been outlined in form and some rough estimates of the relevant parameter ranges of important variables given. The specific configurations described above are two of many possible configurations, and many alternatives exist. It appears in general that the use of "coherent" pumping is more flexible and probably the more practical pumping option. Dynamic phase distortions of the beam resulting from anomalous dispersion of complex gain transitions under saturated conditions and nonre-

sonant optical nonlinearities have been shown to be small but not necessarily negligible under all circumstances. These effects should be assessed for any specific design. It appears that macroscopic phase variations across the amplifier aperture will be dominated by density fluctuations of the laser medium.

Based on the simple analysis carried out to date, our expectation is that even using rare gas-halogen pumps, overall laser-system efficiencies will likely be several tenths of a percent. Although the projected efficiency of the atomic photodissociation laser is marginal in the context of applications requirements as presently defined, it nonetheless serves as a concrete laser system that can be quantitatively modeled with relatively modest effort. Such modeling can stimulate the definition of major subsystems involved in any photolytic or optically pumped fusion laser and provide an expanded kinetics and technological data base from which either the iodine laser or other newly discovered laser media can be more accurately assessed as fusion applications requirements become better defined.

W. F. Krupke

E. V. George

References

1. Laser Program Annual Report—1974, Lawrence Livermore Laboratory, Rept. UCRL-50021-74 (1975).
2. D. C. Lorents, *Physica*, 82 B+C, 19 (1976).
3. J. Jortner, L. Meyer, S. A. Rice, and E. G. Wilson, *J. Chem. Phys.* **42**, 4250 (1965).
4. F. E. Huber, Jr., D. A. Emmons, and R. B. Lerner, *Opt. Commun.* **11**, 155 (1974).
5. G. S. Hurst, T. E. Stewart, and J. E. Parks, *Phys. Rev.* **A2**, 768 (1974).
6. H. A. Koehler, L. J. Ferderber, D. L. Redhead, and P. J. Ebert, *Phys. Rev.* **A9**, 768 (1974).
7. H. A. Koehler, L. J. Ferderber, D. L. Redhead, and P. J. Ebert, *Phys. Rev.* **A12**, 968 (1975).
8. C. W. Werner, E. V. George, P. W. Hoff, and C. R. Rhodes, *Appl. Phys. Lett.* **25**, 235 (1974) and Lawrence Livermore Laboratory, Rept. UCRL-77412 Preprint, (1975). Submitted to *Phys. Rev.*
9. F. E. Nicodemus, *Am. J. Phys.* **31**, 368 (1963).
10. M. J. Berger and S. M. Seltzer, *Studies In Penetration Of Charged Particles In Matter*, Nuclear Science Series Rept. #10, NAS-NRC Pub. 1133, (National Academy of Sciences, Washington, 1964), p. 205.
11. H. M. Colbert, SANDYL, Sandia Laboratories, Livermore, Calif., Rept. SCL-DR-720109 (1973).
12. 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). To be published in the *Proceedings of the International Topical Conference on Electron Beam Research and Technology*, Albuquerque, New Mexico. (Nov. 3-5, 1975).
13. L. G. Schlitt, private communication.
14. See Reference 1, p. 451.
15. P. S. Julienne, M. Krauss, and W. Stevens, *Chem. Phys. Lett.* **38**, 374 (1976).
16. See Reference 1, p. 450 and this report, Sec. 9.3.1.
17. J. R. Murray and H. T. Powell, to be published.
18. G. Black, R. L. Sharpless, and T. G. Slanger, Stanford Research Institute, Menlo Park, California, Rept. MP 75-39; to be published *J. Chem. Phys.*
19. R. Atkinson and K. H. Welge, to be published *J. Chem. Phys.*
20. D. L. Cunningham and K. C. Clark, *J. Chem. Phys.* **61**, 1118 (1974).
21. C. D. Cooper, G. C. Cobb, and D. L. Tolnas, *J. Mol. Spectrosc.* **7**, 223 (1961).
22. D. L. Huestis, R. A. Gutcheck, R. M. Hill, M. V. McCusker, and D. C. Lorents, Stanford Research Institute, Menlo Park, California, Rept. MP 75-18 (1975).
23. M. F. Golde and B. A. Thrush, *Chem. Phys. Lett.* **29**, 486 (1974).
24. J. E. Early, private communication.
25. C. W. Werner, E. V. George, P. W. Hoff, and C. K. Rhodes, to be published *Phys. Rev. A*.
26. L. D. Thomas and R. K. Nesbet, *Phys. Rev. A* **11**, 170 (1975).
27. L. G. Schlitt and J. Taska, private communication.
28. Sandia Laboratories, private communication.
29. G. C. Tisone, A. K. Hays, and J. M. Hoffman, *Opt. Commun.* **15**, 188 (1975).
30. J. J. Ewing and C. A. Brau, *Appl. Phys. Lett.* **27**, 350 (1975).
31. S. K. Searles and G. A. Hart, *Appl. Phys. Lett.* **27**, 243 (1975).
32. E. R. Ault, R. S. Bradford, Jr., and M. L. Bhaumik, *Appl. Phys. Lett.* **27**, 413 (1975).
33. C. A. Brau and J. J. Ewing, *Appl. Phys. Lett.* **27**, 435 (1975).
34. J. A. Mangano and S. H. Jacob, submitted to *Appl. Phys. Lett.*
35. R. Bernham, N. W. Harris and N. Djau, *Appl. Phys. Lett.* **28**, 86 (1976).
36. D. G. Sutton, C. P. Wang, O. L. Gibb, and S. N. Suchard, submitted to *Appl. Phys. Lett.*
37. J. J. Ewing and C. A. Brau, *Phys. Rev. A* **12**, 129 (1975).
38. J. E. Velazco and D. W. Seter, *J. Chem. Phys.* **62**, 1990 (1975).
39. R. S. Bradford, Jr., E. R. Ault, and M. L. Bhaumik, *Appl. Phys. Lett.* **27**, 546 (1975).
40. J. J. Ewing and C. A. Brau, *Appl. Phys. Lett.* **27**, 557 (1975).
41. J. R. Murray, J. C. Swingle, and C. E. Turner, Jr., *Appl. Phys. Lett.* (May 1976).
42. M. V. McCusker, et al., *Appl. Phys. Lett.* **27**, 363 (1975).
43. R. S. Milliken, *J. Chem. Phys.* **55**, 288 (1971).
44. R. O. Hunter, ARPA Review Meeting, Stanford Research Institute, Menlo Park, Calif., Dec. 1975.

45. P. Venkateswarlu and R. D. Verma, *Proc. Ind. Acad. Sci.* **46**, 251 (1957).
46. P. W. Hoff, J. C. Swingle, and C. K. Rhodes, *Opt. Commun.* **8**, 128 (1973); *Phys. Lett.* **23**, 245 (1973).
47. S. Brown and J. Swingle, "Comments on the Reproducible Mixing of Condensable Vapors with High Pressure Rare Gases," Lawrence Livermore Laboratory Internal Document Engr. Note ENE 76-2, Jan. 1976.
48. R. A. Gutchev et al., Stanford Research Institute, Menlo Park, Calif., Rept. MP 75-43 (1975).
49. J. R. Woodworth, "Fluorescence Emissions from Mixtures of Mercury and Xenon," Gaseous Electronics Conf., Oct. 1975, Paper AB-5.
50. See Ref. 1, p. 448.
51. 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); also, Lawrence Livermore Laboratory, Preprint UCRL-78196 (1976).
52. G. R. Fournier, *Opt. Commun.* **13**, 385 (1975).
53. L. G. Peterson and J. E. Allen, *J. Chem. Phys.* **56**, 6068 (1972).
54. L. G. Christophorou, *Atomic and Molecular Radiation Physics* (Wiley, New York, 1971) Ch. 2.
55. D. C. Lorents, D. J. Ekstrom, and D. Heustis, *Excimer Formation and Decay Processes in Rare Gases*, Stanford Research Institute, Menlo Park, Calif., Rept. MP73-2 Sept. 28, 1973.
56. Y. Tanaka, M. Ogawa, and A. S. Jursa, *J. Chem. Phys.* **40**, 3690 (1964).
57. M. J. Pilling, A. M. Bass, and W. Braun, *J. Quant. Spectrosc. Radiat. Trans.* **11**, 1593 (1971); see also Fig. 1 in R. V. Babcock, I. Lieberman, and W. D. Partlow, *IEEE J. Quantum Electron.* **QE12**, 29 (1976).
58. O. J. Dunn, S. V. Filseth, and R. A. Young, *J. Chem. Phys.* **59**, 2892 (1973).
59. S. G. Tilford and J. D. Simmons, *J. Phys. Chem. Ref. Data* **1**, 147 (1972).
60. J. W. Rabelais et al., *Chem. Rev.* **71**, 73 (1971).
61. B. La Cour and J. P. Pocholle, *IEEE, J. Quantum Electron.* **QE-8**, 456 (1972).
62. R. R. Alfano, A. Lempicki, and S. Shapiro, *IEEE J. Quantum Electron.* **QE-7**, 416 (1971).
63. M. Green, D. Andreou, V. I. Little, and A. C. Selden, *J. Appl. Phys.*, **46**, 4854 (1975).
64. W. F. Krupke, *Prospects For Trivalent Rare Earth Vapor Lasers*, Lawrence Livermore Laboratory, Rept. UCRL-77033 (1975).
65. W. F. Krupke, *Dynamics of Trivalent Rare Earth Molecular Vapor Lasers*, Lawrence Livermore Laboratory, Rept. UCID-16993 (1976).
66. W. F. Krupke, "Prospects for Trivalent Rare Earth Vapor Lasers," 2nd Summer Colloquium on Electronic Transition Lasers, Woods Hole, Mass., Sept. 1975. Also Lawrence Livermore Laboratory, Rept. UCRL-77033 (1975).
67. W. Carnall and J. Hessler, Argonne National Laboratory, Ill., private communication.
68. B. R. Judd, *Phys. Rev.* **127**, 750 (1962).
69. G. S. Ofelt, *J. Chem. Phys.* **37**, 511 (1962).
70. W. F. Krupke, *Phys. Rev.* **145**, 325 (1966).
71. W. T. Carnall, P. R. Fields, and B. G. Wybourne, *J. Chem. Phys.* **42**, 3797 (1965).
72. William F. Krupke, *IEEE J. Quantum Electron.* **QE10**, 450 (1974).
73. D. M. Gruen, C. W. DeKock, and R. L. McBeth, *Lanthanide/Actinide Chemistry, Advances In Chemistry* **71**, (American Chemical Society, Washington, 1967), pp. 102-121.
74. D. M. Gruen, "Electronic Spectroscopy of High Temperature Open Shell Polyatomic Molecules," *Progress In Inorganic Chemistry* **14**, 119-172 (1971).
75. J. E. Sicre, J. T. Dubois, K. J. Eisentraut, and R. E. Sievers, *J. Am. Chem. Soc.* **91**, 3476 (1969).
76. H. A. Øye and D. M. Gruen, *J. Am. Chem. Soc.* **91**, 2229-2236 (1969).
77. R. R. Jacobs, M. J. Weber, and R. K. Pearson, *Chem. Phys. Lett.* **34**, 80 (1975).
78. M. L. Bhaumik and M. A. El-Sayed, *J. Chem. Phys.* **42**, 787 (1965).
79. G. A. Crosby, R. J. Watts, and S. J. Westlake, *J. Chem. Phys.* **55**, 4663 (1971).
80. L. A. Riseberg and H. W. Moos, *Phys. Rev.* **174**, 429 (1968).
81. P. Kisliuk and C. A. Moore, *Phys. Rev.* **160**, 307 (1967).
82. John Chrysochoos, *J. Chem. Phys.* **61**, 4596 (1974).
83. John C. Stephenson and C. B. Moore, *J. Chem. Phys.* **52**, 2333 (1970).
84. M. L. Lesiecki and J. S. Shirk, *J. Chem. Phys.* **56**, 4171 (1972).
85. E. Loh, *Phys. Rev.* **147**, 332 (1966).
86. J. R. Clifton, D. M. Gruen, and A. Ron, *J. Mol. Spect.* **39**, 202 (1971).

87. L. Schlitt and L. Bradley, *The Scaling of Electron-Beam Sources for Laser Fusion Applications*, Lawrence Livermore Laboratory, Rept. UCID-16864 (1975).
88. L. Schlitt and L. Bradley, *The Physics of Relativistic Electron Beams in Rectangular and Cylindrical Geometries*, Lawrence Livermore Laboratory, Rept. UCRL-77203 (1975).
89. W. Herrmannsfeldt, Stanford Linear Accelerator Center Stanford, Calif., Rept. 166, (1973).
90. I. Langmuir and K. Compton, *Rev. Mod. Phys.* **3**, 191 (1931).
91. L. P. Bradley, *Electron Beam Pumping of Visible and Ultra-Violet Gas Lasers*, Lawrence Livermore Laboratory, Rept. UCRL-77213 (1975).
92. C. B. Collins and A. J. Cunningham, *Appl. Phys. Lett.* **27**, 127 (1975).
93. G. Dzakovic *et al.*, Lawrence Livermore Laboratory, Rept. UCID-16733.
94. W. Lai, Lawrence Livermore Laboratory, internal document Eng. Note ENE 75-8 (1975).
95. B. W. Schumacher, in *Proc. 1961 Trans. 8th Vacuum Symp.* (Pergamon Press, 1972).
96. R. B. Buksh *et al.*, *Sov. J. Quant. Elect.* **2**, 272 (1972).
97. G. N. Glascoe and J. V. Lebacqz, *Pulse Generators* (McGraw-Hill Book Company 1948).
98. C. R. J. Hoffmann, *Rev. of Sci. Inst.* **46**, 1 (1975).
99. G. Boscolo, *Rev. of Sci. Inst.* **46**, 1535 (1975).
100. R. Burnham, N. W. Harris, and N. Djeu, *Appl. Phys. Lett.*, **28**, No. 2 (1976).
101. O. L. Wang, H. Mirels, D. G. Sutton, and S. N. Suchard, *Fast-Discharge-Initiated XeF Laser*, Aerospace Corporation, Rept. ATR-76(8210)-2, (1975).
102. D. G. Sutton, C. P. Wang, O. L. Gibb, and S. N. Suchard, "Fast-Discharge-Initiated KrF Laser," unpublished report.
103. R. Center, private communication.
104. J. J. Ewing, private communication.
105. W. Williams and S. Trajmar, *Phys. Rev. Lett.* **33**, 187 (1974).
106. T. N. Rescigno, C. F. Bender, C. W. McCurdy, and V. McKoy, Lawrence Livermore Laboratory, Rept. UCRL-77554; *J. Phys. B*, submitted for publication.
107. T. N. Rescigno, C. W. McCurdy, and V. McKoy, *J. Phys. B*, accepted for publication.
108. C. F. Bender, P. K. Pearson, S. V. O'Neill, and H. F. Schaefer III, *J. Chem. Phys.* **56**, 4626 (1962).
109. C. F. Bender, S. V. O'Neil, P. K. Pearson, and H. F. Schaefer III, *Science* **176**, 1412 (1972).
110. S. V. O'Neil, P. K. Pearson, H. F. Schaefer III, *J. Chem. Phys.* **58**, 1126 (1973).
111. C. F. Bender, S. W. Bauochlicher, Jr., H. F. Schaefer III, *J. Chem. Phys.* **60**, 3707 (1974).
112. D. R. Yarkony, S. V. O'Neil, H. F. Schaefer III, C. P. Bashkin, and C. F. Bender, *J. Chem. Phys.* **60**, 855 (1974).
113. S. V. O'Neil, H. F. Schaefer III, and C. F. Bender, *Proc. Nat. Acad. Sci.* **71**, 104 (1974).
114. C. F. Bender, B. J. Garrison, and H. F. Schaefer III, *J. Chem. Phys.* **62**, 1188 (1975).
115. P. K. Pearson, W. J. Hunt, C. F. Bender, and H. F. Schaefer III, *J. Chem. Phys.* **58**, 5358 (1973).
116. D. H. Liscow, C. F. Bender, and H. F. Schaefer III, *J. Chem. Phys.* **57**, 4509 (1972).
117. C. W. Bauschlicher Jr., S. V. O'Neil, P. K. Pearson, H. F. Schaefer III, and C. F. Bender, *J. Chem. Phys.* **59**, 1286 (1973).
118. C. P. Baskin, C. F. Bender, C. W. Bauschlicher Jr., and H. F. Schaefer III, *J. Amer. Chem. Soc.* **96**, 2709 (1974).
119. C. W. Bauschlicher Jr., H. F. Schaefer III, and C. F. Bender, Lawrence Livermore Laboratory, Rept. UCRL-76884 (1975).
120. K. Rajnak, Lawrence Livermore Laboratory internal memorandum, IS 74-619 (1974).
121. L. R. Kahn and W. A. Goddard III, *J. Chem. Phys.* **56**, 2685 (1972).
122. H. F. Schaefer, *The Electron Structure of Atoms and Molecules: A Survey of Rigorous Quantum Mechanical Results* (Addison-Wesley, 1972).
123. T. N. Rescigno, Lawrence Livermore Laboratory, internal memorandum, TAMP 75-054 (1975).
125. T. N. Rescigno, C. W. McCurdy, and V. McKoy, *Phys. Rev. A* **11**, 825 (1975).
126. T. N. Rescigno, C. W. McCurdy, V. McKoy and C. F. Bender, *Phys. Rev. A* **13**, 216 (1976).
127. C. W. McCurdy, T. N. Rescigno, and V. McKoy, *J. Phys. B*, accepted for publication.
128. T. N. Rescigno, C. F. Bender, C. W. McCurdy and V. McKoy, *J. Phys. B.*, submitted for publication.
129. W. H. Miller, *J. Chem. Phys.* **52**, 3563 (1970).
130. J. T. Broad and W. P. Reinhardt, *J. Chem. Phys.* **60**, 2182 (1974).
131. P. W. Langhoff and C. T. Corcoran, *J. Chem. Phys.* **60**, 2182 (1974).

132. T. N. Rescigno and V. McKoy, *Phys. Rev. A* **12**, 522 (1975).
133. T. F. O'Malley, *Phys. Rev.* **150**, 14 (1966).
134. C. F. Bender, Lawrence Livermore Laboratory internal memorandum, TAMP 75-054 (1975).
135. B. R. Kowalski and C. F. Bender, *J. Am. Chem. Soc.* **14**, 2632 (1972).
136. L. R. Carlson, C. F. Bender, and R. H. Pritchard, *Research/Development* (Feb. 1976).
137. L. R. Carlson, C. F. Bender, and R. H. Pritchard, *Pattern Recognition for Understanding and Modeling Material Problems*, Lawrence Livermore Laboratory, Rept. UCRL-76541 (1975).
138. B. R. Kowalski and C. F. Bender, *J. Am. Chem. Soc.* **96**, 916 (1974).
139. R. Cowen, Los Alamos Scientific Laboratory, N. Mex., private communication (1972).
140. R. Cowen, *J. Opt. Soc. Am.* **58**, 808 (1968).
141. J. P. Desclaux, *Comp. Phys. Comm.* **9**, 31 (1975).
142. C. Clement, *IBM J. of R&D* **9**, 2 (1965).
143. E. R. Davidson, University of Washington, Seattle, private communication (1974).
144. J. W. Moskowitz and M. C. Harrison, *J. Chem. Phys.* **43**, 3550 (1965).
145. W. J. Hunt, P. J. Hay, and W. A. Goddard III, *J. Chem. Phys.* **57**, 738 (1972).
146. R. M. Pitzer, *J. Chem. Phys.* **59**, 3308 (1973).
147. T. Dunning, Battelle Memorial Institute, Columbus, Ohio, private communication (1970).
148. B. W. Shore, *J. Chem. Phys.* **63**, 3835 (1975); *J. Chem. Phys.* **59**, 6450 (1973).
149. P. Lanhoff, Indiana University, Bloomington, private communication (1975).
150. J. Muckerman, Quantum Chemistry Program Exchange, University of Indiana, private communication, 1974.
151. T. Valencich, University of California, Los Angeles, private communication (1975).
152. B. Johnson, Aerospace Corp., private communication (1975).
153. L. A. Cox, Jr. and C. F. Bender, Lawrence Livermore Laboratory, Rept. UCRL-16915 (1975).
154. E. Henry and V. Hanpel, Lawrence Livermore Laboratory, private communication (1975).
155. J. V. V. Kasper and G. C. Pimentel, *Appl. Phys. Lett.* **5**, 231 (1964).
156. K. Hohla and K. L. Kompa, *Appl. Phys. Lett.* **22**, 77 (1973).
157. K. Hohla, G. Brederlow, W. Fuss, K. L. Kompa, J. Raeder, R. Volk, S. Witkowski, and K. J. Witte, *J. Appl. Phys.* **46**, 808 (1975).
158. V. A. Gaidash, G. A. Kirilov, S. B. Kormer, S. G. Lapin, V. I. Shemyakin, and V. K. Shurygin, *JETP Letters* **20**, 107 (1974).
159. N. G. Basov, L. E. Golubev, V. S. Zuev, V. A. Katulin, V. N. Netemin, V. Yu. Nosach, O. Yu. Nosach, and A. L. Petrov, *Sov. J. Quantum Electron.* **3**, 524 (1974).
160. *Laser Focus*, September 1975, p. 26.
161. *AEC Laser and Electron Beam Programs: Five Year Plan FY 1976-FY 1980*, U. S. Atomic Energy Commission, Washington, Dept. WASH-1363 (1974).
162. J. C. Swingle, C. E. Turner, Jr., J. R. Murray, E. V. George and W. F. Krupke, *Appl. Phys. Lett.*, to be published; see also Sec. 9.3.2 of this report.
163. W. F. Krupke, *Proc. 2nd Summer Colloq. Electron. Transition Lasers* (M.I.T. Press, Cambridge, Mass., (1975).
164. M. A. Gusinow, *IEEE J. Quantum Electron.* **E11**, 929 (1975).
165. M. A. Gusinow, *Appl. Optics* **14**, 2645 (1975).
166. W. T. Silfvast, L. H. Szeto, and O. R. Wood II, *Appl. Phys. Lett.* **25**, 593 (1974).
167. A. V. Antonov et al., *Sov. J. Quantum Electron.* **5**, 123 (1975).
168. L. D. Pleasance and L. A. Weaver, *Appl. Phys. Letters*, **27**, 407 (1975).
169. C. A. Brau and J. J. Ewing, *J. Chem. Phys.* **63**, 4640 (1975).
170. F. T. Aldridge, *IEEE J. Quantum Electron.* **QE-11**, 215 (1975).
171. W. Fuss and K. Hohla, Max-Planck Institut für Plasmaphysik, W. Ger., IPR Rept. IV/67 (1974).
172. T. D. Padrick and R. E. Palmer, *J. Chem. Phys.* **62**, 3350 (1975).
173. R. E. Beverly III, *Opt. Commun.* **15**, 204 (1975).
174. J. B. Trenholme, NRL Memorandum Rept. 2480 (1972).
175. J. A. Glaze, S. Juch, and J. B. Trenholme, *Appl. Optics* **13**, 2808 (1974).
176. G. Brederlow, K. Hohla, and K. J. Witte, Max-Planck Institut für Plasmaphysik, IPR Rept. IV/74 (1974).
177. J. A. Mangano and J. H. Jacobs, *Appl. Phys. Lett.* **27**, 495 (1975).
178. W. Setser, University of Kansas, Lawrence, private communication.

179. R. Hellwarth, *Characterization of Self Focusing Mechanisms in Laser Materials*, University of Southern California, Los Angeles, Subcontract 7509105, Lawrence Livermore Laboratory (1975).
180. V. S. Zuev, V. A. Katulin, V. Yu. Nosach, and O. Yu. Nosach, *Sov. Phys.-JETP* **35**, 870 (1972).
181. A. D. Buckingham and D. A. Dunmur, *Trans. Faraday Soc.* **64**, 1776 (1968).
182. J. F. Ward and Irving J. Bigio, *Phys. Rev. A* **11**, 60 (1975).