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Laser Program **Annual Report-1978**

Volume 1

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**Lawrence
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Laboratory**

Laser Program **Annual Report – 1978** **Volume 1**

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FOREWORD

This report reviews the unclassified activities of the Laser Program at the Lawrence Livermore Laboratory of the University of California for the calendar year 1978. The laser program, which includes both Inertial Confinement Fusion and Advanced Isotope Separation, is sponsored by the U. S. Department of Energy, and is headed by John L. Emmett, Associate Director for Lasers. The report is presented in three volumes for the convenience of the reader; an accompanying classified volume is being published separately.

Our intent in publishing this comprehensive report goes beyond a simple chronicle of accomplishments. We explain our theories, experimental results and techniques, and system studies in sufficient depth to allow the reader to either reproduce the results or call the person directly responsible and discuss the work in detail. The year 1978 was rich in accomplishment and in furthering our scientific understanding, which we share in this report along with our assessment of the future risks and uncertainties.

The three-volume report is organized in sections that correspond closely to the line responsibilities within the program. In Volume 1, we first give an overview of the entire program (Section 1), in which we preview the report, highlight our progress in 1978, and summarize the facilities and resources of the laser program. Next, we describe the Argus, Shiva, and Nova laser facilities (Section 2). Finally in Volume 1, we discuss the theory of fusion target design (Section 3), as well as the specialized techniques of target fabrication (Section 4).

In Volume 2, we detail the year's experiments, data, and analysis (Section 5). Also, we report on the technology development programs required for the high performance we need in target diagnostic instrumentation (Section 6) and in solid state laser components (Section 7).

In the final volume, we document our progress in advanced quantum electronics—primarily the quest for advanced rep-rateable short-wavelength lasers with high efficiency. Also, in Volume 3, we describe our application studies in electrical energy production and fissile fuel production (Section 9), and we present selected highlights of our advanced isotope separation program (Section 10).

A report of this magnitude, with so many individual articles, requires an extraordinary effort by both the scientific and clerical staff. Authors' names appear at the end of the articles, along with the names of major contributors where applicable. Also, we have tried to include the names of personnel from our contractors where ever possible. Manuscript production was a great additional responsibility for the program secretaries and the administrative assistants, who put in long hours to get the job done. In this regard, my own secretary, Audrey Heine, deserves special mention.

For preparing the report for publication, I am indebted to the following members of the Technical Information Department: Karen Minkel and Elsa Pressentin, who both strived hard to keep the report on schedule; Wilma Leon, who guided and coordinated the illustrative and layout tasks; Ron Meogrossi, who designed the covers and dividers; and Wally Clements, Maureen Donahue, Bill Fisher, Larry Gottlieb, and Chuck McCaleb who, with Rob Johnson and Doug Vaughn of EG&G, were responsible for the excellent editing of the manuscripts. Also, I appreciate the responsive efforts of the numerous Compositors and Proofreaders of TID's Composition Group. I extend my appreciation to Olga Parker, who spent endless hours in running down many of the illustrations reproduced in the report. I thank William Harford and Philip Coyle for helping out at particularly critical junctures. From the department of classification, Rick Pond and Tom Reitter also merit recognition for their determined efforts under trying circumstances. Brian Jarman was the managing editor of this report. He is a true expert, is very easy to work with, and deserves much of the credit for the production of this report. I also thank my assistant Suzi Anderson for her very professional assistance in the management control of this large project.

Michael Monsler
Scientific Editor

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Section 1

**Laser
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Overview**

SECTION 1

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SECTION 1

LASER PROGRAM OVERVIEW

1.1 Introduction

In 1978, Lawrence Livermore Laboratory's Laser Fusion Program focused on bringing Shiva into routine operation as a target irradiation facility and on demonstrating the compression of DT fuel in inertial fusion targets to intermediate densities of several g/cm³. In 1977, after achieving the 10-kJ milestone and thereby demonstrating that the Shiva laser system had met its design goals, we began some simple target experiments. By the end of 1978, Shiva carried an extensive array of target diagnostics, and fully integrated, complex experiments had become a daily reality. In the course of these and other experiments on Shiva, we first demonstrated a maximum power level of 26 TW on target in May and achieved a target neutron yield of 2.7×10^{10} in September, establishing new records for the inertial fusion field.

After a thorough and careful year-long series of physics experiments, we reached fuel compressions of over ten-times liquid density in several implosion experiments late in the year. This experimental effort included the development of new diagnostic techniques to supplement existing x-ray measurements, neutron energy measurements, and imaging measurements. Building on these successful developments, we were then able to plan higher-density compression experiments and low-density, high-temperature experiments, which are scheduled for 1979.

Perhaps more important than the first medium-density results themselves were the series of experiments on Argus that made possible the fully integrated, high-density experiments on Shiva and that have important implications for the future. These Argus experiments achieved the proper physical conditions required not only for high-density implosions on Shiva, but also for scientific breakeven experiments on Nova and for high-gain, fusion microexplosions with any appropriate driver for future reactors.

Many advances in target fabrication technology were required to make some of these

results possible. In particular, the new capabilities to produce very high-quality targets over a wide range of sizes, and to produce various materials in a precisely controlled fashion, were essential in attaining medium-density compressions. Similar advances in target fabrication will be required for high-performance targets to meet future milestones.

The design of the Nova system is now complete, including a prototype laser chain and pulse-power system. Cost estimates for this design confirm original CP&D study estimates and, indeed, improve upon them. We are confident of the projected 300-kJ performance at long pulses and have verified that Nova will be adequately sized to complete the physics milestones in the Inertial Confinement Fusion (ICF) Program.

The first two major subsystems of the RAPIER KrF/CH₄ laser system—a technology test-bed for an advanced, short wavelength driver—have been assembled and partially tested. We have demonstrated 1 J of KrF pump energy in the "front end" of the system and are building the test-bed to measure 25-J performance through the first power amplifier. This small but important effort is critical to a new interest, within the ICF community, to develop reactor class drivers on a time scale that can mesh with the achievement of key physics milestones on Shiva and Nova.

The first phase of a point design for a fusion reactor prototype has been completed in partnership with Rockwell International, Energy Technology Engineering Center, Bechtel Corporation, Colorado School of Mines, and the University of California, Davis. This design protracts the engineering credibility of laser fusion power in many important areas, including improved economics, dramatically reduced radioactive wastes, and reactor structure lifetime. The study proved to be an important example of the extent to which industry, universities, and the national laboratories can work together to advance the ICF program, given its classification limitations and still undeveloped nature.

In general, 1978 progress in core program research was good but noticeably slower than

originally planned. We lost time that may prove critical to a national review of fusion options in the mid-1980's. Added resources could have helped prevent this loss. In the near term, the coupling between resource levels and progress will be even tighter than it was in 1978.

In the short reviews that follow, we summarize the major advances in target design and experiments and in associated laser technology that characterize 1978. Also, we discuss briefly the new developments in advanced drivers and applications issues that are now beginning to dominate the national program.

1.1.1 Solid State

The laser systems for current fusion experiments at LLL are developed and built under the Solid State Laser Program. At present, the program is responsible for (1) design of the new Nova laser system; (2) required technology developments to make the operating systems (Argus and Shiva) as effective as possible in terms of power, energy, reliability, and experimental flexibility; and (3) the preparation for system upgrades, such as additional Argus target stations, additional spatial filters, and booster amplifiers for Shiva, and Super Argus, to meet the possible future needs of the laser fusion program.

These solid state systems are the foundation of the National Laser Fusion Program. Argus now performs at 5 TW, Shiva operates routinely at 20 TW, and Nova will operate at 300 TW and 300 kJ. In fact, if we achieve proposed advances in design and technology, Nova will exceed 400 TW and 400 kJ. Nova is upgradable to 2700 kJ, or in its present configuration can be frequency-converted to yield about 100 kJ of UV (2600 Å) radiation.

During 1978, we accomplished essentially all of our stated milestones. Our major objectives were to design the Nova laser and building (Fig. 1-1), and to bring Shiva up to full operating potential with the addition of the 20-cm booster amplifiers. We successfully attained these objectives. In addition, we received Nova laser glass for the largest-diameter amplifiers, although additional work is required to bring the glass to its final specification.

During the experimental target series in 1978 on both Argus and Shiva, we learned a great deal about the performance of Nd:glass lasers at longer pulse durations and about the pulse requirements of our advanced targets. We now have a better understanding of: prepulse and pulse rise-time control, pulse shaping, front end reliability, long-pulse coating damage problems (especially antireflection coatings), relaying and beam modulation levels, the

Fig. 1-1. Nova laser fusion facility (existing Shiva laboratory, left; modified Nova laboratory addition, right).

need for a more rapid experiment turnaround rate, and additional automatic control to minimize manpower requirements.

In addition, we steadily improved our laser technology, which we can apply to present operational problems as well as to Nova and future systems. Improvements include new optical coatings, new pulse-power systems based on the compensated alternator, new and efficient pump-laser cavity configurations, a new laser front-end configuration for versatile pulse generation and efficient amplification, a basis for efficient frequency conversion of our 1.06- μm systems to the 2nd or 4th harmonic, and more efficient diagnostic systems.

In 1978, we completed the design of the Nova laser system and developed new technologies to enhance the performance of Nova, present operating systems, and future reactor drivers.

1.1.2 Fusion Experiments

During 1978, we devoted the majority of the resources in the Fusion Experiments Program to the activation of Shiva and to the implementation of full, Shiva target diagnostics. The Shiva activation phase lasted until the end of August. However, during this period we were able to perform a few simple target experiments to demonstrate system performance. On May 18th, we shot a Hyperion target with 26 TW in 95 ps, using all 20 beams of the Shiva laser. The target produced a new record number of DT neutrons: 7.5×10^9 . Virtually all Shiva's subsystems performed flawlessly. During the rest of May, we shot a number of ball-in-plate targets to calibrate a recently added x-ray microscope and an alpha spectrometer, and to further check laser performance.

In June, July, and August we completed the final laser activation work and continued to calibrate diagnostics. We solved electrical noise problems in the oscillator, completely cleaned the optics in the front end and beam-splitter array, and installed the flashlamp preionization lamp-check system (PILC). In addition, we completed a host of small projects to prepare for a full target-experimentation schedule in September.

In September, we began the Hyperion target series. We performed 11 full system shots that month. Six were Hyperion target shots at power levels ranging from 14 to 20 TW (90-ps pulse duration). From this series we obtained a new record neutron yield of 2.7×10^{10} . Also, the shot results

enabled us to compare data with theoretical expressions relating neutron yield to absorbed laser energy, over a yield range of two orders of magnitude. We continued the Hyperion series through the second week of October with seven shots, producing data interrelating ion temperature, absorbed energy, and neutron yield.

Starting in mid-October, we converted the Shiva laser system to a 1-ns operation in preparation for high-density target experiments. We generated numerous system shots to set up and adjust the laser preamplifier sections for the longer pulse operation, to balance the energy output of the amplifier chains, and to verify their chain performance with the predictions from our laser-performance code calculations at 1-ns pulse duration. These shots showed that we could accurately simulate Shiva's performance over a wide range of input energy values.

Through November, we irradiated a variety of targets with pulses at energies from 3 to 8 kJ and with nominal durations of 1 ns. These irradiations were precursor shots for the high-density targets. On November 22nd, we obtained the first detectable neutron yield from a high-density target. This result paved the way for continuing investigations with the use of improved diagnostics.

During the first week of December, we completed our initial survey of 1-ns, complex target experiments. A second iteration of a high-density target design produced $4.6 (\pm 1.8) \times 10^6$ neutrons, a new record. This yield is indicative of high compression and it increased our optimism regarding reliable diagnostics. Following this iteration, we reconfigured the laser to obtain an absorption measurement, using a larger target at 2 ns to support the Nova design. (This target and pulse duration closely represent the Nova operating region.) We achieved the 2-ns pulse length by offsetting in time 10 outer beams (5 in each cluster) with respect to the 10 inner beams. The larger target gave typical absorptions for targets of this type, with no indication that Brillouin backscatter was adversely affecting the result. We conducted a total of eight target experiments during the first two weeks of December. The remainder of December and half of January were spent in installing required instruments for diagnosing high-density targets and in making improvements in the laser alignment systems to increase experiment turnaround rate. The installed diagnostic instruments were Dante, a

time-resolved, sub-keV, x-ray spectrometer to measure x-ray outputs; and FFLEX, a 3-to-300-keV x-ray spectrometer that measures the suprathermal x-ray spectrum and laser pulse-thermonuclear reaction interval time. All these instruments are now in operation and we have made all the above measurements on high-density targets.

The primary role of the Argus laser until November was an attempt to produce high-density (10-100X) implosions that would allow us to develop our density diagnostics. Although this development goal was not achieved, the implosion experiments themselves, as well as other physics experiments on Argus, were vital in contributing to our present understanding of laser plasma physics. We demonstrated high absorption of the laser energy for pulse lengths of 200 ps to 2 ns. We also learned much more about electron preheating from suprathermal electrons.

In the first and fourth quarters of 1978, we were able to maintain only one shift on Argus; in the second and third quarters, we re-established two shifts that enabled us to complete the target campaign precursor for the high-density experiments on Shiva.

The use of the Janus system to support laser program experiments was terminated in 1978; Janus is now utilized exclusively by the Nuclear Weapons Program for equation-of-state experiments.

In addition to the diagnostic implementation discussed above and as part of our ongoing research and development program for advanced diagnostics, we have developed CCD arrays for use in streak cameras, oscilloscope tubes, and optical imaging cameras. We plan to field these arrays in the experiments program in the coming year.

1.1.3 Target Design

In 1978, we continued to direct our target design activities toward the sequence of major milestones that mark our progress. These activities include many precursor experiments to help us understand detailed effects and laser-target phenomena that are crucial to the success of the more complex, fully diagnosed experiments.

We made important advances in the plasma and atomic physics of the laser-plasma interaction. Computer calculations of laser-irradiated high-Z disks agreed well with diagnostic measurements of absorption, total x-ray output, and x-ray spectra. Experiments with more sophisticated diagnostic in-

struments are being devised to validate the plasma physics approximations that we used in the calculations. The milestone designs undertaken in 1978 are as follows:

10-100X. The objective is to compress DT to 10-to-100 times liquid density and, at the same time, achieve high enough temperatures so that the resultant density can be diagnosed with high confidence, using several techniques.

Currently, we are designing and fabricating a family of targets that are more resistant to preheat. Experiments in late 1978 produced a few results at compressions above 10 times liquid density. We expect to fully achieve the 100X milestone early in FY 1979.

Low-Density, Significant TN Burn (STNB). The objective is to achieve DT gains in the range of 0.1 to 1, approaching thermonuclear (TN) conditions of density, confinement time, and temperature where the fusion energy is comparable to the DT thermal energy. Because the compressed fuel density is near liquid density, and the ρr is relatively small, this milestone is one step from the threshold of ignition: deposition of the charged-particle fusion energy in the DT.

100-1000X. The objective is to implode DT to 100-to-1000 times liquid density and, at the same time, reach a high enough temperature so that we can diagnose the resultant density with high confidence. This density (1000X) is of particular significance, because it characterizes the density of targets designed to achieve high-density STNB on Shiva, scientific breakeven and scientific feasibility on Nova, and very high gains with suitable reactor drivers. Several driving systems are being considered. During the year, a 100X prototype of the 1000X target was being built for Shiva experiments in FY 1979.

High-Density STNB. The objective is to implode the DT to the temperature and ρr that exist at the threshold of ignition: when reinvestment of the kinetic energy of charged particles from the fusion reaction significantly increases the DT reaction rate and TN yield. Preliminary analysis indicates that, with Shiva, one of the target designs can be imploded to 1000X density and to a temperature of 1.5-2 keV. Bootstrapping could then increase the burn rate by as much as a factor of two.

Scientific Breakeven/Scientific Feasibility. The objective of achieving scientific breakeven is to generate fusion energy equal to the incident laser

energy, while that of scientific feasibility is to achieve gains of 10 to 100. In order to achieve scientific breakeven, the DT fuel must ignite, bootstrap itself to temperatures greater than 10 keV, and reach burn efficiencies of several percent. Code calculations predict that Nova-scale Nd:glass lasers are required to achieve the scientific breakeven milestone with high confidence levels. Depending on advances in target design and on favorable resolution of uncertainties in laser-plasma physics, it should be possible to achieve gains greater than 10 with the Nova laser. We have made two-dimensional (2-D) calculations of a Nova-driven target design that attains scientific breakeven. This design reflects our understanding of stimulated scattering losses and of filamentation-generated superthermal electrons.

Advanced Target Development. We are exploring advanced target designs and plan to test theoretically unstable targets to validate our present theoretical understanding of instability. We are also designing reactor targets for KrF lasers and heavy ions.

Heavy Ions. During 1978, we worked with heavy-ion-accelerator physicists from Berkeley, Argonne, and Brookhaven to design reactor targets that are specially suited to proposed accelerator designs. This work is being closely coordinated with the heavy-ion beam focusing in LLL's M Division, and with heavy-ion reactor designs in the laser program.

1.1.4 Target Fabrication

In 1978, we were able to produce exceptionally high-quality, glass shells with surface smoothnesses of 100-300 Å and concentricity defects less than 1% of the wall thickness; we greatly increased the sizes and wall thicknesses of these glass shells: available inside diameters have grown from about 300 μm to just less than 1 mm and thicknesses from about 6 or 8 μm to more than 20 μm.

Our major method of producing glass shells is by liquid droplet, glass solution dehydration, and subsequent fusing. Glass shell thickness and size are determined by the solution concentration, droplet size, and furnace conditions. By producing the shells in a controlled atmosphere, any desired gas (within limits, of course) can be introduced into them during the formation stage in which the glass shell is porous and not fully fused. We have suc-

cessfully introduced argon, xenon, and krypton gases into the shells.

Some current and future targets require glass shells coated with layers of Teflon-like material. We have satisfied this requirement by using plasma polymerization techniques to deposit CF₂ polymer layers with very high uniformity, with good surface finish, and in thicknesses greater than 30 μm.

By using similar techniques, we have been able to deposit hydrocarbon polymer layers of up to 100 μm in thickness on glass shells. The control of surface finish on very thick layers is more difficult than it is on thinner layers. Fortunately, for very thick layers, the surface finish requirements are relaxed, allowing a peak-to-valley variance of about 1 μm.

The characterization of the glass shells and of the coated shells has been a significant effort since each shell had to be "4π" characterized. Shell manipulation is now semiautomatic; a fully automated system is in the check-out phase. Our present method still requires a trained operator to inspect each shell visually in the interference microscope, in order to find and measure any defects and to "certify" the quality of the shells and coatings. The fully automated system will completely characterize a shell in about 45 seconds and plot a contour map of its quality (thickness, density, or composition variations in terms of thickness-equivalent defects).

The 4π examination of a shell's surface in the scanning electron microscope (SEM) can be a very time consuming task. To aid in this important method of characterization, we have developed and installed a computer controlled, 4π shell manipulator in the chamber of the SEM. The manipulation is synchronized with a magnetic storage unit capable of recording SEM information about the shell's entire surface. Magnetic video tapes of 4π-scanned shells can be examined to determine the shell's surface quality. Each frame of the video tape "movie" can be stopped and studied, i.e., the target designers can examine the entire surface in detail for preshot analysis.

We have achieved some significant results in the deposition of beryllium on flat surfaces and on spheres. The first beryllium layers we made were typical of many deposited material layers. They looked like the surface of a cauliflower, the result of "cone" growths on the layers. Larger parts may be buffed or mechanically worked to produce smooth surfaces, but because of our problems with part size,

we chose to try to improve the deposition process. By controlling temperatures, pressures, deposition rates, etc., we were able to produce very high quality layers on copper and glass. It has been possible to produce pure amorphous beryllium layers—an achievement not yet reported by anyone else in the published literature.

A number of techniques are also being studied for the deposition of high-Z, high-density layers on target spheres. Electrodeposition, chemical vapor deposition, and physical vapor deposition offer the promise of producing quality layers. We have accomplished the deposition of tungsten from WF_6 , although the quality as yet is unacceptable. However, the use of some of the techniques we have developed to improve surfaces on other materials should permit us to deposit high-Z layers within specifications.

Future ICF reactors will require the production of targets at high rates and low cost. The small effort we have expended on target factory techniques has resulted in a successful method of transporting targets by electric fields. A charged particle can be contained and transported in a quadrupole structure. And such a structure can be "bent" into a circular track, to move targets through several coating steps in which they may be coated by atomic, ionic, or molecular beams. We have built an operating structure of this type in which particles have been suspended and transported. Particles have also been suspended, coated, and recovered in other types of quadrupole devices and in other types of levitators.

1.1.5 Advanced Quantum Electronics

The main function role of the Advanced Quantum Electronics (AQE) Program is to identify, demonstrate, and assess laser-driven systems for use in laser fusion power reactors. To this end, we conduct experimental, theoretical, and computational studies that span the entire range of microscopic atomic and molecular issues, quantum electronic issues, and technological and systems issues. A further function of AQE is to validate the effectiveness of selected, advanced laser systems for pellet implosions.

The technical and programmatic logic of the AQE effort expended in 1978, continuing in 1979,

and projected for the next few years, is based on extensive laser system studies conducted in 1977, which compared the applications potential of four candidate driver systems. From these studies, we concluded that:

- All four systems appear scalable to reactor size with efficiencies exceeding the required 1% minimum.

- The associated technologies for scaling are distinct for the four systems and largely undeveloped at present, but they appear to be tractable.

- Reactor laser-driver systems that incorporate the Raman pulse-compressor concept (KrF/CH_4) offer the highest efficiency (6%) potential, shortest operating wavelength (0.27 μm), and greatest richness in technological options for their implementation.

- The other system candidates (Group VI atoms, rare earth ions) are efficiency-inferior because of relatively inefficient pumping techniques.

On the basis of this comparative assessment, about 65% of our 1978 activities strongly emphasized the research and development of the Raman pulse-compressor concept. The remainder focused on an aggressive search for, and a preliminary assessment of, new laser media and/or pumping techniques that could result in driver systems of operating efficiencies in excess of 10%.

The key evaluative tool in our assessment of the Raman pulse-compressor concept is an experimental, 100-J/1-ns/0.1-TW laser system test-bed called RAPIER (Raman Amplifier Pumped by Intensified Excimer Radiation), which we are designing, building, and operating over a three-year period. The experimental data, system normalization, and operational experience obtained from RAPIER will provide the technical basis for constructing an operational, TW/ns Raman pulse-compressor, laser system for pellet implosion experiments in 1982 and for designing larger, repetitively-pulsed laser systems.

During 1978, our RAPIER work concentrated largely on the design and construction of the system's hardware, controls, and diagnostics for operation up to the 10-J level. Our 1978 progress has provided us with the operational capability to address the following major technical milestones in 1979/1980:

Energy level	Objective
1J	Secure refined values for critical scaling parameters (gain coefficient, saturation fluence, pressure dependence, etc.).
1J	Establish the operating boundaries of efficient Raman compression at moderate-to-high compression factors ($K \approx 10$)—higher order nonlinearities and parametric processes.
25J	Determine the maximum efficiencies of excimer pumps (KrF, XeCl, etc.) under high excitation conditions and test pump amplifier simulation models. Design the KrF power amplifier to extend RAPIER to the 100-J energy level.
100J	Demonstrate the technical efficiency of the pulse-stacking, Raman-compression hybrid concept for large-scale systems.

In our advanced research, we completed benchmark kinetics and laser measurements on Group VI photolytic media (S, Se), Nd and Tb rare earth molecular vapors, and Tm^{3+} : glass hybrid media. The results confirmed the viability of these energy-storage media for fusion lasers, but not for fusion drivers because of the inefficiency of their pump sources. Also, in 1978, we studied new, incoherently radiating excimer gases of potentially high efficiency (particularly molecular ions), exploring their kinetics and conducting theoretical modeling; we plan to continue these studies in 1979.

1.1.6 Systems and Applications Studies

Our goal in this area is to anticipate the opportunities and problems involved in the engineering development of inertial fusion for both energy and military applications. In this respect, our studies form a bridge between the current physics research program and the potential users of fusion—the energy industry, the utilities, and the military community. Our objectives are to identify the most promising applications of inertial fusion, to formulate programs for their required technology development, and to provide management information that will enable program resources to be directed toward yielding maximum benefits in the shortest time.

Energy Applications. Conceptual design studies of power plants and test facilities are among our most useful tools for uncovering technical issues far in advance of them becoming critical problems. They include assessment studies of emerging new technologies and require us to work with the established energy industry on engineering and commercialization aspects. In this way, we can effect substantial savings in development resources by creating design innovations that can significantly shorten required development time. Finally, we work closely with industry to plan the required technology development programs and strategies for addressing the technical issues in a realistic time frame and with realistic costs.

In conjunction with a team of university and industrial contractors, we developed a conceptual design of a 1050-MW_e electric power plant that we call the High Yield Lithium Injection Fusion Energy (HYLIFE) converter. Our design requires neither a first-wall replacement for the entire life of the power plant, nor the use of exotic materials or techniques requiring a lengthy period of technology development. The major characteristics of the HYLIFE power plant are:

Laser energy	3 MJ
Pellet gain	900
Yield per pulse	2700 MJ
Pulse rate	1 Hz
Fusion power	2700 MW _f

Gross thermal power	3215 MW _t
Net electrical power	1050 MW _e
Recirculated power fraction	15%
Net electrical efficiency	33%
Saturated steam cycle	—

When this design study was initiated a year ago, we intentionally chose a very high gain to determine the design constraints and considerations for high-yield, pulsed energy conversion systems. This combination of pellet gain and driver energy is currently considered to be at the optimistic end of theoretical pellet performance.

In this design concept, a very dense array of lithium jets are injected into the conversion chamber between each laser pulse, providing an effective 1-m-thick blanket between the fusion pellet and the inner steel wall. The blanket reduces the 14-MeV

neutron flux by over a factor of 100, allowing the 5-m-radius inner wall to operate 21 full power years (30 years at 70% availability) at an integrated neutron flux of 0.32 MW/m^2 . Since the wall fluence in the absence of lithium protection would be 5.6 MW/m^2 , the power density within the reactor vessel is very high, approaching that of a fission reactor vessel. A common, low-alloy ferritic steel (2-1/4% chrome, 1% molybdenum) is used throughout the structure. The tritium breeding ratio is controllable between 1.0 and 1.7. Finally, the enormous area of fluid at relatively cold temperatures (500°C) acts as an effective condensation pump, avoiding the need for vacuum pumping the hot plasma mechanically.

The HYLIFE power plant requires 16 liquid metal pumps to inject the lithium at 4.4 m/s into the 5-m-radius chamber. These lithium recirculation pumps require 20 MW_e of prime power, which is only 1.6% of the gross electric power. The combination of features—low recirculating power, high power density, use of common steels, low temperature operation, no first-wall replacement, and standard liquid metal pumping techniques—should lead to an economically attractive power plant. Environmentally, since the lithium protection will reduce the induced activation by over a factor of 20 (curies or kg), and since the first wall will not need replacing 10 to 15 times during the plant's useful life, the savings in radioactive waste will be significant compared to other fusion reactor concepts. Finally, the use of isotopically tailored molybdenum offers an unprecedented possibility in fusion reactor design: being able to reuse the steel structure after 20 years (the required time before it will be environmentally and radioactively safe), instead of after 800 years (the required time for common Mo steel).

In addition to the HYLIFE design, we completed neutronic studies of several innovative ^{232}Th and ^{238}U - ^{232}Th blanket designs for fusion-fission hybrids. The fast fission preblankets are best for all after-blanket options because the 3-6 multiplications in energy and the 1.7 to 1.9 multiplications in neutron number always improve performance. We found that one depleted uranium hybrid can fuel ~ 6 LWR's, and one thorium hybrid as many as 12 LWRs of equivalent thermal power, with the possibility for bettering these values by a factor of two when using advanced converters. The cost of the Th-fueled breeder is 2.5 to 3.0 times the reference LWR on a $\$/\text{kW}_e$ basis and the U-Th-

fueled breeder is 2.0 to 2.5 times an LWR. These values lead to electricity costs only 10 to 25% higher than those from the reference LWR with $\$43/\text{lb}$ uranium.

Military Applications. In 1978, we continued to study the capabilities of laser fusion in providing physics information for nuclear weapons technology, in improving diagnostics for underground testing, and in determining the hardness of reentry vehicles, missiles, satellites, and their components against nuclear radiation. We placed the main emphasis on evaluating the potential of the Nova laser system, which included our participation in the design of the Nova target chamber and building to assure a military testing capability.

Also, during 1978, we began to study applications that require higher energies, such as simulations of the atmospheric effects of nuclear weapons and the laser-impulse kill of reentry vehicles. Finally, we identified potential contributions of the military applications of laser fusion to the nation in the event of a complete test ban treaty, including the impact of an expanded military applications effort on LLL programs.

1.1.7 Advanced Isotope Separation

The primary goal of our Advanced Isotope Separation (AIS) Program is to develop an Atomic Vapor Laser isotope Separation (AVLIS) process that can enrich natural or depleted uranium for LWR fuel-grade usage and achieve efficient tails stripping with unit costs (FY 1980) in the $\$10$ to $\$40/\text{SWU}$ range. The resultant major reduction in the capital cost of enrichment plants will influence the entire nuclear fuel cycle. It will affect financing, ore production and utilization, reactor deployment, private and government participation, international politics and the U.S. share of the nuclear fuel market, the U.S. balance of payments, and the replacement of power-intensive gaseous diffusion plants. In comparison with one of the latter plants, an AVLIS plant will realize approximately a 5-to-10-times reduction in capital cost; also, its operating (including power) cost will be considerably less (3 to 10 times) than that of a conventional diffusion or centrifuge plant. Depending on U.S. and international nuclear policy, the overall benefits could easily exceed $\$100$ billion over the 30 years following implementation. Thus, the AVLIS process effort may offer one of the few options in the entire energy

Table 1-1. Resources of laser fusion and AIS programs for FY 1978 in comparison with those of prior years.

	Fiscal year									
	1970	1971	1972	1973	1974	1975	1976	1976 ^a	1977	1978
Operating costs (\$ million)										
Laser fusion	1.9	6.5	9.5	13.5	18.4	19.9	22.2	7.0	30.8	40.4
Advanced isotope separation	—	—	—	—	0.74	4.8	7.2	2.1	8.1	10.9
Manpower										
Laser fusion	43	124	156	232	223	230	244	259	281	355
Advanced isotope separation	—	—	—	—	23	70	90	92	94	116
Equipment (\$ million)										
Laser fusion	0.1	0.4	0.9	1.1	1.17	2.0	2.4	0.5	2.8	3.6
Advanced isotope separation	—	—	—	—	0.13	0.7	1.5	0.3	2.4	1.9

^aTransition quarter.

field for actually reducing an existing fuel cost. Considering our program success in 1978, we are now convinced that AVLIS can meet the very low separative work cost and the very low capital cost consistently projected for AVLIS economics.

1.2 Program Resources

The resources of the laser fusion program and the AIS program for 1978 are compared with those of prior years in Table 1-1. In FY 1978, the operating budget of the laser fusion program was \$40.4 million and the budget for AIS was \$10.9 million. The manpower numbers reflect all personnel in direct support of the program: scientific, technical, nontechnical, clerical, and craft. A breakdown of the two programs by FY-1978 budget category and manpower is given in Tables 1-2 and 1-3, respectively.

In addition to the operating and equipment budgets, the Nova line-item project was fully authorized in FY 1978 and the first \$3 million for the project was appropriated. During 1978, Nova averaged 35 LLL staff members (including Nova CP&D, 26 without) who were assigned to complete the physical design of the laser system itself and to design the conventional portions of the construction project.

1.3 Program Facilities

1.3.1 Introduction

In 1978, we built and activated new facilities and upgraded and modified our existing ones. We

completed two new facilities: an office trailer complex and the Venus laboratory addition to Building 177. In addition, we activated support facilities associated with the Vulcan and Venus experiments and modified Buildings 381 and 391 in support of

Table 1-2. Laser fusion program—FY-1978 costs and manpower by budget category.

Budget category	Manpower	Cost, \$ thousand
Nd: glass laser development	61	8,720
New laser development	30	2,950
Pellet design and fabrication	98	10,890
Target interaction experiments	125	14,070
Diagnostics development	29	2,540
Reactor systems studies	7	810
Heavy-ion source development	5	400
Total	355	40,380

Table 1-3. Advanced isotope separation program—FY-1978 costs and manpower by budget category.

Budget category	Manpower	Cost, \$ thousand
Laser development	31	2,950
Separation experiments	59	5,550
Supporting technology	21	2,100
New concepts	5	300
Total	116	10,900

Table 1-4. Space distribution for facilities of laser fusion program, including AIS.

Permanent office	50,930 ft ²
Owned office trailers	52,047
Rental office trailers	6,016
Permanent laboratories	187,548
Technician support facilities	34,609
	<u>331,150</u>

target fabrication activities. Also, landscaping improvements and increased parking space were incorporated. By year's end, the program occupied 331,150 ft² of office and laboratory space, a 6.5% increase from 1977. Table 1-4 summarizes the distribution of space.

1.3.2 New Facilities Completed in 1978

New Office Trailer Complex T3724. Our third 15,000-ft² office trailer complex was completed and occupied by the solid state group during July. This complex is identical to its two predecessors and is a T-shaped assembly of thirty-six, 10-by-42 ft modules. The acquisition of this space allowed us to partially alleviate the crowded conditions in Building 381.

Building 177. We started the construction of a 2200-ft² addition for the Venus copper vapor laser system in March and finished it in October. This addition provides air conditioning, electrical power, process water, and space for the laser array, its control and diagnostic equipment, and power supplies. The addition is integrated with the other isotope separation experiments within Building 177, providing an interaction capability that was one of the design goals. Activation of the experimental area began in October and the majority of the work was completed by the end of the year. Final activation depends on the delivery rate of the copper vapor lasers.

Portable Buildings. Continuing program growth, particularly in the AIS and target fabrication group, necessitated the purchase of two 2160-ft² modular units to house a portion of the electronics fabrication section for AIS, and a coating development laboratory for target fabrication. The

interior of the latter is being designed and the laboratory will be operational in 1979.

1.3.3 Continuing Projects and Significant Accomplishments

Nova. The design of Nova continues to be a significant task. The original concept described in the 1976 Laser Program Annual Report (UCRL-50021-76) has been modified extensively. Among the major changes are: relocation of the target room to the north of the laser bay and inclusion of a switchyard to direct the laser beams to the north; deletion of the clean room; relocation of the diagnostics and control room; and the addition of a separate master oscillator room.

Preliminary design concepts of the office building have evolved into a two-story, stand-alone, 55,000-ft² building connected to Building 381 by an overhead walkway (Fig. 1-2). The building in outline is similar to a chevron with an angle of 120° between the office wings. It will be located directly east of Building 381, which will necessitate the relocation of the drainage ditch and the inner loop road.

Mars (Bldg. 175). A \$440,000 general plant project is now in progress for building a new 4000-ft² structure to house the AIS Mars electron beam vaporization experiment. This experiment is an outgrowth of the present electron beam experiments and is an important element in the AIS development program.

The Title I design has been completed and some pertinent project details are:

Location:

30 feet south of Building 177

Cost:

Engineering, design, and inspection	\$ 50k
Building construction	265
Equipment	14
Site utilities	60
Contingency	51
Total	<u>\$440k</u>

Schedule:

Complete design and review	4/79
Complete bid and award	7/79
Complete construction	12/79

Fig. 1-2. Nova facilities (Nova office building adjoining existing Shiva administrative building, left; Nova laser fusion laboratory, right).

Additional Office Space in Trailer Complex. The continuing growth of both the fusion and AIS programs has led to the addition of the fourth wing to Trailers 3724, 3725, and 3726, thereby transforming the T-shaped structures into X-shaped complexes. All design work is finished and the bid award process was underway at year's end. The three additional wings should be ready for occupancy by mid-1979.

Target Fabrication Program Facilities. Increasingly complex target designs have led to severe crowding in many target fabrication laboratories. To relieve this crowding, we have initiated an FY-1980 line item that will add 27,700 ft² to the south

side of Building 391 (existing Shiva laser facility) at a cost of \$7.6 million. Figure 1-3 depicts the exterior and Fig. 1-4 depicts the floor plan interior of this addition (fusion target development facility). If the project is approved, construction will begin in late FY 1980 and end in late FY 1982. Apart from alleviating most of the present crowding, the addition will help to consolidate target fabrication development and assembly.

In the interim, we have converted several non-optimum facilities into laboratory areas. A 1700-ft² area of the basement in Building 391 has been changed into a glass-sphere production area. Since this space was originally designed to house

Fig. 1-3. Exterior of fusion target development facility (addition to Bldg. 391).

LEGEND

- 1 FURNACE SYSTEMS
- 2 GENERAL & ORGANIC CHEMISTRY
- 3 OPTICAL ELECTRONICS & MECHANICAL
- 4 GLASS BLOWING
- 5 CHARACTERIZATION AND SURFACE ALTERATION LEVITATION
- 6 TRANSPORT LEVITATORS
- 7 ROTATOR COATING LEVITATORS
- 8 ULTRA-MINIATURE LEVITATORS AND PLASMA COATING
- 9 CRYOGENIC TARGET CHAMBER SYSTEMS
- 10 CRYOGENIC OPTICAL SYSTEMS AND ELECTRONICS
- 11 CRYOGENIC MULTIPLE LAYER FORMATION
- 12 PHOTO EQUIPMENT
- 13 PHOTO LAB
- 14 DARK ROOM
- 15 PHOTO FILES
- 16 MICORADIOGRAPHY AND ELECTRONICS
- 17 OPTICAL MICROSCOPY
- 18 FUEL FIL CHARACTERIZATION
- 19 LASER RAMAN AND SPARK SOURCE MASS SPECTROMETRY
- 20 STEM AND SAMPLE PREPARATION
- 21 HAZARDOUS MATERIAL HANDLING
- 22 LASER DRILLING
- 23 TRITIUM FIL
- 24 PRE-FIL PROCESSING LAB
- 25 SCANNING ELECTRON MICROSCOPE
- 26 AUGER
- 27 COMPUTER SYSTEM AND DATA PROCESSING
- 28 REFLECTIVE INTERFEROMETRY
- 29 TRANSMISSION INTERFEROMETRY
- 30 ACOUSTIC MICROSCOPY

Fig. 1-4. Interior floor plan of fusion target development facility.

capacitor banks, extensive modifications were required to install the sphere-production furnaces and associated test equipment. Work on converting a 2160-ft² portable building into a coating laboratory was in progress at the end of the year; mechanical utilities are in place and completion is projected for March.

As more complex targets are required, we will need additional space in rental trailers. Consequently, we are planning a \$200,000 general plant project for providing a site and adequate utilities for 20,000-ft² of space; construction should be underway by the middle of 1979.

RAPIER Laser System. We revamped most of Building 166 to accommodate the RAPIER test bed. We installed new ceilings, walls, electrical distribution, air conditioning, mechanical utilities, and negative air systems, and a 400-ft² addition to the control room is in progress. The building is now adequate for the next two years of development work.

Overall Site Improvements. One of our continuing goals is to improve the appearance of program facilities and to increase their utility. During 1978, we contracted for two major landscaping projects around the office trailers, consolidated our owned and rented trailers in a more convenient location, built a new government vehicle parking lot and main entrance into the officer trailer complex, and completed a new alternate electrical feeder for

Buildings 381 and 391. In addition, the following projects were either in construction or procurement: a new red badge conference room near Building 381, additional pathways and landscaping between Buildings 381 and 391, and the relocation of a fuel-oil pumping station.

1.3.4 Future Projects.

We have contracted with an outside-facilities consultant to help us study the use of tilt-up buildings. This method of construction uses concrete slab on grade, with concrete walls formed and tilted into place at the construction site. The roofs are conventional and are supported by glued and laminated beams and steel columns. The resulting structures are semimodular, low in cost, quick to erect, and are used extensively in the electronics and light manufacturing industries. In addition, most buildings are built under the turnkey approach.

While not every experiment can be located in such a building, most light and medium laboratories in our program could be. If the results of the study are favorable, we will select a future building and propose this method of construction. The potential savings are large, and our preliminary results indicate that a 50,000-ft² building can be built for one-half of what it would cost using normal methods of construction.

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SECTION 2

LASER FACILITIES

2.1 Introduction

In 1978, we dedicated our efforts to activating the Shiva laser facility and to designing the Nova baseline system. In addition, we substantially improved the performance and reliability of the Argus laser system. We achieved high-density DT fuel compression on Shiva and developed a Nova design that produces 300 TW in 100 ps and 300 kJ in 3 ns.

The Shiva laser system passed its 10-kJ laser performance milestone in November 1977. In 1978,

we configured the system for target experimentation, and we added the δ -amplifier booster stages (Fig. 2-1). We began our target experimental program at low power in late winter, 1978, and we steadily increased the power during the following spring and summer. The laser was completely activated in September, operating reliably at 20 TW in 120 ps. In November 1978, we configured the system to provide 10-kJ, 1-ns pulses for high-density target experiments. By the end of 1978, the laser had

Fig. 2-1. A portion of the amplification chain of the Shiva laser system, showing the δ -amplifier booster stages.

Fig. 2-2. Design of the Nova laser fusion facility.

operated at two shots per day for target experimentation.

In addition to successfully activating the laser, we substantially improved the Shiva control systems. We can now perform laser diagnostics, align the spatial filters, and select pulse power from the central control room. This flexibility reduces operating costs. We have also been pleased with the low frequency of major maintenance problems. We have had no significant difficulties with flashlamps, coatings, or alignment. Shiva is now a well-developed tool for fusion experiments. In 1979, we will complete the integration of the central control system, further reducing operational costs and reducing the time required for a target shot and for the subsequent data collection and analysis.

We designed the 40-beam Nova baseline system in late 1977 (Fig. 2-2). It was costed and presented for review to DOE and to the technical community in 1978. We expect this system, when implemented, to produce 300 TW in 100 ps and 300 kJ in 3 ns. Key technical issues, which determine the ultimate system performance, were resolved in 1978. These issues involved the propaga-

tion of smooth high-power laser beams, the effect of saturation and gain recovery in laser glasses, the identification of high-damage-threshold laser coatings, the demonstration of the 34-cm Nova amplifier, the receipt of our first full-size fluorophosphate laser disks, and the experimental verification of key target-system radiological design parameters. (The details of component and materials developments appear in §7 of this report.) Compared with our early Nova design, shown in the 1977 annual report,¹ the reader will note significant progress in system performance. We feel confident that we can achieve the 300-TW, 300-kJ objectives and, if technologies such as coatings improve, we should surpass these goals.

In 1978, operation of the Janus laser system was transferred to H-Division for equation-of-state measurements. On Argus, we began emphasizing 1-ns experiments in spring, 1978. We found that, with 1-ns 1-kJ pulses, we were accumulating coating damage at an intolerable rate because of beam peak-to-average ripples of 2 to 1 and because of the great variability in the long-pulse damage resistance in commercial coatings. Therefore, we restaged the

laser to expand the output beam diameter from 20 to 28 cm, improved the optical relaying, and fanatically pursued clean optics (Fig. 2-3). As a result, Argus is now performing routinely at 2 kJ in 1 ns, and has achieved $>5 \text{ TW}$ at 100 ps. A very important benefit of this work on Argus is that this level of laser performance supports the basic Nova design criteria, in particular the spatial-filter closure strategies, the beam peak-to-average fluence levels, the efficacy of relay imaging, and the saturation behavior of laser glass during 1-ns pulses.

Reference

1. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), §2.3.

Authors

J. Holrichter
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2.2 Shiva Accomplishments

The Shiva laser system, through the 15-cm-y-amplifier stages, became operational in November 1977. At that time, we successfully fired all 20 arms simultaneously and achieved an output of 10.2 kJ in a single subnanosecond pulse. This performance exceeded the goal set for the congressional line-item portions of the Shiva project. In 1978, Shiva was developed into a full target-irradiation facility. This development began with the installation of the 20-cm δ -amplifier stages shown in Fig. 2-1 and culminated with shots that produced a record neutron yield and the first detectable neutrons from a target designed to reach high density. In May, the laser produced a record power output of 27 TW. This power exceeds that achieved by any other laser system. Figure 2-4 summarizes pertinent Shiva performance milestones.

Figure 2-5 depicts the Shiva shot history for the past year. The open bars represent shots for which

the full laser system was activated; the crosshatched bars represent target shots. In January, we suspended laser system shots to install the 20-cm-aperture δ output amplifier. The addition of this amplifier boosts Shiva performance to 30 TW for short pulses and to 15 kJ for long pulses. During this time, we also modified the oscillator and preamplifier stages for short pulses, and we added extensive target diagnostics to the target chamber in preparation for our first target experiments.

In February 1978, we performed our first target shot. This was a single-arm shot at 1.8 TW (100 ps), designed to provide a signal for the recently installed diagnostics. From the end of February through the first week of March, we performed 4- and 10-arm target shots and several full-system shots. This series completed the qualification of target diagnostics and much of the target data-acquisition system.

During the March shot series, we noticed that a number of beams were being clipped by beam tubes

and other limiting apertures between the output amplifiers and the focusing lenses on the target chamber. We discovered that several of the first turning mirrors on the target spaceframe were offset from the principal beam lines. We achieved satisfactory alignment by remounting these mirrors and repositioning some of the beam tubes.

From mid-April through the early part of May, we again made system shots to verify beam alignment. Also, we performed several 10-arm target shots at 12 to 13 TW to check on arm-to-arm energy balance and pulse synchronization, and to compare performance with laser-performance code calculations. In addition, we added further target diagnostic instrumentation.

On May 18, we performed our first 20-beam target shot. We irradiated a 265- μ m-diam target with a 27-TW (95-ps) pulse. The neutron yield was a record 7.5×10^9 . Virtually all of Shiva's subsystems performed flawlessly. During the rest of the month, we shot a number of ball-in-plate targets to calibrate a recently added x-ray microscope and an alpha spectrometer and to further check laser performance.

In June, July, and August, we completed the final laser activation work and continued to calibrate diagnostics. We solved electrical noise problems in the oscillator, completely cleaned the optics in the front end and beam-splitter array, and installed the flashlamp preionization-lamp-check system (PILC). In addition, we completed a host of

small projects to prepare for a full target-experimentation schedule in September. In September, we began the Hyperion target series. We performed 11 full-system shots that month. Six were Hyperion target shots at power levels ranging from 14 to 20 TW (90-ps pulse duration). From this series, we obtained a new record neutron yield of 2.7×10^{10} . Also, the results enabled us to compare experimental data with theoretical neutron yields, as a function of laser energy absorbed, over a yield range of two orders of magnitude. We continued the Hyperion series through the second week of October, with seven shots producing data interrelating ion temperature, absorbed energy, and neutron yield.

Starting in mid-October, we converted the laser system to 1-ns operation, in preparation for high-density target experiments. We generated numerous system shots to balance the energy output of the amplifier chains and to verify the predictions of our laser-performance code calculations for 1-ns pulses. These shots showed that we could accurately simulate Shiva's performance over a wide range of input energy values.

Through November, we irradiated a variety of targets with nominal 1-ns pulses at energies from 3 to 8 kJ. These irradiations were precursor shots for the high-density targets. On November 22, we obtained the first detectable neutron yield from a high-density target.

During the first week of December, we completed our initial survey of 1-ns target experiments. A second high-density target shot yielded a record $4.6(\pm 1.8) \times 10^6$ neutrons. This yield suggested a high fuel density, and early in 1979, we confirmed that the density was 50 to 70 times liquid density. We conducted eight target experiments during the first two weeks of December. The remainder of the month was spent installing new experiments in preparation for a campaign to determine target density and temperature.

In summary, activation of the Shiva target irradiation facility has progressed smoothly. This facility is now capable of routinely irradiating targets at power levels of 25 to 30 TW with short (about 100-ps) pulses and up to 15 kJ with long (about 1-ns) pulses.

Author

J. Glaze

2.2.1 Laser System Performance

Introduction. Following the 10-kJ milestone shot in November 1977, we installed δ -amplifiers and Faraday rotators, completed integration of the target chamber, and shortened the laser pulse to 90 ps in preparation for Shiva's first target campaign. At the conclusion of these experiments, the pulse was again lengthened to about 1 ns and target experimentation resumed.

During these experiments, targets were routinely irradiated with pulses of up to 20 TW at 90 ps and 10 kJ at 1.0 ns. The experiments were performed as scheduled with little optical damage or deterioration of the laser system, demonstrating the overall excellence of the Shiva design. We experienced some difficulties with individual components, but these problems were not serious enough to hamper system operation. Early shots at power levels exceeding 26 TW did cause some damage to target room optics, requiring that we limit the output power to about 20 TW. Subsequently, we designed and built output spatial filters that will allow a significant increase in power after they are installed in early 1979.

Performance with 90-ps Pulses. Target irradiation with 90-ps pulses currently provides up to 20 TW on target with little penalty to the laser and beam-focusing system. Operation at this level requires a 0.09-J output from the preamplifier and approximately a 1.0-J output from the 50-mm rod amplifier in each arm. Both outputs are well within the capabilities of these sections. Figure 2-6 shows the design and measured performance for a typical Shiva arm at an output of 1.0 TW. To provide more smoothing of beam filaments that arise from the larger B(Ref. 2) buildup with short pulses, we use smaller-diameter spatial-filter pinholes than with long pulses. Table 2-1 shows pinhole sizes used for 100-ps and 1.0-ns operations. For 20-TW operation, total B is 4.7 Np; for 10-kJ operation, 3.0 Np.

Initial short-pulse experiments with up to 27 TW on target produced several optical damage spots 1 to 3 mm in diameter on some target-room turning mirrors and focusing lenses. Following these experiments, near-field photographs of the beam, taken in the target bay at individual beam outputs of greater than 1.0 TW, showed 1- to 3-mm-diam spikes with intensities more than ten times the beam average. These intensities are well above the damage threshold of thin-film coatings on the

mirrors and focusing lenses. Figure 2-7 shows one of the beam photographs, and Fig. 2-8 is a densitometer scan through a portion of the photograph containing one of the spikes. Subsequent analysis with the MALAPROP system-simulation code

helped identify the cause of the spikes and quantified the benefits of reducing spike intensity with output spatial filters (see §2.2.3). After discovering this phenomenon, we limited subsequent shots to 20 TW of maximum power on target. More power

Fig. 2-7. Near-field photograph of Shiva beam 6, taken at the input to the IBD package during 100-ps pulse operation. Beam output power is 1.5 TW. The dark square at the upper right was produced by an attenuating filter with a transmission of 0.13.

Table 2-1. Shiva spatial - filter pinhole sizes.

Spatial filter	Pinhole size, μm	
	100-ps operation	1-ns operation
$\alpha\text{rod} - \beta\text{rod}, f/7$	1500	1500
$\beta\text{rod} - \beta\text{disk}, f/10$	300	300
$\beta\text{disk} - \beta\text{disk}, f/10$	300	600
$\beta\text{disk} - \gamma\text{disk}, f/10$	300	600
$\gamma\text{disk} - \delta\text{disk}, f/10$	400	600

will be available after the output spatial filters are installed. Since setting the permissible power limit at 20 TW for short-pulse experiments, no additional damage to target room mirrors or focusing lenses has occurred.

Measured chain performance at 1.0-TW output compares favorably with design performance. In Fig. 2-9, midchain energy, measured at the output of the 50-mm-diam Pockels cells, is plotted against measured system output power. Energy measured at this midchain location is particularly useful for system operation, because it monitors the output of the last rod amplifier in each chain and allows direct

tuning of the drive energy input into the disk amplifiers. Rod amplifiers are fired at 10-min intervals, whereas, to prevent optical distortion, 1 to 2 h must elapse between disk shots. The solid curve in Fig. 2-9 is from a system-simulation calculation using component design performance as input. Agreement between actual and design performance is good.

Quality of the Shiva beams at 1.0-TW output is excellent, as illustrated in Figs. 2-10 and 2-11. Figure 2-10 shows beam photographs from the incident-beam diagnostics (IBD) array camera in planes optically equivalent to 450 μm before, at, and 450 μm beyond beam focus of the f/6.0 target chamber focusing lenses. The beam spots are superimposed on a scaled 200- μm -diam circle, which is about the size of a small fusion target. Below each beam photograph is a radial average of the intensity generated by computer from a microdensitometer scan of the photo. Figure 2-11 is such a computer-generated, radially averaged, microdensitometer scan of the beam at best focus, showing beam brightness at 1.0-TW output. Superimposing 10 such beams on a common spot, which is within the capabilities of the Shiva beam-alignment system, produces an intensity of in excess of 10^{17} W/cm^2 at the common focus.

Fig. 2-10. Photographs and computer-reduced microdensitometer scans of a focused Shiva beam in planes equivalent to 450 μm before, at, and 450 μm beyond the best focus. Output was 92 J, and pulse was 99 ps. The figure shows the beam intensity calculated from the energy measured by the beam calorimeters and the radially averaged beam area.

Fig. 2-11. Photograph and radially averaged denatometer scan of data from best focus in Fig. 2-10, reduced to give beam brightness vs angular radius.

The radial average of the intensity at best focus yields additional information on the focusability of the Shiva beams. Figure 2-12 shows the measured radial average for a low-power 0.2-TW beam and the average, calculated with the MALAPROP propagation code, including: (1) no aberrations, and (2) an amount of astigmatism and spherical aberration that brings the calculation into agreement with the measurement. Figure 2-13 shows the same data for a high-power 1-TW beam. In this case, the inclusion of 1.5 waves of astigmatism and 0.5 waves of spherical aberration was not sufficient to bring the calculations into agreement with the measurements. These calculations do not give a detailed match to the aberrations actually present, but they indicate the magnitude of aberrations in current Shiva beams. These examples are typical and show that Shiva beams are readily focusable onto 200-μm diameter (170 μrad) fusion targets.

Table 2-2. Shiva beam energy balance for a typical 90-ps shot (#88101106).

Beam no.	Power, TW	Waveplate attenuator transmission
1	0.77	1.0
2	0.81	1.0
3	0.93	0.83
4	0.89	0.95
5	0.88	0.64
6	0.90	0.89
7	0.81	0.74
8	0.87	0.74
9	0.84	0.47
10	0.88	0.82
11	0.94	0.70
12	0.78	0.59
13	0.90	0.55
14	0.88	0.28
15	0.77	0.61
16	0.98	0.62
17	0.98	1.0
18	0.70	1.0
19	0.88	0.57
20	0.79	0.68

Average 0.86 ± 0.07

Total 17.2

Half-wave plate attenuators at the input to the Shiva beams provide good control of the individual beam output energies. While the gross gain of arms may differ more than twofold, we are able to maintain beam balance to better than $\pm 10\%$ by adjusting the individual beam waveplates. Table 2-2 shows the waveplate attenuator transmission and individual beam output powers for a typical short-pulse shot.

Performance with 0.6-to-1.0-ns Pulses. Current experiments with 0.6- to 1.0-ns pulses typically call for 6 to 8 kJ on target and require an output from the laser's preamplifier section of approximately 0.5 to 1.0 J. Subsequent amplification, splitting for the 20 arms, and transmission through the chain input aperture yield approximately 10 mJ for each arm. Resulting output energies from the β rod amplifiers are 3.0 to 6.0 J. Figure 2-14 shows the calculated and measured performance typical for a Shiva arm at 10-kJ output. Figure 2-15 shows system output energy as a function of midchain energy, measured at the 50-mm-diam Pockels cell.

Fig. 2-16. Near-field photo of Shiva beam taken at input to the IBD package during long-pulse operation. Beam output energy is 182 J.

The near-field photograph of a 20-cm beam, shown in Fig. 2-16, was taken at the input to the IBD's. Beam energy was 182 J. The beam is considerably smoother (a peak-to-average modulation of 4) than the high-power, 100-ps beams, even though larger pinholes were used (see Table 2-1). This greater smoothness is a result of the lower B value accumulated in the system at the lower power. The modulation that persists arises partially from dirt on optical elements at the front of the arms. As with higher power pulses, this modulation increases

between the laser output and the target chamber, because there is no relay in this section.

Figure 2-17, taken from IBD array camera photographs, illustrates the focusability of long-pulse Shiva beams. Shown is a 0.2-TW beam in planes optically equivalent to 450 μm before, at, and 450 μm beyond beam focus of the f/6.0 target chamber focusing lenses. The photos are superimposed on a scaled 200- μm -diam circle. In this example, aberrations are small, and the spatial filtering is adequate to ensure that all of the beam energy is

Fig. 2-17. Photos and microdensitometer scan of a focused Shiva beam, in planes equivalent to $450\ \mu\text{m}$ before, at, and $450\ \mu\text{m}$ beyond best focus. Output was $182\ \text{J}$ and pulse duration was $0.90\ \text{ns}$. The figure also shows the beam intensity calculated from the spot area and the energy measured by the beam calorimeters.

focused on the target. Along with the photograph of the beam at best focus is a radial average of the intensity obtained by computer-processing a microdensitometer scan of the photograph. These results typify long-pulse operations.

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Author

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2.2.2 Oscillator and Preamplicifier Performance

We made a number of significant modifications and adjustments to the Shiva oscillator and preamplicifier subsystem during 1978, including:

- "Hardening" the oscillator-electronics controls to improve noise immunity.
- Adding a second avalanche-transistor driver package to the KD*P Pockels cells switchout, to improve contrast and rise time.

- Installing image relay optics to improve spatial beam quality at the preamplifier table and at the beam splitter array outputs.

- Adding a remotely insertable dye cell to reduce prepulse and ASE energy striking the target.

- Activating the pulse synchronization system.

- Installing and calibrating optical and electrical diagnostics.

Shiva Oscillator Performance. The operating principles of the actively mode-locked, Q-switched Nd:YAG oscillator (AMQO) have been described elsewhere.^{3,4} Here, we summarize important aspects of the AMQO operation on Shiva. Table 2-3 summarizes the flashlamp pumping and rf drive parameters of the current system.

Figure 2-18 presents the results of pulse width measurements taken from streak camera data,⁵ and Fig. 2-19 shows output energy levels determined from calibrated photodiode measurements for the Shiva oscillator. Both sets of data are plotted as functions of the rf drive level to the acousto-optic

(AO) modulator. The pulse width data compare favorably with the expected one-fourth-power dependence of pulse width on drive power, derived by Kuizenga and Siegman.⁶ The pulse width data also agree with earlier characterizations of this oscillator, using sampling data.⁴ The output energy data are consistent with earlier data,⁴ showing a slight roll-off at the low-power end from interpulse noise buildup, and a pronounced roll-off at the high-power end from nonlinear losses in the modulator.

The Shiva oscillator is used over a wide range of pulse lengths and pulse energies. Pulse length stability is $\pm 5\%$ (limited by measurement resolution) and the switched-out, pulsed energy stability between major alignment and pulse width adjustments is $\pm 5\%$. The short-term stability of the oscillator-switchout combination is better than $\pm 2\%$, as shown in Fig. 2-20 for 100 shots.

Oscillator-Electronics Controls. The initiation of target experiments placed increased demands on the optical and electrical subsystems of Shiva. As

Table 2-3. Operating parameters of Shiva actively mode-locked, Q-switched Nd:YAG oscillator.

Flashlamp pumping parameters (2XILC #4-3087 series)	
Supply current	2 A
Supply voltage	400 V
Simmer current	1.0 A (dc)
Simmer voltage	400 V
Pulsed current	5 A/4.0 ms + 24.5 A/4.1 ms
Pulsed voltage	450 V/8.1 ms
Lamp fire rate	10 Hz
H ₂ O flow rate	1 gal/min
H ₂ O temperature	20°C
H ₂ O pressure	25 psi (15 psi drop across pump cavity)
Modulator/Q-switch parameters (SiO₂ Brewster substrate, LiNbO₃ transducer)	
A/O modulator rf frequency	65.3435 MHz (cavity round-trip time approx. 7.7 ns)
A/O Q-switch rf frequency	65.3435/2 MHz
Modulator drive power	approx. 10 mW to approx. 1 W/50 Ω , depending on pulse width (see Fig. 2-19)
Q-switch drive power	approx. 15 W/50 Ω
Optical parameters	
Nd:YAG rod	6 $\times$ 75 mm dbl. Brewster, 1.1% doped
Pulse width	approx. 0.1 to 1 ns
Pulse shape	Gaussian to $1/e^2$ points
Output coupling mirror	Flat, T = 30%
Beam Size @ Output Mirror	$r_o = 0.61$ mm ($1/e^2$ intensity radius) — beam is slightly astigmatic because of Brewster angle components ($r_{o, \text{horiz.}} = 0.58$ mm, $r_{o, \text{vert.}} = 0.64$ mm)

more output control functions and data channels became operational on the power conditioning control system, the effective electrical noise isolation of the oscillator control interface decreased. This decrease occurred despite a careful grounding scheme and optical isolation, which were used to maximize noise immunity.

Figure 2-21 is a schematic block diagram of the present oscillator-electronics controls, which have been discussed elsewhere.^{4,7} Two major problems in this system were solved during 1978.

The first problem was a frequent, intermittent shutdown of the oscillator flashlamps. During normal operation, the power conditioning computer issues a "lamp fire" command to the oscillator bus-interface unit (BIU) address at a 10-Hz rate. This

command pulse passes through the oscillator-electronics interface unit (see lower left-hand section of Fig. 2-21), where it is level-shifted from the complementary metal oxide semiconductor (CMOS) level (15 V) of the BIU to the transistor-transistor logic (TTL) level (5 V)—the level required by the rest of the internal switching and control electronics. Incorporated into this portion of the system are two safeguards. First, if more than 130 ms elapse between fire pulses, a "rate fail" warning is issued and a panel warning light is turned on. The second and more serious situation arises

Fig. 2-21. Schematic of Shiva oscillator electronics controls. The noise problems described in the text occurred in the interface, rf on/off delay, and Q-switch driver sections of the control circuitry.

when the lamp's firing rate exceeds 11 Hz. This circumstance presents a high-duty cycle to the oscillator flashlamps and begins to overload the lamp power supply and regulator circuitry. Therefore, if less than 90 ms elapse between CMOS fire pulses, the system automatically shuts down the flashlamps to prevent this overload.

The cause of the lamp shutdown was the existence of randomly occurring noise pulses on the computer BIU. Although these noise pulses (at about 2 to 5 V and 50 ns) are well below normal CMOS level, they fed through the standard CMOS-to-TTL converter electronics and tripped the lamp fire circuitry. We corrected this problem by incorporating in the CMOS-TTL interface a voltage comparator that switches at exactly one-half the supply voltage. Noise spikes, while still present, are not of sufficient amplitude to pass through the

comparator, and the lamp shutdown has not reoccurred.

The second problem was the occurrence of an early Q-switched output pulse from the oscillator about 580 μ s prior to normal Q-switch time (Fig. 2-22). Fig. 2-22(a) shows the normal oscillator prelude cycle, with the normal single Q-switched output near the end of the prelude.³ Figure 2-22(b) illustrates the occurrence of the double Q-switch. This early pulse was caused by noise entering the rf gating circuitry [rf (on/off) in Fig. 2-21]. This noise pulse caused a loss of rf drive to the Q-switch, producing the unwanted Q-switched output.

This second problem was solved by disconnecting the portion of the rf gating circuitry that normally switched on the Q-switch rf only when the oscillator flashlamps fired. The purpose of this circuitry had been to reduce the average power applied

Fig. 2-22. Q-switched output pulses from the Shiva oscillator. (a) Normal display, with single Q-switch output occurring near the end of the oscillator prelude. (b) Noise-induced double Q-switch occurrence. The extraneous early pulse was eliminated by modifying the rf gating circuitry to prevent noise pulses from firing the Q-switch prematurely (see text).

to the Q-switch and modulator. With this circuitry disconnected, the additional power dissipation requirements imposed on the Q-switch by continuous operation are well within the capacity of the flowing-water temperature control system. This circuit modification, while not eliminating the noise source, has corrected the problem.

Since these two problems were corrected, the oscillator interface has operated satisfactorily on all laser system shots.

The anticipated installation of pulse-shaping circuitry and multiple oscillators (for generating synchronized diagnostic pulses) will place additional demands on the oscillator-electronics controls. These additional burdens on the control system will erode the noise margin of the present system. This prospect, coupled with a desire to simplify the oscillator controls, prompted a decision to redesign the controls. The new design will incorporate the experience accumulated from operating the Shiva system and will be easier to operate and maintain. Details of the design, which we expect to complete in mid-1979, will be described in subsequent reports.

Shiva Switchout. We modified the Shiva switchout to increase its reliability and to improve electrical matching between the avalanche driver and the Pockels cells. Originally, the two switchout

Pockels cells were driven by a single parallel/series avalanche driver,⁸ which required that transistors be replaced every four months. In 1978, we added a second avalanche driver, giving each Pockels cell its own driver. In the 10 months since this change, no transistor failures have occurred.

Independent drivers permit better impedance matching, because interactions between Pockels cell reflections are eliminated. Better matching has reduced postpulse leakage to approximately one-thousandth of the switched-out pulse. Prepulse isolation is greater than 10^6 .

Spatial Beam Characteristics. The solid line in Fig. 2-23 shows the propagation path of the main pulsed beam on the oscillator and preamplifier tables. Although the location of most elements, such as oscillators and rod amplifiers, has remained unchanged during 1978, the optical staging has undergone a significant transition. The original zoom telescope and input-beam-expanding telescope were removed and replaced by a single 5-m-focal-length lens, 588 cm from the oscillator output mirror. This lens serves as an image relay element, which transfers the oscillator beam waist ($r_0 = 0.61$ mm) to a point inside the first α rod amplifier and expand it by a factor of 3.8 ($r_0 = 2.3$ mm). From this point, the beam propagates through a dye cell and is expanded $\times 2.1$ ($r_0 = 5.1$ mm) by an inverted

Fig. 2-24. Example of beam quality improvement produced by front-end optical relay system. (a) Beam at arm input shows strong low-frequency spatial modulation arising from unwanted diffraction effects. (b) A much smoother beam is produced in the same location as a result of the improved optical relaying scheme. Note the relative absence of low spatial frequency defects on this beam. (The obvious circular fringe pattern resulted from a damaged spot on an upstream beamsplitter/mirror, which has since been replaced.)

Galilean telescope located in the return leg of the preamplifier table (see Fig. 2-23). This beam passes through the alignment sensor, is expanded an additional $\times 2.1$ ($r_0 = 10.6$ mm), and passes through the β rod amplifier and 1:1 spatial filter. After passing through the spatial filter the beam passes through a 5-m-focal-length input lens for the penthouse optical relay. This relay, which has its 5.5-m-focal-length output lenses in the penthouse, transfers an image plane at the output of the 1:1 spatial filter on the preamplifier table to a point in the middle of the beam splitter ladders.

Figure 2-23 shows beam waist sizes ($1/e^2$ intensity radii, in mm) and propagation distances. Spatial relaying on the Shiva front end has produced a marked improvement in beam quality. Figure 2-24(a) is a photo of a typical input beam to one of the Shiva arms, before the relaying scheme was implemented. Substantial diffraction effects have produced a "hole" in the beam center, as well as other spatial modulation. Figure 2-24(b) shows a beam at the same position after front-end optical relaying. The improvement is evident, producing a much more uniform input beam to the amplifier arms. (Only the center of the beam is transmitted through the 9.5-mm-diam beam-forming apertures.)

Amplified Spontaneous Emission (ASE) Pockels Cells. As described in detail elsewhere,⁹ 40 large-aperture Pockels cells provide bidirectional isolation for the Shiva amplifier chains. One α cell (diameter 25 mm) and one β cell (diameter 50 mm) are located in each arm at points immediately following the rod amplifiers of corresponding size and letter designation. (The Pockels cells, designated P.C., are shown in the staging diagram, Fig. 2-6.)

Electronically triggered, high-pressure (SF_6 , ≤ 5 atm) spark gaps¹⁰ drive the Pockels cells. During 1978, we measured the transmission characteristics as a function of time for the Shiva ASE Pockels cells. To establish the system timing jitter, we monitored both the electrical waveforms at the cable terminators and the optical transmission of the Pockels cells using a fixed-time reference trigger signal. Figure 2-25 shows typical optical and electrical waveforms. Spark-gap timing jitters of ± 8 ns were observed during these tests. Amplitude variations observed on the voltage waveform in Fig. 2-25(c) imply a corresponding transmission variation in the Pockels cells of about 10%. However, we obtain good energy balance and ensure reproducibility (within $\pm 5\%$) of outputs among

Fig. 2-25. Optical and voltage waveforms on Shiva ASE Pockels cell. (a) Oscillator pulse train with Pockels cell ungated. (b) Pulse train with Pockels cell gated. (c) Voltage waveform at Pockels cell electrical terminator. A series of these data shows indicated a jitter of ± 8 ns in gate timing and a 10% variation in optical transmission during the "on" time of the gating pulse.

the arms by carefully setting up and maintaining the spark gaps, by keeping the timing gate windows sufficiently wide, and by ensuring that the pulse is centered in the gate window. The Pockels cells provide about 30 dB of ASE suppression.

Early problems with high-voltage arcing in the Pockels cells were traced to a probable overvoltage at some units during setup and checkout of the laser. Figure 2-26 shows an example of damage to a β Pockels cells crystal. We have streamlined the electrical operation of the cells to avoid this problem. Corrective measures included minimizing the application of dc bias to the cells and periodic "high-potting" to verify voltage holdoff. Since taking these corrective steps, no electrical failure on any Shiva Pockels cells has occurred.

In summary, the performance of the Shiva Pockels cells has been quite satisfactory over the

past year. Adequate timing stability and output amplitude stability, ensuring good arm energy balance and reproducibility, have been achieved with only minimal attention to spark-gap settings at maintenance.

Pulse Synchronization System. The Shiva pulse synchronization system (PSS) ensures equal optical path lengths for the 20 amplifier chains, thus ensuring that the 20 laser pulses arrive on target simultaneously (± 5 ps). The operating principles of the PSS, an optical heterodyne system developed by Hughes Aircraft Company under contract to LLL, are described in the 1977 annual report.¹¹

After the PSS became operational on the Shiva laser system in 1978, we first measured the passive, round-trip (source to target to source) attenuation of each Shiva arm. This attenuation is approximately 60 dB—less than the 80 to 90 dB with which

Fig. 2-26. High-voltage arc-over damage to beta (50-mm) Pockels cell crystal. Voltage is applied between the gold electrode bands, and the damaged region appears as a track on the crystal surface. The "footprints" on the lower (high-voltage) electrode are caused by high current passing through the fingerstock electrode contacts between the housing and the KD*P crystal.

the PSS can operate. Second, we checked the path-length adjustment hardware on each arm and conducted a series of time-of-flight (TOF) measurements, using a fast photomultiplier-tube (RCA C3100A) receiver, a pulsed oscillator source, and an oscilloscope triggered by a fixed-time reference signal. These measurements had a time resolution of ± 500 ps, which allowed us to position the path-length adjustment platforms to within approximately ± 15 cm. The PSS uses a periodic oscillator input signal ($t = 3.3$ ns), and the TOF measurements guarantee that the lengths of all 20 arms are the same integer multiple of the oscillator period.

Following the TOF adjustments, we could use the PSS to correct the path lengths further (± 5 ps, ± 1.5 mm). We begin each such fine adjustment by

acquiring a return signal from a spherical surrogate target in the center of the target chamber. We then optimize signal levels by making x,y, and focus (z) adjustments, using the PFC sensor and the final focus-lens drivers. Finally, we search for a null-error meter signal for the arm being checked (with the remaining 19 arms blocked) by driving an adjustable timing-optics platform in the $\pm z$ -direction with a stepper motor/worm gear arrangement (158 motor counts per millimeter of path length change).

We encountered some difficulty in optimizing the PSS signal-to-noise (S/N) response in the presence of large background, or "ghost," signals, which arose from reflections from normal surfaces (such as windows, waveplates, Faraday rotator disks, cube beam splitters, etc.). These ghost signals

were small by normal standards ($\sim 0.1\%$), but were in many cases larger than the target return signal. We reduce these signals by range-gating and component repositioning. Range-gating selects a local reference arm position for which spurious noise signals are at a minimum with all laser arms blocked near the target. The remaining noise is then reduced by slightly tilting the reflecting components so that they are not normal to the incident beam.

We increased the absolute signal level by reducing the PSS beam diameter to approximately 1 cm ($1/e^2$ intensity diameter) at the input to the arms by inserting a $\times 1/5$ inverted Galilean telescope near the preamplifier table output. This increased the transmission of the PSS beam through the 0.95-cm arm-input aperture from 20 to 40% to greater than 90%. Because the S/N ratio for the PSS is proportional to the square root of the average laser input power,¹² the resulting increase in S/N was about twofold.

Following these procedures, the PSS operation on Shiva has become tractable and it is possible to synchronize all 20 arms to within ± 5 psec in a period of 2-4 h.

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2.2.3 Final-Relay Spatial Filter

With development of the MALAPROP system-simulation code, the full benefits of a final spatial filter, located between each amplifier chain output and the beam transport and final focusing optics, could be assessed quantitatively. In brief, computations showed that remanent spatial modulation at the entrance to an amplifier arm, although growth-checked by sequential relaying spatial filters, could nevertheless self-focus to catastrophic intensity during the final free-space propagation distance (typically 20 m) to the final focusing optics (target lens). Figure 2-27 illustrates a particularly violent example of this propagation behavior. Here, a peak-to-average intensity ratio (P/A) of 2:1 in the entrance beam grows to P/A $\sim 4:1$ at the chain output and to P/A $> 16:1$ at the target focusing lens. This computation was carried out for a nominal 1.5-TW shot, using pinhole diameters actually used on Shiva. From such calculations, we can infer that peak near-field intensities can reach 100 GW/cm², far in excess of damage thresholds for coated optical surfaces.

To avoid such excessive growth, a final spatial filter was clearly required. Further computations demonstrated that a relaying spatial filter ($f/22$ or longer) would provide optimal protection for turning mirrors and the target lens. Unfortunately, a filter this long would bridge the gap between the laser and target frames. Large estimates of adjustment and alignment errors prompted us to compromise on a somewhat shorter ($f/14$) filter, located entirely within the target room and mounted only on the target frame. This filter is long enough to provide adequate image relaying and low-pass filtering, without pinhole closure at longer pulse durations. Figure 2-28 shows its efficacy for short-pulse, high-power Shiva operations. For output power greater than about 1.5 TW, peak intensities are higher at the entrance lens of the $f/14$ filter than

at the final lens. Therefore, it appeared prudent to leave the entrance lens of this final spatial filter uncoated (bare surfaces have higher optical damage thresholds than do AR coatings). While the concomitant Fresnel losses (9%) can easily be made up in short-pulse operation by increasing chain input power, the performance improvement at longer pulses with this added filter is not so clear. At 1 ns, the component most susceptible to damage is the AR-coated entrance lens of the β - γ spatial filter. The damage threat to this component (in excess of 5 J/cm² at an operational output of 750 J) is illustrated in Fig. 2-29.

In the event that a second δ -amplifier is installed at the chain output section, the $f/14$ spatial filter reduces the peak fluence on the target optics to a level equivalent to the peak fluence at the β - γ spatial filter entrance lens (curve 3 of Fig. 2-29). This would permit operation with on-target energy greater than 1 kJ per beam (20 TW at 1 ns). The combination of the $f/14$ output spatial filter and the additional δ -amplifier would, therefore, represent a significant addition to the present system.

We are currently installing the $f/14$ spatial filters, as sketched in Fig. 2-30. These filters are too large (20 ft) to be prealigned; they must be aligned

Fig. 2-30. Shiva f/14 spatial filters, shown in blue, will be mounted on the target space frame. This addition will immediately improve the 100-ps performance by about 50% and will insure $> 15 \text{ kJ}$, 1-ns performance.

in situ. We are working out alignment procedures, which we expect to be of value during assembly of the Nova laser system (which incorporates still larger spatial filters).

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2.2.4 Prepulse Amplified Spontaneous Emission on Target

Energy preceding the laser pulse, which might damage or destroy the target, is of major concern in lasers used for fusion research. In Shiva, where the

input pulse originates in an actively mode-locked oscillator, this energy arises from three sources:

- Remnants of oscillator pulses, which are incompletely rejected by the switchout.
- Amplified spontaneous emission (ASE) that is within the solid angle intercepted by the target.
- Flashlamp light from the final amplifiers, which is focused on the target.

A double-Pockels-cells switchout and a bleachable dye cell in the preamplifier system control oscillator prepulses from Shiva. The prepulse leakage through the switchout is typically 2×10^{-7} (-67 dB) of the main pulse. The finite rise time

(<3 ns) and trigger jitter (± 0.5 ns) of the switchout restrict its ability to provide prepulse isolation immediately preceding the main pulse.

Acceptable prepulse levels on target dictate an overall isolation ratio of better than 10^{-8} for leakage pulses from the oscillator. To achieve this isolation level, we installed a remotely insertable dye cell at the output of the second α rod on the Shiva preamplifier table. The active region of the cell consists of a 1-mm thickness of EK 9740 dye, dissolved in 1,2-dichloroethane, with the molar concentration adjusted to give a small-signal transmission of approximately 10^{-3} . The cell has a clear aperture of 40 mm. Window parallelism is verified interferometrically to within 1". Figure 2-31 shows the transmission of the dye cell as a function of input flux.

Prepulse measurements are routinely made at the dye cell output, as part of the system operation.

Fig. 2-31. Measured transmission of the bleachable dye cell in the Shiva preamplifier as a function of input flux. Small signal transmission was 3×10^{-3} .

Fig. 2-32. Diagram of instrumentation used to measure amplified spontaneous emission from Shiva beam 10.

The measurements are made in two stages. First, the contrast of the oscillator switchout is checked and adjusted to less than 2×10^{-7} . Second, the small-signal transmission of the dye cell is checked; it must be less than 2×10^{-3} . The measurements thus ensure that the contrast of the switchout-dye cell combination is less than 10^{-9} . This contrast implies that, for a 10-kJ shot, including the effects of gain saturation in the amplifiers, less than 30μ J of oscillator prepulse energy reach the target.

The combination of the preamplifier dye cell and two Pockels cells in each arm control ASE from the system amplifiers. The Pockels cells eliminate

essentially all ASE that originates in the rod amplifiers, except that which occurs within their 60-ns open gate. The dye cell limits the ASE from the preamplifier α rods and prevents the power within the Pockels cells gates from becoming unacceptably large.

Figure 2-32 is a schematic drawing of the diagnostics used to measure ASE from a single Shiva beam. We measured the total ASE and flashlamp light with a calorimeter behind a $400\text{-}\mu\text{m}$ -diam pinhole located at the beam focus in the target chamber. The acceptance angle of the pinhole was $330 \mu\text{rad}$, considerably larger than the $180\text{-}\mu\text{m}$ acceptance angle of the last spatial-filter pinhole in the chains. The time history of the ASE pulse was recorded with a photodiode located in the incident-beam diagnostics package and recorded on a fast oscilloscope. Figure 2-33 shows a pair of typical signals from the photodiode. The pulse in Fig. 2-33(b) consists of a broad $300\text{-}\mu\text{s}$ (FWHM) pedestal of ASE and flashlamp light from the disk amplifiers, with a sharp spike on top, which consists of the rod amplifier ASE transmitted during the Pockels cell open gate and amplified by the disk amplifiers. The flashlamp contribution to the calorimeter energy was determined by firing only the δ -amplifier, and the total contribution from the disk amplifier was determined by firing only the disk amplifier section. Figure 2-34 is a sketch of the ASE pulse, showing the contributions from each of these three sources during a series of shots with laser settings appropriate to a 30-TW output with a 100-ps pulse. To obtain the total energy on target, one must multiply the values in the figure by 20.

The instantaneous ASE power P may be estimated numerically from the formula

$$P = \frac{h\nu}{\sigma\tau} A \frac{\Delta\Omega}{8\pi} f(g)T,$$

where $h\nu/\sigma\tau$ is the saturation intensity (approximately 10^4 W/cm^2), A is the cross-sectional area of the emitting radiator, $\Delta\Omega$ is the limiting solid angle of the radiation reaching the detector, $f(g)$ is the spectrally averaged Nd^{+++} 1.06- μm gain curve, and T is the passive transmission of all elements between the radiator and the detector. Table 2-4 summarizes the experimental data and the numerical estimates of ASE from a single arm, for laser settings appropriate to a 30-TW output in 0.1 ns and to a 10-kJ output in 1.0 ns. The second entry in the table is the ASE during the 60-ns Pockels cell gate, with the preamplifier, ASE suppressing dye cell in place. The third entry is the additional contribution from the preamplifier α rods if the dye cell is removed.

The ultimate test of target survival is to fire the total laser system, with the oscillator switchout disabled and the beams aligned on a target in the target chamber. We have performed such tests on typical targets with laser settings appropriate to a 30-TW output in 0.1 ns and a 10-kJ output in 1.0 ns. In both cases, we recovered the targets after the shot and counted them for tritium loss. No tritium loss occurred, confirming the adequacy of our isolation measures. In irradiation experiments, the targets will be subjected to approximately one-half of the energy they were subjected to during these tests.

2.2.5 System Alignment

The major subsystems for Shiva alignment are described in previous annual reports,^{13,14} but the

hardware and the techniques have both evolved during the first year of Shiva operations. Three examples of this evolution are described here, together with the output alignment activities for a typical target shot.

Front-End Alignment. The oscillator alignment system continued to operate reliably during 1978. It routinely controls beam centering and pointing to 0.2 mm and 10 μrad , respectively. The local operator station for the oscillator alignment system allows control not only for the alignment sensors and gimbals, but also for the beam-switching functions required to select the continuous-wave (cw), pulsed, or pulse synchronization oscillators.

During 1978, control of three adjustable attenuators has been incorporated into the local operator station. Each attenuator consists of a rotatable half-wave plate, followed by one or more polarizers. The rotatable waveplate is driven by a stepper motor, which receives commands from the oscillator-alignment control system. The three attenuators, for which the rotatable waveplates and polarizers are identified in Fig. 2-25, are used to adjust the cw signal level, the pulsed signal level at the dye cell, and the pulsed signal level at the output of the preamplifier table. The digital displays and control switches on the oscillator-alignment control panel allow the operator to read the current transmission of any of these attenuators and to change the transmission settings to meet the requirements of a particular alignment or shot situation.

Amplifier Chain Alignment. The chain input pointing system described in previous reports^{13,14} points the beams reproducibly at the input to each beam line. However, this does not in itself guarantee a perfect beam profile, or exactly the correct position or propagation direction for the beam at the

Table 2-4. Measured and calculated ASE on target, from a single Shiva arm.

Source of ASE	Measured ASE energy, μJ (at 30 TW)	Calc. ASE (at 30 TW)		Calc. ASE (at 10 kJ)	
		Power, W	Energy, μJ	Power, W	Energy, μJ
Diak amplifier 300- μs FWHM	6 ± 3	0.043	13	0.17	50
60-ns Pockels cell gate (with preamplifier dye cell)	5 ± 2	50	3	58	3.5
Preamplifier α rods contribution if dye cell is removed	a	150	9	580	35

^aNot measured.

chain output.¹⁵ Small errors in the positions of chain components can cause the beam to be clipped, offset, or, in the case of spatial-filter lenses, re-pointed. To monitor the alignment of the chain, we remotely insert crosshairs at each end. The input crosshair is indexed to the limiting aperture, and the output crosshair's position coincides with the center of the first of two output turning mirrors. The components in a chain are correctly positioned only if (1) the centers of the crosshair diffraction patterns coincide, and (2) the periphery of the beam is defined entirely by the input limiting aperture, not by any of the numerous component apertures along the chain.

Each of the 20 pointing, focusing, and centering (PFC) sensors in the target bay provides us with a closed-circuit television image of one of the beams. The operator examines the display to verify the alignment. We correct small offsets of one cross hair pattern with respect to the other by moving the

input limiting aperture. To eliminate "aperturing" within the chain, we must locate the offending component and move it, or redirect the beam by slightly moving a spatial-filter lens. In practice, such adjustments are required infrequently.

Spatial-Filter Pinhole Positioning. Shiva currently comprises 122 spatial filters, 6 in each of the 20 amplifier chains and 2 on the preamplifier table. Figure 2-35 illustrates the back-illumination technique in current use for pinhole alignment. For each chain, an optical system looking through the second turning mirror in the target room images the spatial-filter focal plane onto a television camera. This camera is one of several major components contained in the chain's incident-beam diagnostics (IBD) sensor. The image of the focused beam is centered on a reference cross hair, as shown in Fig. 2-35(a). A remotely insertable lens is then placed in the beam near the chain input. The lens is chosen to focus the beam ahead of the pinhole. The

Fig. 2-36. Output alignment components for a representative beam. This view is from the side and about one-third of the way up the seven-story-tall steel space frame in the target room. The pointing, focusing, and centering (PFC) sensor, large gimbals, and supporting hardware are used to position the output beam accurately on the target.

beam then expands to a spot larger than the pinhole in the nominal focal plane of the filter. Figure 2-35(b) is a television display of this large illumination field, with the pinhole removed.

The pinhole is mounted on a three-axis, motor-driven manipulator, and when it is brought into the vicinity of the focal plane, its silhouette can be seen on the TV monitor, as shown in Fig. 2-35(c). Accurate transverse position is then obtained by centering the pinhole image on the cross hair. Proper position along the propagation axis corresponds to sharpest focus of the pinhole image.

These pinhole alignment steps are currently performed by system operators from the alignment console in the control room. However, equipment has been purchased to digitize video data from the television network and to make it available to the alignment system computers. Pinhole alignment will become an automatic closed-loop function when we have completed the software development.

Output Alignment Summary. The 20 beams emerging from the laser pass through ports in the wall of the laser bay and enter the target room. There, large turning mirrors direct 10 of them to the top of the target chamber and 10 to the bottom. Each beam must then be centered on its target-chamber focusing lens, and pointed and focused on

the target by the PFC system. For each 20-cm-diam beam, this system consists of a PFC sensor, two motor-driven mirror gimbals, and a three-axis, motor-driven positioner that holds both the focusing lens and a retroreflecting centering screen.

All of these components, along with the target chamber and related hardware, are mounted on the target-room space frame. All have been described elsewhere.¹³⁻¹⁵ Figure 2-36 shows the arrangement of alignment components for a representative beam.

The output alignment activities during a typical shot can be summarized by looking at the functions of the PFC system.

- **Centering on the focus lens.** To center each beam on its focusing lens, we first determine the position of the beam relative to the lens by inserting a retroreflector array indexed to each lens. When the centering screen is in place, the light that would have entered the focusing lens is reflected back toward the output pointing gimbal. A fraction of this light is transmitted by the second turning mirror and collected in the PFC sensor.

The principal components of a PFC sensor and its attached reflected-beam diagnostics (RBD) package are shown in Fig. 2-37. During beam centering operations, the insertable mirrors of the PFC are retracted, and the optics in the PFC sensor

Fig. 2-37. Principal components of an Aerojet ElectroSystems PFC sensor and its attached diagnostics package. During alignment, the position-sensitive detector (a lateral-effect silicon photodiode) provides error signals for closed-loop automatic control. An operator can simultaneously monitor alignment status by selecting an appropriate lens-turret position to view either far-field or near-field planes with the vidicon camera.

simultaneously image the plane of the centering screen onto a position-sensitive detector and a silicon vidicon. Because the sensor has been previously aligned to look directly at the center of the focusing lens, any offset of the beam on the centering screen generates an error signal. From this signal, the PFC microprocessor calculates the appropriate motor commands for the two gimbals to remove the centering error without changing pointing.

Because the chain output has been previously centered on the cross hair at the first turning mirror, the operator can visually verify centering by inserting this cross hair to see that its diffraction pattern is centered on the centering screen in the operator's TV display. The lens turret gives the operator a choice of magnifications for obtaining a clear view of the diffraction pattern, as shown in Fig. 2-38. A centering error of 1 mm, which is 0.5% of the 20-cm beam diameter, is readily detectable by this technique.

- Pointing at the surrogate target. A typical laser fusion target is far too small to serve as a convenient reference for an automatic output pointing system. Therefore, we initially align the beams on a spherical surrogate target, 5 mm in diameter. This approach assumes that we can accurately replace the surrogate with the fusion target and that each beam can be precisely offset from its aligned-to-

surrogate position to conform to the irradiation geometry required by the specific fusion target. These capabilities are discussed later.

To obtain accurate beam-pointing, we retract the centering screens and observe the light reflected from the surrogate. As shown in Fig. 2-39, the beam now reflects from the surrogate target, back through the focusing lens and the output pointing mirror, into the PFC sensor. Because the sensor is imaging the plane formerly occupied by the centering screen, any offset of the reflected beam as it passes through that plane generates an error signal from the sensor. When the incident beam is pointed at the target, with its central ray perpendicular to the surface, the offset and the error signal disappear.

The PFC microprocessor calculates motor commands for the output pointing gimbal only, because a typical pointing correction causes a negligible change in beam-centering at the lens. As with beam-centering, the pointing operation can be monitored and verified on the operator's TV screen.

- Focusing on the surrogate target. Moving the focusing lens toward or away from the surrogate target changes the diameter of the reflected beam. The smallest diameter is obtained when the incoming beam is focused toward a point halfway between the center and the front surface of the surrogate, that is, when $Z = R/2$, as shown in the inset of

Fig. 2-39. In this situation, the reflected beam is collimated at the surrogate surface and expands by diffraction as it propagates back toward the lens.

To focus the beam toward $Z = R/2$, the lens is positioned by a system operator who remotely drives the focusing lens along the beam axis until the spot on the operator's TV monitor is at its smallest and brightest. Digital processing of video information, as described for spatial-filter pinhole positioning, will make it possible in the future to automate output focusing.

- Target exchange and beam offsets. Since the PFC system accurately positions all of the beams with respect to a surrogate target, we must next remove the surrogate and replace it with the real target before firing the system. The two targets are mounted on a common stalk and are easily interchanged using the motor-driven target positioner. However, it is impossible to monitor this exchange with the desired accuracy of $5 \mu\text{m}$, using standard viewing instruments and TV monitors. The surrogate is 1000 times larger than the resolution required and would, therefore, exceed the approximately 500-line TV field of view. The Shiva target-positioning viewers, thus, use a multiple-field design described in the 1977 annual report¹⁶ to meet the conflicting requirements of high resolution and large field of view.¹⁷

With a fusion target in place, the final step before the system can be fired is to translate the focus lenses slightly, moving the beams to the target coordinates specified by the shot plan for that particular target. As each beam is known to be pointed directly at the center of the target and focused 1.25 mm ($R/2$ for a 5-mm-diam surrogate) in front of it, the required focus-lens motions can be calculated by a simple computer program at the control console. The operator enters the 20 desired beam positions, and the lens-drive microprocessor sends the appropriate offset commands to the three stepper-motors at each lens.

A set of transducers with $2\text{-}\mu\text{m}$ resolution, one on each translation stage, enables us to compare the actual motion with the commanded motion. To further assure that the offsets are accomplished dependably, a test program is run periodically that measures the repeatability and backlash of the lens drives and recalculates the scale factors for the transducers.

- Alignment verification. Completing the preceding steps can in principle guarantee that each

Fig. 2-39. Schematic of the relationships that underlie operation of the PFC system in the pointing and focus modes. To obtain the proper pointing, the mirror angle α is changed until $\Delta y = 0$. Focusing to the half-radius point on the surrogate target is achieved by slewing the focus lens along the beam axis until the spot diameter D is minimized. In the inset equation for the divergence of the beam reflected from the surrogate, $\Delta Z = Z - R/2$, and $R = 2.5 \text{ mm}$ for the 5-mm surrogate target used in Shiva.

beam is properly positioned on the target to within $10 \mu\text{m}$ in the transverse direction, and is within $50 \mu\text{m}$ of perfect focus. Nonetheless, some level of verification is frequently desired before making the shot. The PFC/RBD sensor shown in Fig. 2-37 provides a way to obtain such verification for transparent targets.

Fig. 2-40. TV view of a glass ball target with a single beam positioned on it. The beam diameter is about one-half that of the target. This photograph is a double exposure, because the backlit target and the beam cannot be seen simultaneously.

Two of the PFC lens-turret positions produce different magnifications of the target plane on the silicon vidicon. Inserting the internal mirrors of the PFC system and routing the beam through the RBD part of the sensor make available additional magnification, together with the capability for internal focus and offset adjustments. With the target backlit from the opposite side by a remotely insertable illuminator, the sensor produces an image of the fusion target, whose position can be marked on the TV screen. When the illuminator is removed, we see an image of the opposing beam in the target plane so that its position and size can be visually compared with expectations. Figure 2-40 is a double exposure, showing both the target and one of the beams illuminating it.

Tasks for 1979. A major goal for 1979 is to further reduce the time required for complete alignment of the system. Significant progress in this area will follow our development of the software for automatic pinhole positioning and a relaxed requirement for operator verification of the target alignment for all 20 beams. The latter change in procedure depends on documenting a history of agreement between automatically positioned beams and operator observations. We have begun to accumulate such documentation.

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2.2.6 Operations

During 1978, we operated Shiva as a target irradiation facility. The following paragraphs

Fig. 2-41. Sequence of events for a Shiva target shot.

describe a typical operational sequence, which is shown graphically in Fig. 2-41.

Prior to the beginning of a shot series, we complete general preparations, which include laser alignment and cleaning, laser diagnostic calibration, new target-diagnostics installation, necessary component replacement, controls subsystem checkout, power subsystems maintenance, and waveplate adjustments to balance the beam output energies. Preparations may take up to two weeks, depending on the size of the task scheduled. When preparations are complete, the laser is ready for two weeks to a month of daily target shots.

Shot day begins with receipt of final requirements for the day's target experiments, including energy, pulse duration, beam-focusing requirements, and target diagnostics requirements. Laser preparation begins with minor adjustments to the laser and oscillator, including verification of pulse width, diagnostic triggering, and beam-pointing and beam-centering. Parallel tasks follow that are associated with laser alignment, target diagnostics,

and laser diagnostics. The longest single task during this period is pinhole alignment, which takes two or three hours. All 100 spatial-filter pinholes are focused and centered by essentially manual techniques. During pinhole alignment, final preparations of the target chamber and target diagnostics are completed, the laser diagnostic system is checked for proper calibration and data acquisition, and the target is installed in the target chamber. The shot director calculates laser power-supply voltages and attenuator values, which are then set for the shot by the power conditioning and laser operations crews.

Pinhole alignment completes the laser preparation, allowing target alignment to begin. If the target is classified, the area is secured and a guard is posted before the target is delivered and installed. Target alignment, which takes two or three hours, comprises three steps (see §2.2.5). First, all 20 beams are aligned to a surrogate target positioned in the center of the target chamber. Second, the real target is properly positioned to replace the surrogate.

Finally, the positions of the beams on the target are adjusted and verified.

With target alignment complete, final preparations for a shot take about one hour. First the system is converted from cw operation, used during alignment, to pulse operation for the shot. The Sentry system (Ref. 18, pp. 3-18 to 3-21) is locked onto the target, and final target diagnostics preparations begin. Beam attenuators, which adjust the preamplifier energy and beam balance, are set and the settings verified. Next, the front portion of the laser system, up to and including the β rods, is fired to verify the drive energy for the disk amplifiers. During these shots, the beamline shutters are closed at the target bay wall. Comparing the output energy at the β rods with the information depicted in Figs. 2-9 and 2-15 makes it possible to verify that the correct energy will be on target.

When rod shots are complete, the laser diagnostic film is loaded and the remaining power supplies are properly set for the target shot. The shot director checks that all subsystem checklists are completed, and the beam shutters are opened. Finally, about six hours after shot-day preparations began, the target is irradiated. Target irradiation, however, does not end the shot sequence. Acquisition of target diagnostics data takes about two hours. At the same time, several other tasks go on. The laser cooling system is set on high flow for one hour, and amplifier performance can be verified using the waveform-analysis data system (WADS) and pulse ionization lamp check (PILC) subsystem (Ref. 18, pp. 2-46 and 2-47).

If no problems occur, all the tasks in the shot sequence can be performed in about eight hours or less. Preparation for the next shot can usually begin one hour after the cooling system is returned to low flow. It is now possible to fire two shots in a 16-hour day if no unusual problems arise. At the beginning of 1978, a typical shot sequence required 13 to 15 hours.

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Authors

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2.2.7 Computer Code Support

Several computer codes have been developed to analyze and predict laser chain performance, to aid with beam alignment, and to provide guidance in selecting target irradiation geometries. Four of these codes are discussed briefly below.

SHOP. Shiva optimized performance¹⁹ is a laser-chain-performance code, which can compute:

- Chain output energy and flux loading on components for specified input energy and amplifier gains or specified charge voltages.
- Input energy needed to provide optimum output energy for specified amplifier gains or charge voltages.
- Output energies for a specified range and increment of input energies. This computation generates a table of output energy as a function of input energy.
- Output energy as a function of pulse length for a specified range and step size, with the maximum flux below a specified damage threshold.

About 60% of the code is devoted to bookkeeping that allows the assembly and modification of a complex laser chain. The pulse length, saturation flux, fill factor, absorption loss, and scatter loss per surface may be specified. About 20% of the code is devoted to file manipulation; this includes establishing and retrieving data files for the laser system and printing results on the line printer or terminal. The remaining 20% performs the actual calculations. The physics that underlies the calculations includes the gain model, the calculation of the B integral, and the model for the transmission of the spatial filters.

The SHOP code is an outgrowth of the SPACE code concept developed by W. Hagen and J. Trenholme. It is a direct descendant of a Fortran version of the SPACE code, which was translated from Basic by G. Suski. It is routinely used to calculate Shiva performance parameters.

XTRAN. Beam alignment onto the target requires positioning control of the final focusing lens for each of the 20 Shiva beams. The mount for each focusing lens allows movement in three orthogonal directions, which are chosen as the axes of the lens coordinate system. The target coordinate system²⁰ has its origin at the center of the target chamber, with the positive z-axis directed upward and the x-axis coincident with the target stalk and positioner. XTRAN^{21,22} computes the target-lens coordinate

transformation, i.e., the lens coordinates for all beams when the foci positions are given in target coordinates, or vice versa.

BSTER. For each of the 20 Shiva beamlines, tip and tilt adjustments of the first and second turning mirrors are used to center the beam on the centering screen in front of the target focusing lens and to point the beam at the surrogate target during the initial beam alignment phase. The BSTER code²³ uses a mathematical relationship between the four independent variables describing mirror orientation and the four dependent variables that specify beam-centering and beam-pointing. Output of the code includes six pointing and centering transformations for each of the 20 Shiva arms, as well as the unit vectors of the mirror coordinate systems in terms of the laboratory reference coordinate system.

LITAR. The laser irradiation on target²⁴ code computes and displays beam irradiation patterns on spherical and planar targets. It computes both the incident and absorbed intensity and allows the user to display the results in tabular form, either on a line printer or as an intensity-coded color display on a TV monitor. This code is used routinely to evaluate focusing geometries for Shiva targets.

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2.3 Shiva System Development

2.3.1 Electrical Subsystems

During 1978, several improvements were made to the electrical subsystems on the laser. These changes were directed primarily at improving laser performance, reliability, and repeatability, and at reducing maintenance costs.

Pulse Ionization Lamp Check (PILC) Modifications. Installation of PILC, as described in the 1976 annual report,²⁵ was completed in September. During subsequent testing, a number of troublesome problems appeared. These problems, though conceptually simple, were difficult to diagnose and fix, because Shiva was being used for target experiments, making maintenance time scarce. Furthermore, the PILC packages are installed in the space frame, where service is difficult.

The most destructive problems were caused by defective current transformers. The potting on the transformers was faulty; therefore, during a laser shot, current arced from the pulsed-power ground to the transformer coils and would often damage the PILC packages connected to the transformers. Temporary insulation was added to those transformers that had less than 10-kV isolation, but a permanent solution, requiring new transformers, will not be available until mid-1979. The temporary insulation protects the PILC packages during normal laser shots, but if a fault appears elsewhere in the system during a laser shot, the insulation breaks down and the PILC packages are damaged.

Two other significant problems were caused by component failures due to the very high noise levels near the PILC packages. An analog-to-digital converter and a 15-V power supply frequently ceased operation during a laser shot. These components were modified and currently function satisfactorily.

The PILC packages are now all operating and acquiring useful data. Figures 2-42 and 2-43 are examples of lamp current waveforms captured by PILC packages. These waveforms are useful for diagnosing laser problems, because they allow rapid discrimination between electrical and optical faults. In several instances, where low output power from an amplifier chain was observed, the PILC waveforms showed that the cause was not an electrical malfunction. This result prompted detailed analysis of the optical train as the source of the problem.

Three tasks remain to be finished before PILC operation becomes completely reliable and automatic: (1) new current transformers must be installed, (2) noise immunity must be increased by identifying and modifying those components that are still sensitive to system faults, and (3) a software package must be added to streamline analysis of the PILC-package data.

Fig. 2-42. Flashlamp current waveform during a laser shot. The vertical scale is 2000 A per division, and the horizontal scale is 400 μ s per division.

Timing Channel Additions. The automatic sequencer is a software feature imbedded in the power conditioning LSI-II microprocessor. Early in 1978, the only functions implemented in the sequencer were those dealing with the actual ignitron firing. (These functions occur in the last 10-ms before firing and use the internal computer clock as the timing source.) All other functions were performed manually.

Manual charging is extremely hard on the capacitors in the preamplifier section of the laser. These power supplies arrive at voltage more than a minute before those in the disk-amplifier sections, which comprise 64 times as many capacitors. To reduce this time at voltage, sequencing of the power supplies, to enable all sections of the bank to reach voltage at the same time, was the first manual function committed to the sequencer. This required 13 of the 70 spare computer-interrupt-driven channels in the sequencer.

The next function committed to the sequencer was the application of Pockels cell bias and spark-gap voltage. The original design assumed that both the gap and the Pockels cells would have unlimited life in a dc standoff mode. Unfortunately, ex-

perience with the β Pockels cell showed that, with time, electrode-edge field-effects broke down the index-matching fluid, subsequently causing electrode erosion and breakdown across the crystal surface. The most expedient solution to this problem was to apply voltage to the cells just before charging the rod amplifiers. This reduced the voltage on-time from several hours to approximately 45 s per shot. The spark-gap high-voltage supply was included in this modification to reduce the number of self-break occurrences, thus prolonging gap life.

When target shots began, the Sentry²⁶ system was brought on-line. This system was initially designed to detect target destruction immediately before a shot; however, because of target illumination difficulties, the reticon-detector integration time had to be increased. This change increased the response time to approximately 200 ms. At the same time, the task of integrating Sentry with the oscillator proved difficult because of the low noise immunity of high-speed electronics in the oscillator. As a result, we disconnected the hardware interface to the oscillator Q-switch module and added checks for a Sentry-requested abort to the sequencer. These tests require the sequencer to abort if Sentry is not

Fig. 2-43. A PILC-simulator current waveform. These waveforms are generated by each PILC package for complete self-checking of electronics. The vertical scale is 200 A per division, and the horizontal scale is 400 μ s per division.

locked on the target both at 2 s and at 11 ms before a shot. In retrospect, this addition was appropriate, in any case, because it prevents a useless firing of the disk amplifiers with no oscillator switchout if Sentry detects target failure before the shot.

Another function that has been added to the sequencer is a Faraday rotator at-voltage test. In the original design, a shot was to be aborted if any supply did not reach its commanded voltage by shot time. This proved overly optimistic during the initial phase of laser and target shooting, because one-third of the shots were being aborted for one reason or another. Therefore, this function was disabled. In its place, we added a test to ensure that the β rotators were at voltage. This prevents the potentially disastrous consequences of a large back-reflection from the target, in the event that a rotator is not up to voltage.

During routine operation of the laser, it became apparent that personnel in the laser bay needed direct indication of an approaching shot. Therefore, seven chimes are now sounded by the automatic sequencer.

When PILC was introduced, three more sequencer channels were required. The first sets up

the PILC packs (mode selection, sample rate, reset, etc.). The second issues a trigger during the final sequence to initiate waveform sampling. Finally, after the shot, the data are collected from all 1200 waveforms by sequencer command and are translated to disks for subsequent evaluation.

When target shots began, a dye cell was added to the preamplifier table to suppress ASE (see §2.2.4). Initially, this cell was manually inserted and removed for each shot. To decrease turnaround time and eliminate human error, an automatic insertion mechanism was built. Three sequencer channels are now used to insert and remove the dye cell and to verify this function on each shot.

The final addition to the sequencer in 1978 was prompted by the loss of a target during a preparatory rod shot. The beam blocks at the laser bay wall had been visually verified as closed; however, the target was destroyed, suggesting an open beam port. Subsequent evaluation of archived data indicated that the target disappeared at shot time and that, in fact, a beam block was not completely closed. To preclude a recurrence of such an accident, a sequencer channel now requests the PDP-11/34 to check a set of conditions prior to the

shot. Currently, this checklist includes only the beam blocks; however, expansion is underway to add cross hairs, wigwags, oscillator configuration, and a beam diagnostics test to the list.

As can be seen from this discussion, the sequencer has proved to be a valuable tool, readily responsive to changing laser requirements. Of the 127 original sequencer channels, 61 are still available without extensive software modification.

New Laser and Target Bay Functions. When the laser system was constructed, it was recognized that many original ideas might require refinement in the light of experience. During 1978, several design deficiencies were observed and solutions were implemented. For example, each laser amplifier location serviced by PILC was originally provided with spare even-driven outputs and event- and analog-input capability. This flexibility was provided at low cost simply by adding connectors and wiring. By now, this additional capability has been completely absorbed in the rod amplifier section of the laser. Among the added functions are additional alignment aides, maintenance indications, and automatic checks of the configuration required at shot time. We have also reduced the number of triggers required from the master oscillator.

In the alignment area, reference cross hairs have proved necessary far more frequently than originally thought. They have been added (or are being installed) in the penthouse, in the beam splitter ladder, at the beam-defining aperture (20 cross hairs), and in the target-bay insertion boxes (20 cross hairs). Control and position verification of these cross hairs is provided by a new alignment system B processor (stepper-motor driver) in the penthouse and ladder area, by use of spare PILC capability, and by an additional computer bus that services a variety of functions throughout the target bay.

Another area where a significant number of design improvements were made is the laser oscillator/preamplifier section. Triggers originating at the oscillator, which serviced the preamplifier streak camera and the oscillator alignment system, were removed to make the oscillator more immune to noise. The functional equivalent of these triggers is now obtained from the sequencer, using the PILC package under the preamplifier table. This change left only the nanosecond timing channels of the spark gap and switchout tied to the oscillator. As discussed above, high-voltage switches were added

to the spark gap high-voltage and bias supplies to prevent electrode breakdown in the Pockels cells and spark gap. These functions and the dye cell inserter were also assumed by PILC package channels.

During the course of the year, the "O" rings retaining the index-matching fluid in the α rods started leaking. This suggested a need for a fluid-flow and reservoir-level sensor in each rod amplifier to detect failures before they affect the optical performance of the system. Addition of these 80 sensors finally exceeded the spare capacity of the PILC package in the rod section of the laser. However, an increase in the spare connector size will allow accommodation of this function at minimal cost. This modification was in progress at the close of 1978.

Capacitor Bank Modifications. In general, the Shiva capacitor bank performed flawlessly during 1978. The preamplifier circuits now have more than 2000 shots on them. Since the δ amplifiers were not operational until after the 1976 10-kJ milestone shot, they have approximately 100 shots—the fewest of any circuit. There has not been a single failure among the 7000-plus capacitors in the system. At present, the most common failure within the capacitor bank is the occasional failure of an ignitron switch, which either prefires or fails to fire. No target shots have been lost on account of these problems, because they have been in the δ region, where they effect only one or two arms.

With this success record, few modifications have been incorporated in the bank and associated circuits. The dummy loads that were originally installed to aid in troubleshooting were removed from the space frame to facilitate installation and maintenance of PILC. As a result, the gaseous nitrogen system was simplified.

We also made a simple modification to eliminate long-term (weeks) drift in the 100-kVA power-supply calibration. The trim pots in the high-voltage divider networks were removed in favor of an expanded-range pot on the gain adjustment of the isolation amplifiers. This measure reduced the number of pots in the system by two and removed all pots from the high-voltage section. Calibration is now much simpler, because all adjustments are made in the low-voltage section.

Amplifier Changes. We made two electrical changes to the amplifiers during 1978. At first the α rods proved hard to fire, and the difficulty appeared to increase with time. As a result, a trigger rod has

been added next to the flashlamps. During the initial design of the rod amplifiers, 15-mm-bore lamps were chosen as the driving source. During subsequent experiments, this proved to be a good choice for the β rods, but the gain profile of the α rods could be improved by using a smaller-diameter lamp. After considerable testing, a lamp with a 13-mm bore was chosen, and the α rod amplifiers were subsequently converted.

Oscillator Interface Modifications. When the oscillator was installed in the Shiva laser system, several problems surfaced. In general, the oscillator worked well as a stand-alone device, but it did not integrate well into the large Shiva system. For example, the computer interface was not redundant, and its control and monitoring functions had insufficient depth. Furthermore, when the interface was hooked to the computer, occasional noise problems appeared when both the primary and backup power conditioning computers were running. Also, as already pointed out, noise problems occurred when the oscillator was configured to trigger the Pockels cells spark gaps and streak cameras, or to receive an abort signal from Sentry.

Solutions to these and other problems have been stop-gap measures; therefore, an overall redesign of the oscillator control electronics has begun. Where reasonable, the current oscillator controls components will be used. For example, we will undertake little modification of the lamp current regulator, the switchout driver, or the rf amplifier packages. On the other hand, components such as the events counters, Q-switch driver, acousto-optical modulator driver, and computer interface will be substantially modified. In general, the controls will be divided into two chassis: a computer interface chassis and a high-frequency controls chassis; this will consolidate many of the components scattered by recent modifications.

References

25. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977), p. 2-125.
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2.3.2 Mechanical Subsystems

Recent mechanical improvements, which allow remote insertion of cross hairs, lenses, and shutters at different places in the 20 laser chains, facilitate alignment of the beams. Previously, system operators installed and removed these components manually. A typical Shiva arm, showing these mechanisms, is shown in Fig. 2-44. Other improvements include the addition of alignment jack assemblies, modification of the rod amplifiers, installation of a retractable dye cell, and modification of the crowbar assemblies.

Four-Aperture Insertion Stage. The four-aperture insertion stages allow remote insertion of beam-expanding lenses, shutters, and clear apertures in each of the 20 laser beams. They are located between the timing optics and the beam-defining apertures. One of the apertures in each stage provides a register for a lens to backlight the spatial-filter pinholes for pinhole alignment. The other three apertures are a clear aperture, a shutter for blocking the laser beam, and a spare lens for future uses. The geometry of Shiva's 20 arms permit two or three sets of four apertures to be grouped on a common stage. Stages with three sets of optics (as in Fig. 2-44) satisfy the outer arms on the space frame; stages with two sets of optics are used on the inner arms. Hence, only eight assemblies were required for the 20 beams.

The stage is commanded to any of its four positions by digital control from the LSI-11 computer. Each stage is driven by a 16-pitch lead screw, directly coupled to a dc stepper motor. The stepper motor, at 1.8° revolution per pulse, translates the stage 7.95 μm /pulse. The stage velocity, at the maximum pulse rate of 300 steps/s, is 14.27 cm/min. Limit switches define the maximum excursion of the stage. Redundant readout switches provide status signals to verify that the clear aperture is in the beam for a target shot.

Remote Insertion Cross Hair/Fixed Aperture.

The remote insertion cross hair/fixed aperture assemblies, one of which is shown in Fig. 2-45, are located between the four-aperture insertion stages and the first optical relays. The aperture defines the laser beam diameter, and the cross hair, when inserted in a beam, is used for system alignment. The cross hair is used in conjunction with the fixed 9.5-mm-diam beam-defining aperture, the chain input pointing sensor, and a last cross hair at the output of the 20-cm δ disk amplifier.

Fig. 2-44. Schematic of typical Shiva arm with recently added improvements.

Fig. 2-45. Remote insertion cross hair/ fixed aperture assembly.

motor-driven translation stage, is moved on command into each beam. For this purpose, 20 beam block shutters are mounted on the wall separating the laser bay from the target room. Redundant readout switches provide status signals that indicate a fully open or fully closed shutter.

Remote Insertion Cross Hair Assembly. The remote insertion cross hair assemblies allow remote insertion of large, 27.9-cm-diam cross hairs in each of the 20 laser beams. The assemblies are mounted at the incoming beam port of the insertion boxes on the target space frame (Fig. 2-46). They are used during system alignment and verification, together with the remote insertion cross hair on the front-end beam-defining aperture and the chain input pointing sensor.

All components of each assembly, except the cross hair limit stops, are mounted on a single plate. The mechanism is basically a lever with a cross hair at one end and a pneumatic actuator at the other. Two pairs of opposed screws allow fine adjustment of the pivot shaft subassembly. An adjust-and-lock fixed stop on the vertical face of the insertion box

defines the "in-beam" position. Redundant readout switches provide status signals to verify that the cross hair is out of the beam for a target shot.

Alignment Jack Assembly. Alignment jack assemblies facilitate the alignment of heavy optical components (disk amplifiers, spatial filters, and rotator-isolators) on the laser space frame. Each component is supported by a pair of cradles on the space frame. A movable and lockable interface plate between the component and the cradle allows the necessary two-axis adjustment at each end. A jack assembly, secured between the cradle and plate, permits fine positioning of the component along two axes, with a pair of lead screws.

This method of alignment was used during construction of Shiva. However, the jacks were cumbersome, weighing 27 kg, and could be used only in certain locations. A new jack was designed for use during the operational phase. It weighs 14 kg and is symmetrical so that it can be used on either end of the component being aligned. It comprises one horizontal translation stage and a scissor-type jack for vertical positioning.

Fig. 2-46. Remote insertion cross hair assembly, showing the cross hairs out of the beam path.

Rod Amplifier Modifications. The α and β rod amplifiers and their associated assembly fixtures have been upgraded to improve high-voltage protection and liquid-coolant sealing.

Before recent modifications, it was possible that an internal high-voltage wire to the lamp assemblies could break and make contact with the grounded amplifier case, creating an electrical hazard. A high-voltage shroud now encases all internal leads, providing a barrier between the leads and the case. The complex geometry of the shrouds were made by a rotational molding process. The material is RF-1001 flame-retardant, high-density polyethylene plastic. The 6.3-mm wall thickness satisfies a high-potential test of 60 kV.

The leak problems, at metal-to-glass seals at the ends of the Nd:glass rods, were eliminated by making a deeper cavity and by using two O-rings, with a Belleville washer between them, at both ends. The Belleville washer maintains a constant pressure on the O-rings.

We redesigned the assembly fixture to facilitate assembly and to provide a leak test before the amplifier is installed on the space frame.

Dye Cell. A newly designed dye cell, with a 50-mm aperture, was installed on the preamplifier table. We took several measures to ensure less than 1" of beam steering. We used windows with no appreciable wedge and separated the windows with three small ($2.0 \times 2.0 \times 1.0$ mm thick) glass spacers

cut from the same blank. The BSC-2 glass windows, each 60.0 mm diam $\times$ 10.0 mm thick, are held in a stainless steel housing by two flanged rings. Three pressure points, 120° apart on each ring, load the windows in compression only at the spacers, thus providing a dye cell cavity with virtually no wedge. Viton O-rings on the outside diameter of the windows seal the unit. The O-rings are uniformly expanded against the cylindrical surface of the window with a pressure ring. A satisfactory seal for the 1,2-dichloroethane solvent is thereby achieved with minimum distortion of the windows. A Twyman-Green interferometer was used to test the final assembly.

Figure 2-47 shows the dye cell mounted in its retractable carriage on the Shiva preamplifier table.

Crowbar Rework. There are 188 crowbar assemblies in the basement of Shiva, beneath the laser space frame. Each crowbar has seven contacts, which are closed and opened by redundant sets of double-acting pneumatic cylinders. The extremely long lines from the one central pneumatic control valve causes staggered closure times of the crowbar contacts.

We are now reworking the pneumatic system along the lines of a system built in July, 1978, for Nova tests. In the Nova system, a dual solenoid, four-way pneumatic valve is closely coupled to its bank of crowbars. In addition, inexpensive quick-dump shuttle valves are installed on each end of every cylinder. Closure time between contacts on different crowbars will be reduced from several seconds to less than 50 ms.

Crowbars made from a more flame-retardant material—pultruded polyester glass rod—are being installed during the rework.

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2.3.3 Computer and Control Systems

Overview of Architecture. We have made major improvements in the control and diagnostics capabilities of the Shiva laser, within the framework of the original control system design (shown in Fig. 2-48). The goal has been to make Shiva operations more efficient.

Laser facility control functions can be subdivided into four major subsystems: power conditioning control, laser alignment control, laser

beam diagnostics, and target diagnostics. Originally, three levels of computers were used:

- Forty-five LSI-11-based front-end processors (FEP's), which are distributed throughout the facility. These processors perform control functions and gather data from the laser and target systems.

- Four PDP-11/34-based central subsystem-control processors, two of which are now fully operational and performing integrated subsystem controls.

- One PDP-11/70-based data-analysis and software-development processor, which is fully utilized.

The PDP-11/34's and the PDP-11/70 run Digital Equipment Corporation's RSX-11M operating system. Further details of the system architecture are discussed in the 1976 and 1977 annual reports.^{27,28}

PDP-11/70. We currently use the Shiva analysis and software-development processor (the PDP-11/70) far more extensively than originally intended. Careful management of the operating system has extended its use to a variety of applications: development and enhancement of FEP's that perform control functions; archiving of laser, target, and control system performance data; prediction of laser and target performance, depending on shot parameters; and analysis of actual laser and target performance. The PDP-11/70 currently supports 54 users on 91 separate accounts, with 15,000 files of information. Since startup, users have signed onto the system some 26,800 times.

There are eight languages available on the PDP-11/70:

FORTRAN (two versions), Basic, Pascal (two versions), PL/1, Macro Assembly, and Indirect Commands. Some of these languages are experimental efforts aimed at finding better controls techniques. Currently, FORTRAN 4 Plus, Macro Assembly, and Indirect Commands are the main operational languages. There are 12 major editing and file-manipulation packages serving a variety of functions, plus the usual variety of task builders, and library routines.

Some commercial base-level data-management packages are on the system (for example, RMS-11, Datatrieve, Scientific Subroutine Package), but they are not widely used. Much of the effort aimed at target data reduction and analysis depends on internally written routines, which access specific data from the available files.

Fig. 2-47. Dye cell in retractable carriage.

Hard-copy graphics (Versaplot) are available, and the system includes several Tektronics terminals. On-line color TV monitors are often used to display predicted and actual laser and target performance, as well as block diagrams of control system operation. A second large disk-storage unit and a quiet terminal room, separate from the machinery area, have recently been added.

Beam Diagnostics Central Data Processing. As an example of the way central control and processing is performed on Shiva, we can discuss the beam diagnostics central data processing system—one of the four major control subsystems.

The Shiva beam diagnostics system uses more than 100 photodiodes and 80 calorimeters to measure laser pulse energy and other parameters. Sensors detect low or abnormal laser amplifier gains and degradation in beam quality. The laser diagnostics system also provides a detailed record of the focusable light hitting the target and the fraction reflected from it—information that is essential for understanding target performance. Sensors are located at the oscillator, throughout the preamplifier and penthouse sections, at various places along the amplifier chains, and at the target chamber.

The function of the control system is to acquire the data from these sensors, keep track of calibration information, archive test and shot data, verify proper sensor ranges and operations, and provide quick-look shot analyses. All of these functions are controlled from the central, easily operated console shown in Fig. 2-49.

The data are acquired and some preprocessing is performed in a set of seven LSI-11-based FEP's, which are connected to the central beam diagnostics PDP-11/34 by fiber optic data links.

Software within the PDP-11/34 is organized as a hierarchical structure of distinct logical functions, each of which is implemented as a program. Six separate programs, or tasks, run concurrently, as shown in Fig. 2-50. This multitask approach, which greatly simplifies the design and programming of the system, is supported by the operating system (RSX-11M).

All tasks are event-driven: their execution is synchronized with the occurrence of specific well-defined events. The arrival of a message from another task is one such synchronizing event (as is the operator making a request, or an FEP supplying some data). A message is an array of data in a

predefined format, where some elements denote the type of message and others denote a string of associated values or message parameters. A message will typically contain an encoded request for specific services to be rendered by the receiving task. The receiver program attempts to perform the service, then informs the requesting task of its success or failure, using a return message. If no return message is received from a requested service within a certain time, the requesting task undertakes recovery procedures.

Calibration and shot data from all sensors are stored in a shared region of the computer memory, where they are available to all tasks. (The shared region is shown schematically at the bottom of Fig. 2-50.) It is structured for easy modification without recompiling all tasks that refer to it.

As operators change the calibration data through the control panel, the affected data set is transmitted to the appropriate FEP. In turn, sensor amplifier over-range and out-of-tolerance indicators, and calculated shot energies, are received from the FEP's and stored in the shared region. This centralized data base facilitates quick-look diagnostics of the laser.

The six tasks that run in the PDP-11/34 are the panel processor, panel command monitor, FEP command monitor, status display generator, SHIVANET message router, and transient digitizer analyzer. These tasks are shown in Fig. 2-50 as round-cornered boxes.

The panel processor periodically receives network messages from an LSI-11-based control panel unit attached to the panel shown in Fig. 2-49. The panel processor decodes the pushbutton and digit-switch settings in the message and enters them into the shared region. Switch settings and actions that require more processing are passed to the panel command monitor. The latest status information is obtained from the shared region and passed back to the control panel unit.

The panel command monitor is the main organizational task of the system. It receives requests of three types from the panel processor: enter data, display data, and shot sequence control. Commands to enter data require the panel command monitor to interpret a set of switch panel information in the shared region. If the command is to change calibration data, the data base in the shared region is modified. In addition, a command to have this updated data transmitted to the appropriate

Fig. 2-49. Central control console for the Shiva beam diagnostics, data acquisition and processing system. The console is connected through a PDP-11/34 to seven front-end processors, which acquire diode and calorimeter data. A color video display, tabular information on terminals, and hardcopy printouts keep the operator informed of beam performance during a shot.

FEP is sent to the FEP command monitor, as shown in Fig. 2-50. Other commands include setting the shot number, defining calorimeter locations, and retrieving archived shot energies and calibrations from disk storage.

Display commands to the panel command monitor include requests for printouts, color status-displays, or storage of shot energies and calibrations. The panel command monitor first sends to the FEP command monitor a request that the appropriate data be obtained from the FEP's. Once the data are received and stored in the shared region, the panel command monitor may display it in tabular form on the console CRT, write it on a printer, or load it onto a disk file for later recall and processing. Within seconds after a shot, operators can have a display of shot energies from all sensor locations. Within minutes, all calibrations and energies from all sensor locations can be printed for

future reference. Data from any shot can be retrieved from disk and reprocessed later.

Shot sequence control includes the startup of data acquisition, various tests and trigger signals, and abort-shot operations. The panel command monitor sends to the FEP command monitor a message requesting that the FEP's be put into the appropriate shot sequence state. An error message is generated by the FEP command monitor if any FEP fails to respond. The operator is notified by the panel command monitor and by the status display generator if the system is not in the correct preshot or postshot state.

All commands between the second-level processor (the PDP-11/34) and the laser diagnostic FEP's are controlled by the FEP command monitor. Whenever it receives a message from another task that is meant for an FEP, it adds data from the shared region that is appropriate to the

Fig. 2-51. An example of a color video display in the central control room, showing the status of all FEP's for the beam diagnostics system.

receiving FEP, then sends the message on to the SHIVANET message routing program. If the message is a command to return data, the return message will contain the data, which is then placed into the shared region. Information regarding any network or FEP communication errors are placed in the light-data area for transmission to the control panel unit for display.

Routing of data messages between the various tasks in the PDP-11/34, as well as to and from the FEP's, is performed by the SHIVANET message routing program, which directs traffic based on information within the messages.

The transient digitizer analyzer communicates with an FEP digitizer controller. The switchout

signal of the oscillator Pockels cell is digitized and retained in the FEP until requested by the analyzer. The analyzer monitors the processor status data in the shared region, waiting for the systems to enter postshot data. Then, the digitized data are requested and stored locally in the analyzer. The data are normalized and plotted on the color video display for immediate viewing. The transient digitizer analyzer must share the video unit with the status display generator, thereby interlocking these two tasks.

The status display generator polls the FEP's every six seconds for vital status information and displays it on a color TV monitor (see Fig. 2-51). The display, which tells the operators how well the

Fig. 2-52. Color block diagram generated by an on-line computer during the alignment of spatial-filter pinholes. Such displays keep operators well informed of system performance.

FEP's are responding, has proved to be an invaluable tool during shot setup.

The beam diagnostics system has operated successfully on laser shots to date and occupies approximately 80% of available memory and disk space.

Color Video Displays. The Shiva control system uses several computer-driven color TV monitors to display continuously updated status information

and color-enhanced analyses of shot-related data. As system status devices, these color displays have several direct benefits:

- **Cost reduction.** There are over 15 major, independent control and data acquisition functions in Shiva. Some of these functions require several types of status information. In the past, this information was often conveyed to the operator by

Fig. 2-54. Plasma discharge display, used on the PDP-11/70. The operator simply points at items on the display that he wishes activated or reviewed. His finger interrupts a pair of light beams from among a matrix of beams in front of the display. This is a display of the CHOP alignment control system, which includes new software written in FORTRAN 4 Plus.

There are 6 color displays in the Shiva central control room.

Plasma Discharge Display. A second, highly interactive display has been operated successfully with the PDP-11/70 development computer. The plasma discharge screen has a bright orange display, with a matrix of light beams just in front of the display screen (Fig. 2-54). An operator can select items from the display for action or for more detailed review simply by pointing.

References

27. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977).
28. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), §2.2.6.

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Fig. 2-55. The ten upper pointing, focusing, and centering (PFC) sensors with attached reflected-beam diagnostics (RBD's). Several incident-beam diagnostic sensors (IBD's) are also visible. These sensors are mounted on top of the target bay space frame.

2.3.4 Alignment Systems

During 1978, the remaining output pointing, focusing, and centering (PFC) sensors and all of the reflected-beam diagnostics (RBD's) were installed and activated. They are now in routine use as described in §2.2.5. Figure 2-55 is a photograph of the upper 10 PFC sensors and attached RBD's, mounted on the target bay space frame.

Following the installation of the final PFC and RBD components, the part of the electro-optics laboratory in which the sensors and gimbals were tested was reorganized. The laboratory is now devoted to maintenance and continued development of the Shiva electro-optic systems. Figure 2-56 shows the current arrangement of the electro-optics lab. The lab includes a simulated Shiva chain, which incorporates an operating spare of each type of gim-

bal and sensor, along with many of the other motor-driven components of Shiva. This simulated chain allows components that have been removed from the system for maintenance to be tested under realistic conditions. It is also used for trying new alignment techniques. For example, software development for automatic pinhole positioning is now in progress, using the motor-driven pinholes in the simulated chain.

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2.3.5 Target Diagnostics

A discussion of Shiva target diagnostics must cover the fielding, maintenance, and operation of the target experiments, the data acquisition systems, and the target chamber systems.

During 1978, we acquired data on target shots spanning three target campaigns: Shiva startup, high-yield, and high-density target survey. The number of diagnostics grew from 6, on the first one-arm target shot of February 3, to 20, on the last shot of December 12. Not all diagnostics were deployed on every shot. Table 2-5 summarizes the characteristics of the 20 types of detectors.

The target chamber (Figs. 2-57 and 2-58) has over 190 ports. As the number of diagnostic instru-

ments increased, we needed an aid to help in port selection and to identify experimental conflicts. Therefore, we devised a target diagnostic data base, which encompasses all target chamber ports (including laser and blast shield ports), the experiment or experiments assigned to each one, the data-recording system parameters for each experiment, and all other equipment mounted on the chamber. We began realizing results of this development late in the year when we were able to predict experimental conflicts and line-of-sight blockages of one or more diagnostics. We also expect to use this data base to establish a link between the data in the recording system data file and each experimenter's data analysis routines.

Table 2-5. Shiva target diagnostics.

Type of experiment	Type of detector	Number of detectors	Type of measurement	Month activated
Neutron				
Yield	Scintillation/PM	6	Time resolved and time integrated	January
TOF	Scintillation/PM	2	Time resolved	January
Yield	Cu activation	2	Counting	April
Yield	Pb activation	1	Counting	October
P_r	CR-39 track	4	Multichannel proton counting	October
Yield	Dioxane activation	1	Counting	December
X ray				
7 shooter	Pin diode	7	Time integrated	January
3 microscope	Film	4	Spatially resolved	March
Zone plate	Film	3	Spatially resolved, multispectral time integrated	April
8 microscope	Film	4	Time integrated	June
Spectrometer	Film	1	Time integrated	June
Streak camera	Film	1	Time resolved	September
Angular high-energy	fluorescence/pin diode	3	Time resolved	November
Pinhole microscope	Film	1	Spatial resolved and time integrated	December

Target Data Acquisition. We have acquired most target data with the target diagnostics data acquisition system, which is described in the 1977 annual report.²⁹ The basic features of the system can be summarized as follows:

- It is a microprocessor-controlled, distributed CAMAC system.
- Single-point grounding is implemented throughout.
- CAMAC serial highway intercrate communications use via fiber optic links.

Master-slave LSI-11 microprocessors run the target acquisition, control, and instrumentation (TACAI) code.³⁰ Operators, interacting with the master processor, control the system. Data are returned to the master from the slave and stored on floppy diskettes. We process these data on the PDP 11/70 and distribute the output to each experimenter and to the shot book.

A variety of detectors, as seen in Table 2-5, provide a wide spectrum of electrical output, which we either integrate or record as time-varying signals. Signals are matched to either high- or low-

impedance integrators, or to slow or fast transient digitizers. The distributed aspect of the system allows us to keep the analog signal paths as short as possible, thus improving response times and reducing noise susceptibility. Induced electrical noise has not been a problem in the recording system. Ground loops do not exist. The absence of these problems can be attributed to single-point grounding, fiber optic communications links, and the practice of isolating detectors and cabling from the target chamber and other points.

The system began with 6 CAMAC crates, 10 transient digitizers, 16 calorimeters, 14 integrator channels, and 1 programmable amplifier. By the end of 1978, it had grown to 7 crates, 17 transient digitizers, 48 calorimeters, 62 integrator channels, and 3 programmable amplifiers. The number of fast oscilloscopes has increased from 8 to 14. Improvements to TACAI software allowed us to progress from version V1.001 to V1.007, with an accompanying improvement in operating performance.

The copper-, lead-, and dioxane-activation neutron detectors are all stand-alone systems. The

Fig. 2-57. Diagnostic instrumentation in the Shiva target chamber.

copper-activation system incorporates a micro-processor-CAMAC counting system, with data output on teletype and floppy diskette. Data from the lead- and dioxane-activation detectors are counted by a pulse-height analyzer, with teletype output. Timing and control signals are provided by the target diagnostic data system.

Eight experiments record data on film or on equivalent media. Zone plate and pinhole x-ray microscope experiments require alignment on target on each shot. We attach these instruments to an x-y-z adjustable shaft, mounted on a special chamber port flange. Preliminary alignment uses a surrogate target, which is mounted on the shaft and positioned in the chamber center using the target viewers. This allows us to determine a position on the shaft that puts the detector at its required distance from the target. Final alignment consists of moving the detector to its required position, viewing it from the opposing port through a telescope that

has been prealigned to the target, then making the necessary adjustments.

We expanded and improved the target data acquisition system in several respects:

- We borrowed 10 transient digitizers from the Nevada Test Site on a long-term loan, to increase our capability of recording fast transients.
- We replaced an old instrumentation system of integrators, sample-and-holds, and an analog-to-digital converter with new LLL-designed programmable charge integrators.
- We calibrated all forty-eight LC-21 and LC-27 calorimeters in place on the target chamber.
- We installed hardware for the Dante, filter fluorescer, and other diagnostics, which were being assembled for the 100X liquid-density target campaign, scheduled for early 1979. We added an additional Shiva target room instrumentation package with cooling, an eighth CAMAC crate, 10 transient digitizers, 48 integrator channels, supporting

Fig. 2-58. Instrumentation on the outside the Shiva target chamber.

hardware, and cabling. A filter fluorescer access platform and extra rack space for Dante instruments were added, and existing detectors on the target chamber were moved to accommodate the Dante experiment.

- We made software improvements, both in the TACAI code and in the process routines used for analyzing the data. Before the changes, incorrectly initialized transient digitizers had caused data to be lost, and incorrectly generated software had produced data errors. We also identified the need for faster digital system response times. By the end of the year, we began testing TACAI version V2. This version includes provisions for operating the filter fluorescer high-voltage power supply.

- We aligned the α -particle time-of-flight spectrometer.

- We gated the main trigger electronics so that triggers occurring more than 7 ms before shot time could not affect the system.

Target Chamber Systems. The design and performance criteria of the target chamber and its vacuum system, the target inserter and positioner, the target viewing system, and the Sentry system were described in the 1977 annual report.³¹ In 1978, we operated these systems, learned their limitations, made improvements where necessary, and established operations criteria. On each shot, we inserted the target, centered it, and aligned the Sentry system and locked it on the target.

Most importantly, we defined the target chamber center to better than 500 μm . By maintaining the center accurately, the alignment of target diagnostics and the alignment of the laser on target

have taken less time. We established the target chamber center by:

1. Stringing wires from orthogonal sets of ports on the chamber equator.

2. Aligning the target viewers to the wire-crossing at the chamber center, thus establishing the viewers as a temporary standard for center definition.

3. Inserting an adjustable-length pylon, with a 5-mm-diam (surrogate target dimensions) sphere on the end, into the chamber from the neutron time-of-flight port, adjusting the pylon length to that defined by the viewers, then tack welding the movable parts in place.

This pylon is now our primary standard for target chamber center definition. A glass microsphere approximately 250 μm in diameter was used as a final target alignment aid. After aligning the viewers with respect to the pylon, the microsphere was positioned at the center of one viewer, while the other was aligned with the target.

Subsequent testing, with the chamber at ambient pressure and with the chamber evacuated, showed that the viewers maintain their mutual alignment. However, chamber evacuation causes a target movement of approximately 125 μm along the axis of the positioner. This positioner movement is reversible and does not constitute a misalignment.

Several instruments protrude into the target chamber beyond the reach of maintenance personnel. Therefore, it is occasionally necessary to enter the chamber. Because of the hazards within the chamber and the limited escape route (one 13-in.-diam port), we developed a safety procedure to minimize the risks.

During 1978, we began work on an auxiliary vacuum system that will provide a means, independent of the target chamber vacuum system, of evacuating the individual diagnostic systems. The system design originated in the LPI group and consists of an auxiliary roughing system, with a high-vacuum module that assures individual high-vacuum pumping on critical experiments.

We installed hardware controls, using CMOS-integrated circuit technology, rather than the standard relay logic. Standard logic and driver boards were designed with on-board jumpering, so that a variety of functions could be implemented. These cards are used for all functions in each subsystem controller. Complete control, interlocking, and permissive features are provided to prevent inadvertent

damage to filters and detectors. Manual override controls are provided at each instrument to allow initial and local system checkout.

The Dante, filter fluorescer, and radio-chemistry diagnostics were scheduled to be the first experiments to use this system, beginning in early 1979.

Other major improvements can be mentioned briefly:

- We modified the blast shield holders so that they would all fit inside the chamber as designed. Cryolite-coated blast shields were first installed in October.

- We modified the lens holders with dowel pins to facilitate the correct mounting of the lenses.

- We redesigned and installed an improved target-insertion ball valve assembly that allows a target to be inserted with the chamber evacuated.

- We modified the target viewers with a locknut to remove slack caused by wear.

- We designed and added shields to the target viewers and to Sentry to prevent bumping and misalignment.

References

29. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), §3.2.5.
30. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL 50021-77 (1978), §3.6.
31. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL 50021-77 (1978), §3.2.2.

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2.4 Nova Development

The technological developments of 1978 ensure that Nova will achieve 300 TW (or kJ) on target; 200 to 300 TW (or kJ) had been promised. This higher laser performance means that the scientific objectives of breakeven and high pellet gain will be achieved at the earliest possible date. The scheduled project completion date and cost remain at July 1984, and \$195 million, respectively.

The past year saw a number of significant developments:

- Three commercial vendors (Hoya, Owens-Illinois, Schott) poured full-sized fluorophosphate laser disks.

- We tested the disks in the energy-efficient, therefore cost-saving, box amplifier.

- Several optical coating techniques with higher damage thresholds were identified.

- By applying a detailed propagation analysis, using the MALAPROP code, we now predict safer performance at high power than had previously been projected.

- We analyzed several 20-beam, larger-aperture laser designs that have significantly better long-pulse performance than the current 40-beam baseline design.

- We implemented, on Argus, Nova-like spatial filtering and beam noise control, which has resulted in extremely clean, high-power beams and little damage.

- Finally, the reliability of Nova is insured by the successful daily operation of Shiva as a complex, many-beam target irradiation facility.

In addition, a number of advances in laser component engineering have occurred:

- We demonstrated the plasma shutter, a 200-ns optical closing gate, which prevents target retropulses from reflecting back into the laser chain.

- The compensated pulsed alternator for cheap and potentially repetitive, electrical energy storage was invented and development begun for Nova at the University of Texas.

- We developed of a higher-density (12.5-kJ) capacitor and tested its expected life.

- We applied thyatron and planar triode switches to drive Pockels cells more reliably.

- We designed and analyzed a more open, accessible space frame.

- CCD detectors, to be applied to beam diagnostics and alignment, were developed.

- We engineered a very reliable Nova-like actively mode-locked and Q-switched laser oscillator, which is now being installed on Argus and Shiva.

- The Title I design of the laser laboratory building, with the horizontal target room configuration, was completed, and the Title II design was begun.

- The conceptual design of the Nova office building was completed, and the Title I design was begun. Construction on both the lab and the office buildings will begin in the first half of 1979.

Finally, in cooperation with the Department of Energy, San Francisco Operations Office, and the Office of Inertial Fusion, and with the relevant LLL offices, we have developed the Nova planning and control system. This system aids in planning costs and schedules and in measuring and controlling project performance. It is based on the project work breakdown structure and is now fully implemented. It has been used to establish the project budget and procurement schedule, based on current cost estimates, and it is used to generate project status reports in the form of tables and graphs.

In summary, several of the advances in solid-state laser technology that we had projected a year ago have now been demonstrated commercially or in our own laboratories. We are anticipating further significant improvements in the areas of optical coatings, electrical energy storage, and large-aperture amplifiers. The Nova buildings have advanced to the engineering design phase, and our project planning and control system has been expanded and computer-implemented.

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2.4.1 Laser System Design

The goal of the Nova design is a laser capable of at least 300 TW for short pulses and 300 kJ for long pulses. The constraints are cost; beam fluence (because of the danger of optics damage); beam intensity (because of nonlinear beam breakup); and the need for isolation to prevent laser oscillations, to protect the target from prepulse illumination, and to protect the laser from target feedback. These constraints determine the design of cost-optimal configurations. The final system will be selected for proper target illumination and for ease of fabrication, implementation, and operation.

The goals and assumptions for the Nova laser design are summarized in Table 2-6. The design is determined primarily by fluence limitations on optical components. Since bare surfaces tolerate a level about 2.3 times greater than the damage threshold of antireflection-coated (AR-coated)

Table 2-6. Nova design guidelines.

Goals: 300 TW for short laser pulses.
 > 300 kJ for long laser pulses.
 200 kJ at 1 ns.

Assumptions: Nonlinear aberration limit equivalent to
 Silva and Argus.
 Average fluence limits at 1 ns.
 Fluence limits scaled with square root
 of laser pulse duration.
 < 11.5 J/cm² on bare surfaces.
 < 5 J/cm² on coated surfaces.
 FWH factor = 0.7.

components, a design evolved that comprises uncoated optics after the amplifier and coated components have sufficient beam expansion. This approach leads to an isofluence amplifier-chain design, with a diameter expansion ratio of about 1.5 between stages.

The average fluence limits of 5 and 11.5 J/cm² at 1 ns, for coated and bare surfaces, respectively,

are scaled with the square root of the pulse duration. In general, we assumed that a damage threshold of twice the fluence limit would provide a safety margin for hot spots in the beam. Recent data show that the damage threshold of present AR coatings does not increase above 1 ns as much as expected from the square root scaling. However, the beam hot spots decrease with increasing pulse duration, which compensates for the lower damage limit (see §2.4.2.). In light of these considerations, the selected fluence limits shown in Table 2-6 are still reasonable design guidelines. In addition, there is some performance contingency in the fill factor of 0.7, because careful apodization and beam-relay design will yield as much as 15% better extraction at the same fluence, or the same extraction at 15% lower fluence.

Nova Laser: Performance, Costs, Options, and Upgrades. The laser chain design in the 1977 annual report consisted of amplifiers with cylindrical pump geometries. The current baseline chain design, shown in Fig. 2-59, is an improvement over this earlier design, because the amplifiers use the more

efficient rectangular (box) pump geometry. Despite the higher efficiency, however, the gain of cost-optimal box amplifiers is somewhat lower than that of the cylindrical (round) pump geometry; thus, more disks are needed to provide the required gain. For this reason, additional 22-cm and 34-cm amplifiers were added to the chain. Figure 2-59 shows both the average beam intensity and the expected noise peak beam intensity along the chain for 1-ns operation.

The performance analysis of this chain is shown for 1-ns pulses in Table 2-7, and the corresponding detailed cost is shown in Table 2-8. This chain design becomes iso-fluient at about 12 J/cm^2 , which corresponds to a laser pulse duration just above 1 ns. The performance of this chain is shown for various pulse durations in Fig. 2-60, for a 40-beam Nova system. This design will easily meet the goals of the Nova project.

An alternative Nova design extends the amplifier chains to include 50-cm amplifiers, as shown in Fig. 2-61, and reduces the number of beams to 20. This design has fewer components, is less costly, and has higher performance than the 40-beam design. However there is some risk using large optical components, and questions remain about the gain of such a large amplifier and about the propagation of a segmented beam. These issues are currently being examined on a 50-cm prototype amplifier and by propagating a segmented beam in the Argus laser. A 34-cm Faraday isolator was added for protection of the chain against target reflection and self-oscillation; however, it may be possible to replace this Faraday isolator with fast pinhole shutters, which are currently being developed.

The component specifications and performance of this alternative design are shown for 1-ns operation in Table 2-9 and the performance for various pulse durations is plotted in Fig. 2-62 for different laser pulse durations. The disks of the 50-cm amplifier are segmented in the design of Fig. 2-62, which will reduce the output of the chain to 11.8 kJ at 1 ns—about 95% of the value shown in Table 2-9.

A significant advantage of the 20-beam design is the availability of the 20-beam Shiva as its driver. This would reduce the cost, as well as the time needed for installation and activation of the Nova system.

Upgrades of the Nova system to several megajoules appear feasible, by extending the amplifier

chains to 75-cm amplifiers and selecting a laser glass with a high energy-storage capability. In addition, frequency doubling and quadrupling, from $1.06 \mu\text{m}$ to $0.53 \mu\text{m}$ to $0.26 \mu\text{m}$, can be achieved at about 15% additional cost to the project. These options, which are listed in Table 2-10, increase the versatility of Nova for laser fusion experiments. A more detailed analysis of these upgrades is underway.

Detailed Design Considerations. For the design of the individual amplifier chains and stages, many variables have been examined in detail. The most important are summarized in Table 2-11. The major conclusions of our analyses are discussed in the following paragraphs.

Laser Material. Fluorophosphate glass was selected for the present Nova design, because it provides better short-pulse performance than do silicate glasses, and reasonable energy storage. We have successfully tested full-sized fluorophosphate disks in a prototype Nova amplifier and are now working with the manufacturers to achieve the required damage threshold under production conditions. Detailed measurements of gain saturation and recovery, and of energy extraction, are underway to verify our design.

Parasitic control in disks by means of appropriate edge cladding is being engineered. Thin, frit-type claddings and thick, monolithic claddings have been applied to fluorophosphate laser glass. The monolithic cladding is preferred because it is more durable.

Controlling parasitic oscillations in large disks is only part of the problem. Even with perfect edge coatings, amplified fluorescence losses will eventually limit the performance of large disks. Segmentation can prevent this loss in stored energy, but it reduces the effective fill factor because of the segmentation voids. Segmentation of disks with the cross section of fluorophosphate glass is, therefore, advisable only for clear apertures greater than 20 cm for short-pulse lasers, and greater than 40 cm for long-pulse lasers. The 50-cm amplifier of the optional Nova chain design will probably be segmented. The issues of segmented beam propagation are being addressed both by experiments on Argus and by simulations using the MALAPROP code.

Amplifier Cavity Design. Features of this design are as follows:

- **Geometry.** The rectangular pump geometry has proved to be twice as efficient as the cylindrical pump geometry used in all previous

Table 2-7. Performance of Nova chain, with box amplifiers, at 1-ns pulse duration (see Fig. 2-59 for schematic of chain design).

ID No.	Item ^a	Aperture, cm	Number reqd.	Thickness, cm	Refractive index		Bank energy, kJ	Gain		Energy, J	B, rad		Fluence, J/cm ²	Cost, \$k
					n	n ₂ , 10 ⁻¹³ cm		Gross	Saturated		Incremental	Total		
0	PA+A						20			88				500
1	SF15	10.0	1	0.8	1.507	1.24	0	0.99	0.99	87	0.03	0.03	1.60	6
2	DISK	10.0	6	2.4	1.426	0.50	120	3.54	2.59	225	0.28	0.30	4.10	53
3	POL	10.0	2	0.8	1.507	1.24	0	0.94	0.94	212	0.10	0.41	4.10	7
4	FR	10.0	1	0.8	1.670	2.10	20	0.98	0.98	208	0.10	0.50	3.85	13
5	POL	10.0	2	0.8	1.507	1.24	0	0.94	0.94	195	0.10	0.60	3.78	7
6	DISK	10.0	6	2.4	1.426	0.50	120	3.54	2.15	419	0.56	1.16	7.63	53
7	SF15	10.0	1	0.8	1.451	0.95	0	0.93	0.93	390	0.10	1.25	7.63	6
									(1.00)	389	1.25)			
8	SF15	16.0	1	1.1	1.507	1.24	0	0.99	0.99	383	0.06	1.32	2.77	3
9	POL	16.0	2	1.1	1.507	1.24	0	0.94	0.94	362	0.10	1.41	2.74	14
10	FR	16.0	1	1.1	1.670	2.10	50	0.98	0.98	355	0.09	1.50	2.57	26
11	POL	16.0	2	1.1	1.507	1.24	0	0.94	0.94	334	0.09	1.59	2.52	14
12	DISK	16.0	4	3.0	1.426	0.50	180	2.55	1.94	648	0.30	1.88	4.60	80
13	DISK	16.0	4	3.0	1.426	0.50	180	2.55	1.71	1106	0.54	2.42	7.86	80
14	SF15	16.0	1	1.1	1.451	0.95	0	0.93	0.93	1029	0.14	2.56	7.86	9
									(1.00)	1026	1.30)			
15	SF15	22.0	1	1.5	1.507	1.24	0	0.99	0.99	1016	0.12	2.68	3.86	10
16	POL	22.0	1	1.5	1.507	1.24	0	0.96	0.96	975	0.09	2.77	3.82	13
17	FR	22.0	1	1.5	1.670	2.10	80	0.98	0.98	956	0.17	2.94	3.66	47
18	POL	22.0	1	1.5	1.507	1.24	0	0.96	0.96	917	0.09	3.03	3.59	13
19	DISK	22.0	3	3.5	1.426	0.50	240	2.08	1.61	1476	0.34	3.37	5.55	108
20	DISK	22.0	3	3.5	1.426	0.50	240	2.08	1.48	2191	0.53	3.89	8.23	108
21	DISK	22.0	3	3.5	1.426	0.50	240	2.08	1.38	3018	0.75	4.64	11.34	108
22	SF15	22.0	1	1.5	1.451	0.95	0	0.93	0.93	2807	0.27	4.91	11.34	12
									(0.98)	2746	2.36)			
23	SF15	34.0	1	2.3	1.507	1.24	0	0.99	0.99	2718	0.20	5.12	4.32	16
24	DISK	34.0	2	4.5	1.426	0.50	360	1.63	1.35	3664	0.33	5.45	5.77	171
25	DISK	34.0	2	4.5	1.426	0.50	360	1.63	1.30	4767	0.44	5.89	7.50	171
26	DISK	34.0	2	4.5	1.426	0.50	360	1.63	1.26	5995	0.56	6.45	9.43	171
27	DISK	34.0	2	4.5	1.426	0.50	360	1.63	1.20	7312	0.69	7.14	11.50	171
28	SF20	34.0	1	2.3	1.451	0.95	0	0.93	0.93	6800	0.42	7.56	11.50	23
									(0.96)	6535	2.65)			
29	FO	50.0	1	15.0	1.507	1.24	0	0.90	0.90	5882	1.40	8.96	4.75	224
									(1.00)	5863	1.40)			
Total							2930		67	5863		8.96		2244

Input energy: 88 J

Pulse duration: 1 ns

Laser wavelength: 1.051 μ m

Emission cross section: 2.57×10^{-20} cm²

Gain recovery time: 2 ns

Effective saturation flux: 4.24 J/cm²

Cost of laser glass: based on ED-2 cost

Large-scale noise: 0.2%

Small-scale noise: 0.02%

Scatter loss per surface: 0.3%

Absorption loss: 0.2%/cm

F₀ factor: 0.7

^aPA = preamplifier, A = alignment, SF = spatial filter, DISK = amplifier disk, POL = polarizer, FR = Faraday rotator, FO = focusing optics.

Table 2-8. Cost breakdown for a Nova chain design shown in Fig. 2-59.

ID No.	Item	Total	Cost, ^b \$ k		
			ME	Optics	EE
0	PA+A	500	80.0	50.0	120.0
1	SF15	6	5.2	1.0	0.0
2	DISK	53	13.3	12.7	27.2
3	POL	7	2.8	4.0	0.0
4	FR	13	6.7	2.4	4.0
5	POL	7	2.8	4.0	0.0
6	DISK	53	13.3	12.7	27.2
7	SF15	6	5.2	1.2	0.0
8	SF15	8	6.2	1.8	0.0
9	POL	14	4.0	10.2	0.0
10	FR	26	7.8	8.4	10.0
11	POL	14	4.0	10.2	0.0
12	DISK	80	17.0	22.0	40.8
13	DISK	80	17.0	22.0	40.8
14	SF15	9	6.2	2.6	0.0
15	SF15	10	7.2	2.9	0.0
16	POL	13	2.9	9.7	0.0
17	FR	47	9.4	21.8	16.0
18	POL	13	2.9	9.7	0.0
19	DISK	108	20.6	33.2	54.4
20	DISK	108	20.6	33.2	54.4
21	DISK	108	20.6	33.2	54.4
22	SF15	12	7.2	5.0	0.0
23	SF15	16	9.3	6.3	0.0
24	DISK	171	27.6	61.9	81.6
25	DISK	171	27.6	61.9	81.6
26	DISK	171	27.6	61.9	81.6
27	DISK	171	27.6	61.9	81.6
28	SF20	23	9.3	14.1	0.0
29	FO	224	45.0	178.8	0.0
Total		2244	457	761	776

Alignment cost: \$250 k/chain

Component length without PA: 61.5 m

Volume of laser glass: 102.9 liters

No. of flashlamps: 184

^aPA = preamplifier, A = alignment, SF = spatial filter, DISK = amplifier disk, POL = polarizer, FR = Faraday rotator, FO = focusing optics.

^bME = mechanical engineering cost, Optics = optical costs, EE = electrical engineering costs.

Nova designs, and in its predecessors, Shiva and Argus. This box amplifier significantly reduces the electrical energy storage requirements. The chain

designs discussed in this section use rectangular pump geometries for the amplifiers. An example of a prototype 34-cm amplifier is shown in Fig. 2-63, and in Fig. 2-64 its performance is compared to that of a cylindrical pump cavity.

● Flashlamps. A nominal 20-kV charge voltage was chosen for previous laser systems to provide self-ionization of the flashlamps, to minimize the number of circuits, and to avoid insulation problems caused by corona discharge.

An important variable is the peak current density in the flashlamps. Fusion lasers require efficient pumping and high gain. However, pump efficiency decreases with increasing current density, because the flashlamps become more opaque and the emitted radiation shifts toward the ultraviolet. Cost-optimal designs balance this loss in efficiency against the need for high gain and hence limit the peak current densities to a relatively narrow range of a few kA/cm² for Nd-glass lasers.

The selection of a charge voltage and current density determines the arc length of the flashlamps for a critically damped pump pulse. On Shiva, this led to a standardization of lamp length at 112 cm and lamp bore at 15 mm. Lamps are used in pairs with 20- to 24-kV banks. These lamps were designed to operate at 20% of the free air explosion limit, but have been run routinely at 25% of the explosion limit, without a significant failure rate. The Nova flashlamps will be designed to operate at the same

Table 2-9. Performance for a Nova 20-beam system, using 50-cm box amplifiers, at 1-ns pulse duration (see Fig. 2-61 for the chain design).

ID No.	Item ^a	Aperture, cm	Number reqd.	Thickness, cm	Refractive index		Bank energy, kJ	Gain		Energy, J	E, rad		Fluence, J/cm ²	Cost, \$k
					n	n ₂ , 10 ⁻¹³ cm		Gross	Saturated		Incremental	Total		
0	PA+A						20			33				500
1	SF15	10.0	1	0.8	1.507	1.24	0	0.99	0.99	33	0.01	0.01	0.60	6
2	DISK	10.0	6	2.4	1.426	0.50	120	3.54	2.96	97	0.11	0.12	1.76	53
3	POL	10.0	2	0.8	1.507	1.24	0	0.94	0.94	91	0.04	0.17	1.76	7
4	FR	10.0	1	0.8	1.670	2.10	20	0.98	0.98	89	0.04	0.21	1.65	13
5	POL	10.0	2	0.8	1.507	1.24	0	0.94	0.94	84	0.04	0.25	1.62	7
6	DISK	10.0	6	2.4	1.426	0.50	120	3.54	2.61	218	0.27	0.52	3.97	53
7	SF15	10.0	1	0.8	1.451	0.95	0	0.93	0.93	203	0.05	0.57	3.97	6
									(1.00)	203	0.57)			
8	SF15	16.0	1	1.1	1.507	1.24	0	0.99	0.99	201	0.03	0.60	1.44	8
9	POL	16.0	2	1.1	1.507	1.24	0	0.94	0.94	189	0.05	0.65	1.43	14
10	FR	16.0	1	1.1	1.670	2.10	50	0.98	0.98	185	0.05	0.70	1.34	26
11	POL	16.0	2	1.1	1.507	1.24	0	0.94	0.94	174	0.05	0.74	1.31	14
12	DISK	16.0	4	3.0	1.426	0.50	180	2.55	2.12	369	0.16	0.90	2.62	80
13	DISK	16.0	4	3.0	1.426	0.50	180	2.55	1.91	705	0.32	1.23	5.01	80
14	SF15	16.0	1	1.1	1.451	0.95	0	0.93	0.93	655	0.09	1.32	5.01	9
									(1.00)	655	0.75)			
15	SF15	22.0	1	1.5	1.507	1.24	0	0.99	0.99	648	0.08	1.39	2.46	10
16	POL	22.0	1	1.5	1.507	1.24	0	0.96	0.96	622	0.06	1.45	2.44	13
17	FR	22.0	1	1.5	1.670	2.10	80	0.98	0.98	610	0.11	1.56	2.34	47
18	POL	22.0	1	1.5	1.507	1.24	0	0.96	0.96	586	0.06	1.61	2.29	13
19	DISK	22.0	3	3.5	1.426	0.50	240	2.08	1.71	1002	0.23	1.84	3.76	100
20	DISK	22.0	3	3.5	1.426	0.50	240	2.08	1.59	1589	0.37	2.21	5.97	100
21	DISK	22.0	3	3.5	1.426	0.50	240	2.08	1.46	2328	0.56	2.77	8.75	100
22	SF15	22.0	1	1.5	1.451	0.95	0	0.93	0.93	2165	0.21	2.98	8.75	12
									(0.99)	2153	1.66)			
23	SF15	34.0	1	2.3	1.507	1.24	0	0.99	0.99	2131	0.16	3.14	3.39	16
24	POL	34.0	1	2.3	1.507	1.24	0	0.96	0.96	2046	0.12	3.26	3.35	29
25	FR	34.0	1	2.3	1.670	2.10	130	0.98	0.98	2005	0.23	3.49	3.22	120
26	POL	34.0	1	2.3	1.507	1.24	0	0.96	0.96	1925	0.12	3.61	3.16	29
27	DISK	34.0	2	4.5	1.426	0.50	360	1.63	1.40	2689	0.24	3.85	4.23	171
28	DISK	34.0	2	4.5	1.426	0.50	360	1.63	1.35	3628	0.33	4.18	5.71	171
29	DISK	34.0	2	4.5	1.426	0.50	360	1.63	1.30	4726	0.44	4.61	7.44	171
30	DISK	34.0	2	4.5	1.426	0.50	360	1.63	1.26	5951	0.56	5.17	9.36	171
31	SF20	34.0	1	2.3	1.451	0.95	0	0.93	0.93	5535	0.34	5.51	9.36	23
									(0.97)	5364	2.53)			
32	SF20	50.0	1	3.4	1.507	1.24	0	0.99	0.99	5310	0.27	5.78	3.90	25
33	DISK	50.0	3	3.5	1.426	0.50	750	2.00	1.54	8186	0.37	6.16	5.96	362
34	DISK	50.0	3	3.5	1.426	0.50	750	2.00	1.44	11751	0.55	6.71	8.55	362
35	DISK	50.0	3	3.5	1.426	0.50	750	2.00	1.34	15795	0.77	7.48	11.49	362
36	SF20	50.0	1	3.4	1.451	0.95	0	0.93	0.93	14689	0.62	8.10	11.49	50
									(0.97)	14181	2.59)			
37	FO	75.0	1	22.5	1.507	1.24	0	0.89	0.88	12551	2.00	10.10	4.59	561
									(0.99)	12413	2.00)			
Total							5310	376		12413		10.10		3919

Table 2-9. (Continued.)

Input energy: 33 J
Pulse duration: 1 ns
Laser wavelength: 1.051 μm
Emission cross section: $2.57 \times 10^{-20} \text{ cm}^2$
Gain recovery time: 2 ns
Effective saturation flux: 4.24 J/cm^2
Cost of laser glass: based on ED-2 win
Large-scale noise: 0.2%
Small-scale noise: 0.02%
Scatter loss per surface: 0.3%
Absorption loss: 0.2%/cm
Fill factor: 0.7

*PA = preamplifier, A = alignment, SF = spatial filter, DISK = amplifier disk, POL = polarizer, FR = Faraday rotator, FO = focusing optics.

25% of the explosion limit and approximately the same voltages and currents. Prototype lamps with 20-mm bores and 2.3-m arc lengths are being tested for possible use in longer amplifier modules containing more amplifier disks. These prototypes use bank modules with high-density capacitors, a somewhat longer electrical pulse, but the same 20- to 24-kV circuit voltage. This configuration

decreases end losses and increases the energy efficiency of the laser for the largest Nova amplifiers.

● Reflectors. The design of the reflector has a significant impact on amplifier performance, both with respect to efficiency and gain uniformity. Elliptical reflectors are most efficient for single-lamp rod cavities; however, the gain is limited in these configurations. For fusion lasers, large disks with many

Fig. 2-61. Alternate Nova chain design for a 20-beam system.

Table 2-10. Configurations and energies of possible Nova upgrades. Energies are given for fundamental, doubled, and quadrupled frequencies.

System	Configuration	Glass material	Long-pulse energy, kJ		
			1.06 μm	0.53 μm	0.26 μm
Nova	40 lamps, 34cm	Fluorophosphate	300	200	100
	20 beams, 50cm		> 300	> 200	> 100
Nova 1500	40 beams, 50cm	Fluorophosphate plus silicate	1500	1000	500
	20 beams, 75cm		> 1500	> 1000	> 500
Nova 3000	40 beams, 75cm	Fluorophosphate plus silicate	3000	> 2000	> 1000

lamps are required. In this case, as discussed in the next paragraph, a parabolic single-cusp reflector for each lamp is most efficient in directing the flashlamp light toward the disks. Many other reflector shapes were tried experimentally, but none exceeded the performance of the single-cusp design. Silver is the most efficient reflector material, though it requires occasional cleaning. Single-cusp silver reflectors are used in the Nova laser design.

● **Pump Cavity Simulations.** The performance of different cavity geometries has been assessed with several ray-tracing codes. Calculations of the angular emission and transmission profiles for different reflector geometries and lamp opacities are illustrated in Fig. 2-65. A single lamp and reflector is first modeled by a reflector-simulation code, without the rest of the pump cavity. An angularly uniform background radiation from the cavity is assumed to determine the amount

of radiation reflected and transmitted by the lamp-reflector assembly. A separate code is then used to model the pump cavity, replacing the individual flashlamps and reflectors with an equivalent, uniform radiating surface in either a cylindrical or rectangular pump-cavity, with radiation profiles determined by the reflector-simulation code. This approach allows separation of variables and individual normalization of the reflector and cavity codes.

The reflector code models the emission profile of the lamp-reflector combination for various assumptions about the emission profile of the lamp

Table 2-11. Major design variables for Nd-glass lasers.

Laser materials
Parasitic control (edge cladding)
Amplified fluorescence control (Segmentation)
Geometry of pump cavity (cylindrical, rectangular)
Operating range of flashlamps
Arc length of flashlamps
Bore diameter of flashlamps
Flashlamp lifetime (reliability)
Reflector shape and materials
Number of lamps per amplifier
Pump pulse duration
Input energy per amplifier
Number of disks per amplifier
Disk thickness
Nd doping
Clear aperture of amplifier
Number of amplifiers per stage
Amplifier chain isolation
Spatial filtering (beam propagation)
Layout, relay imaging (fill factor)

Fig. 2-63. Disks and flashlamp module of 34-cm amplifier with rectangular pump geometry.

and about reemission of absorbed flashlight. The greatest uncertainty is the reemission of absorbed pump light, because few experimental data on the subject are available. Little is known about how much light is reemitted or about its spectral distribution. Other details, such as various radial distributions of the plasma in the flashlamp, reflection losses at the quartz walls, and ray deflection through the quartz tubing, are included in the code, but are generally less important.

From the reflector-code analysis, one expects the single-cusp reflector to provide higher gain, primarily because the effective emission profile has a lobe that points more directly toward the disk than the lobe of the double-cusp reflector (see Fig. 2-65). Experimental results confirmed this conclusion: the single-cusp reflector required about 15% less pump energy to obtain the same gain. The single-cusp reflector is not only more efficient, but also easier to make.

Amplifier Optimization. Several steps in the optimization of an amplifier are shown in Figs. 2-66 through 2-71. These examples are for an amplifier with standard lamps (112-in arc length, 15-mm bore diameter), having a rectangular pump geometry and containing two disks made from LG-810 laser glass. The nominal clear aperture of this amplifier is about 34 cm, depending somewhat on the thickness of the disks.

● **Doping and Pump Duration.** The first step in optimization is to determine the optimum Nd doping and pump-pulse duration for an arbitrary combination of disk thickness, bank energy, and number of lamps. The example shown in Fig. 2-66 is a contour plot (with 5% intervals) of the gain coefficient for the case of 4.5-cm-thick disks pumped by 24 flashlamps at a total input energy of 360 kJ. For this case, the optimum doping is 1.5×10^{20} ions/cm³, and the optimum-pump pulse has a $\sqrt{LC}$ time constant of 250 μ s. Reducing the pump-pulse

duration increases the cavity losses, whereas, for longer pump-pulse durations, fluorescence losses increase. Reducing the Nd doping reduces absorption; increasing the doping promotes fluorescence losses, owing to a quenching of the fluorescence lifetime and to greater face mode losses. (The face mode losses, in turn, are caused by a steeper gain profile through the disks.)

- **Impact of Face Modes.** Face modes can reduce the performance of large disks if the gain along the disk faces overcomes the reflection losses at the edge coating. Figure 2-67 shows a simulation for the same conditions as in Fig. 2-66, with the face mode losses reduced twofold by improved edge coatings. In this case, the optimum doping is about 1.75×10^{20} ions/cm³, while the optimum pump-pulse duration remains the same. Though the optimum doping does not change significantly with better edge coating, the gain coefficient of the amplifier increases—in this case, by about 9%. In other words, while it is important to obtain the best edge coating possible, one can select from a range of Nd dopings and still be near an optimal design, as illustrated in Figs. 2-66 and 2-67, where the 95% contours largely overlap. In a conservative design, one

selects a somewhat lower doping to avoid face modes, whereas, in a more aggressive design, one might opt for a higher doping, in case the edge coatings turn out better than expected.

- **Disk Thickness and Input Energy.** The next step is to repeat the process of determining the optimum doping and pump-pulse duration, for different disk thicknesses and input energies. The results of a series of such determinations appear in Fig. 2-68, which thus displays the cost optimum of energy storage or power capability for the case with 24 lamps. The peak value from the contours shown in Fig. 2-67 appears here as a single point, at 4.5-cm thickness and 360-kJ input energy with 97% of the optimal efficiency.

The optimum disk thicknesses, in this 24-lamp case, are 4.2 and 2.6 cm for long- and short-pulse applications, respectively. The corresponding optimal input energies are 345 and 360 kJ. At lower input energies, gain decreases more rapidly than costs; at higher energies, costs increase more rapidly than amplifier performance.

- **Number of Flashlamps.** The process of determining optimal doping, pump-pulse duration, disk thickness, and input energy is then repeated for different numbers of lamps. Figure 2-69 shows the results for a 12-lamp cavity. The optimum disk thicknesses in this case are 3.6 and 2.2 cm for long- and short-pulse applications, respectively. The corresponding optimal input energies of 190 and 200 kJ are significantly lower than those for the 24-lamp case. This reduction in the optimum input energy is caused not only by reduced pumping efficiency and increased bank cost, but also by a reduction in the flashlamp loading limit to less than 25% of the free air explosion energy. This lower loading limit forces an increase in the pump-pulse duration for increasing input energies, and hence causes larger fluorescence losses. This also explains why the area of optimal conditions for a 12-lamp cavity is much smaller than for a 24-lamp cavity (cf. Figs. 2-68 and 2-69).

- **Optimum 34-cm Amplifier.** Finally, combining the data for various numbers of lamps provides a picture of the full operating regime of a nominal 34-cm disk amplifier with LG-810 laser glass in a rectangular pump geometry, as shown in Fig. 2-70. This contour plot shows large regions of near-optimal conditions, but each point corresponds to a different number of lamps, different Nd

doping, and different pump-pulse duration. Nonetheless, the overlap of the 95% contours for optimal short- and long-pulse applications does allow the choice of a single laser design that is near optimal for both high-power and high-energy applications.

The relative performance of the 34-cm amplifier for various lamp loading limitations is shown in Fig. 2-71. The contour plots are normalized to the peak performance at 30% of the free-air explosion limit. Higher lamp loading is of little practical value, because costs rise faster than performance. As the number of lamps increases, the optimal lamp loading decreases for high-energy lasers, as indicated by the dashed line in Fig. 2-71. If we include the maintenance cost in this analysis, the optimal loadings shift to even lower levels. For a pump cavity with many lamps, there is little incentive to

increase the flashlamp loading much beyond the Shiva operating level.

For a lamp loading limit of 25% of the free-air explosion energy, the optimum number of lamps for this 34-cm amplifier is 18 for high-energy applications and 24 for high-energy and high-power applications. A 24-lamp option was selected for the 34-cm amplifier of the present Nova design, because the gain increases both with lamp count and loading, which reduces the number of disks and components.

Optimization of Amplifier Stages. So far, amplifiers have been optimized alone, without any consideration given to how they fit into an amplifier chain. In essence, the optimization procedure yields cost-optimal amplifiers on a per-disk basis, considering energy storage capability and power

Fig. 2-44. Simulated amplifier performance as a function of doping and pump pulse duration. This simulation is for a 34-cm amplifier with two 43-cm-disk LC-046 disks pumped by 24 lamps in a rectangular pump geometry at 200-kJ input energy. For this case the optimum doping is 1.5×10^{20} ions/cm³ and the optimum pump pulse has a 250- μ s time constant. Contour intervals are 5% of optimal.

Fig. 2-48. Simulated amplifier efficiency as a function of disk thickness and input energy. Simulated amplifier is a 34-cm box with 24 lamps. The single data point, labeled 97%, represents the peak value for the amplifier simulated in Fig. 2-67. The contours in color are for short-pulse applications, those in black are for long-pulse applications. Contour intervals are 5% of optimal.

capability, without worrying about energy extraction. The question then, is, How many of these optimal disks or amplifiers are required to form an amplifier stage for a particular job? The answer de-

pends on the laser pulse duration and on the fluence limitations imposed on the system. But, because the fluence limitations depend also on the pulse duration (because of the damage thresholds of the

Fig. 2-45. Simulated amplifier performance as a function of pump pulse duration and Nd doping. This simulation is for a 34-cm amplifier with two 43-cm-disk LC-046 disks pumped by 24 lamps in a rectangular pump geometry at 200-kJ input energy. For this case the optimum doping is 1.5×10^{20} ions/cm³ and the optimum pump pulse has a 250- μ s time constant. Contour intervals are 5% of optimal.

Fig. 2-49. Simulated amplifier efficiency as a function of disk thickness and input energy, for a 34-cm box with 12 lamps. The contours in color are for short-pulse applications, those in black are for long-pulse applications. The effective input energy is limited by the efficiency and lifetime of the flashlamps. Contour intervals are 5% of optimal.

Fig. 2-70. Composite of optimization results for a 34-cm box amplifier with LG-810 disks. These curves are composites drawn from the data for various numbers of lamps, and each point represents the optimal design (in terms of number of lamps, Nd doping, and pump pulse duration) for the given disk thickness and input energy. Near-optimum conditions for short, also, high-power operation (color) and for long-pulse, high-energy operation (black) exist over a wide range of disk thicknesses and input energies. Contour intervals are 5% of optimal.

Fig. 2-71. Performance of 34-cm box amplifier as a function of number of lamps and lamp loading, normalized to peak performance at lamp loading equal to 30% of free air explosion limit. The dashed line indicates how the number of lamps for optimal power efficiency varies with the loading limit.

Fig. 2-72. Cost effectiveness of extracting energy at 1 ns from 34-cm amplifier stage, as a function of number of flashlamps per amplifier and total number of disks. Output fluence is 11.5 J/cm². The dashed lines show the configurations that produce the indicated saturated gains. The optimal configuration of 9 disks and 12 lamps per amplifier produce a gain of about 2.85.

materials), the pulse duration is the only quantity we need to determine the amplifier stage design.

For Nova, a laser pulse duration of one to a few nanoseconds is desirable, owing to considerations of target irradiation and implosion. This means that Nova is primarily a long-pulse laser, where fluence, instead of nonlinear limitations, dominates.

An example of how the ratio of energy extraction to installation cost varies for different numbers of disks is shown in Fig. 2-72. This example is for a stage consisting of 34-cm disks with an output fluence of 11.5 J/cm², with the laser operating at 1 ns. The contour plot shows that an amplifier stage with 12 lamps per amplifier and 9 disks would be most cost-effective for energy extraction at 1 ns. However, a saturated stage gain of only 2.05 would be available for a simple stage with a spatial filter, but without a Faraday rotator. To match the 34-cm stage to the next, smaller 22-cm driver stage, a saturated gain of 2.4 or more is required. This gain can be obtained for several combinations of total number of disks and number of flashlamps per amplifier, as shown by the corresponding dashed lines in Fig. 2-72. Again, to reduce the number of disks and amplifiers, a four-amplifier option with 2 disks

and 24 lamps per amplifier was selected for the present Nova design. This option is somewhat less cost-effective than a five-amplifier design with 14 lamps per amplifier, but the cost of maintaining fewer amplifiers is less and compensates in part for the loss in capital cost-effectiveness.

Conclusion. The example given here of the optimization of the 34-cm amplifier, starting with the cavity design and considering the performance, cost, configuration, and operation trade-offs, illustrates our design procedure. The sensitivity of the optimum to laser material parameters, component design, and system configuration has given direction to our technological and design developments. The result has been continual performance improvement and simplification of the Nova laser design.

Author

W. F. Hagen

2.4.2 Propagation Considerations

The concepts and consequences of high-power spatial filtering are an integral part of the Nova laser design. Historically, multiple spatial filters (SF's) were first used to control and limit the exponential growth of small-scale irregularities³² initiated by imperfect optical component surfaces and by diffraction. It was then realized³³ that careful spacing of these filters, coupled with a judicious selection of lens focal lengths and low-pass filtering properties, could prove beneficial in many other respects. The resulting complete staging technique, called image relaying,³⁴ was pioneered on the Argus³⁵ laser system at LLL and can be readily scaled to the Nova amplifier chains with their larger apertures.

Image relaying with SF's must accomplish the following:

- Keep the pinholes open for long, high-energy pulses.
- Minimize the near-field spatial modulation peaks to prevent damage.
- Provide a high aperture-filling factor for efficient energy extraction.

The intensity in the wings of the high-power focused beam can be high enough ($>1.0 \times 10^{11}$ W/cm²) to create a high-temperature plasma from the edge material of the pinhole. This plasma expands to fill the pinhole, thus interrupting the beam,

with a characteristic velocity of about 3×10^7 cm/s. The closure mechanism that appears first is refraction of the beam through large angles by underdense regions of the plasma blowoff. (The conditions under which this occurs are discussed in detail in §5.5.) We can avoid this, thus satisfying the first requirement, in one of two ways: (1) by ensuring that the SF's pinhole radii are larger than the product of pulse duration and plasma velocity, or (2) by loading the pinhole below the plasma formation threshold.

To satisfy the second requirement, focal lengths must be chosen so that nonlinearly amplified spatial noise is properly filtered. Finally, spacing between filters must be correct, to minimize diffraction effects and to maintain high spatial filling factors throughout the amplifier, as required for effective image relaying.

Current Strategy. Five SF's are spaced throughout each chain, as shown schematically at the top of Fig. 2-73. The filters provide beam expansion at locations and with magnifications designated by amplifier staging considerations. These considerations lead to two basic constraints, which must be observed in all detailed propagation analysis and design. First, input lenses are subject to the highest fluence levels and are, therefore, most likely to suffer damage. Thus, they are uncoated. Output lenses, where fluence is lessened by magnification, are coated; nevertheless, care must be exercised in filter design to maintain the modulation peak-to-average ratio at a minimum for both lenses. Second, the nonlinear, intensity-dependent growth of small-scale irregularities, modulating the spatial beam profile, must be checked at intervals throughout the amplifier chain. The most severe irregularities grow exponentially with ΔB , a quantity that measures the nonlinear phase retardation that accumulates between successive SF pinholes. Our experience has shown that systems work well when ΔB is less than about 3 rad.

During 1978, we adopted a strategy very similar to that already demonstrated with the Argus laser. We used MALAPROP to estimate pinhole-loading for 1-ns pulses, because, for this pulse duration, ΔB is highest (consequently, near-field modulation is most critical). We chose SF focal lengths for best image relaying so that the lowest spatial noise occurred at the lenses, and we set pinhole radii such that the intensity at their perimeters was less than 10^{11} W/cm². We know

	SF-1	SF-2	SF-3	SF-4	SF-5	
Pinhole diameter, μm (SP-1)	2.0(20)	1.0(32)	1.30(20)	1.30(20)	1.30(20)	(11)
Pinhole axial length, m	1.80	3.20	3.20	4.20	6.24	5.5
Pinhole radius, $^{\circ}\text{mm}$	0.35	0.80	0.70	0.35	1.50	(-)
For 1-ns pulse						
Energy, kJ	0.03	0.27	1.10	2.5	5.5	5.0
ΔE , MeV	—	0.7	1.2	1.9	2.0	1.3
SE, rad	—	0.7	1.9	3.8	5.8	6.1 ^d
Pinhole edge loading, ^a 10^{10} W/cm^2	<10	10	10	10	10	—
For 100-ps pulse						
Energy, kJ	0.001	0.011	0.081	0.215	0.972	0.205
ΔE , MeV	—	0.23	0.72	1.5	3.34	2.81
SE, rad	—	0.23	0.95	2.79	5.03	3.3 ^d
Pinhole edge loading, ^b 10^{10} W/cm^2	—	<10	>10	>10	58	—
For 3-ns pulse						
Energy, kJ	0.18	0.8	2.2	4.2	8.5	7.7
ΔE , MeV	—	0.9	1.0	1.2	1.0	0.7
SE, rad	—	0.9	1.9	3.1	4.1	3.0 ^d
Pinhole edge loading, ^c 10^{10} W/cm^2	—	8	4	1.6	0.78	—

^a Assumed value that the intensity at the pinhole perimeter is 100 GW/cm^2 .

^b Pinhole radius $> v_{\text{group}} \times 1\text{ ns}$ (v_{group} at $300\text{ }\mu\text{m/ns}$).

^c Line width also threshold for plasma formation (100 GW/cm^2).

^d Total expansion phase resolution from the chain at a particular time slice.

Fig. 3-10. Schematic diagram of an X-ray amplifier chain, showing pertinent spatial filter (SF) parameters and laser-edge loading parameters. The "breaks" represent the expanding, long-pulse SF's. Performance parameters are shown for short (100-ps) and long (1-ns) pulse functions.

Fig. 2-74. Cross sections of intensity in the pinhole plane of the focal spatial filter of Argus, for three different pulse durations. For high-power, short pulses (top), the intensity at the pinhole (diameter, 960 μm) is greater than 10^{14} W/cm^2 , but the pulse transmits the pinhole before the plasma can intercept it. For intermediate (middle) and long (bottom) pulses, the intensity at the pinhole perimeter is less than 10^{11} W/cm^2 , below the plasma formation threshold.

Fig. 2-75. (a) Comparison of intensity profiles for Argus and Nova in their final spatial-filter focal planes. Design strategies for pinhole loading are similar in the two cases. (b) Comparison of near-field intensity profiles at the target focusing lenses. See also Table 2-12.

Fig. 3-20. Shear flow across the 1-2-3-4-5-6-7-8-9-10-11-12-13-14-15-16-17-18-19-20-21-22-23-24-25-26-27-28-29-30-31-32-33-34-35-36-37-38-39-40-41-42-43-44-45-46-47-48-49-50-51-52-53-54-55-56-57-58-59-60-61-62-63-64-65-66-67-68-69-70-71-72-73-74-75-76-77-78-79-80-81-82-83-84-85-86-87-88-89-90-91-92-93-94-95-96-97-98-99-100-101-102-103-104-105-106-107-108-109-110-111-112-113-114-115-116-117-118-119-120-121-122-123-124-125-126-127-128-129-130-131-132-133-134-135-136-137-138-139-140-141-142-143-144-145-146-147-148-149-150-151-152-153-154-155-156-157-158-159-160-161-162-163-164-165-166-167-168-169-170-171-172-173-174-175-176-177-178-179-180-181-182-183-184-185-186-187-188-189-190-191-192-193-194-195-196-197-198-199-200-201-202-203-204-205-206-207-208-209-210-211-212-213-214-215-216-217-218-219-220-221-222-223-224-225-226-227-228-229-230-231-232-233-234-235-236-237-238-239-240-241-242-243-244-245-246-247-248-249-250-251-252-253-254-255-256-257-258-259-260-261-262-263-264-265-266-267-268-269-270-271-272-273-274-275-276-277-278-279-280-281-282-283-284-285-286-287-288-289-290-291-292-293-294-295-296-297-298-299-300-301-302-303-304-305-306-307-308-309-310-311-312-313-314-315-316-317-318-319-320-321-322-323-324-325-326-327-328-329-330-331-332-333-334-335-336-337-338-339-340-341-342-343-344-345-346-347-348-349-350-351-352-353-354-355-356-357-358-359-360-361-362-363-364-365-366-367-368-369-370-371-372-373-374-375-376-377-378-379-380-381-382-383-384-385-386-387-388-389-390-391-392-393-394-395-396-397-398-399-400-401-402-403-404-405-406-407-408-409-410-411-412-413-414-415-416-417-418-419-420-421-422-423-424-425-426-427-428-429-430-431-432-433-434-435-436-437-438-439-440-441-442-443-444-445-446-447-448-449-450-451-452-453-454-455-456-457-458-459-460-461-462-463-464-465-466-467-468-469-470-471-472-473-474-475-476-477-478-479-480-481-482-483-484-485-486-487-488-489-490-491-492-493-494-495-496-497-498-499-500-501-502-503-504-505-506-507-508-509-510-511-512-513-514-515-516-517-518-519-520-521-522-523-524-525-526-527-528-529-530-531-532-533-534-535-536-537-538-539-540-541-542-543-544-545-546-547-548-549-550-551-552-553-554-555-556-557-558-559-560-561-562-563-564-565-566-567-568-569-570-571-572-573-574-575-576-577-578-579-580-581-582-583-584-585-586-587-588-589-590-591-592-593-594-595-596-597-598-599-600-601-602-603-604-605-606-607-608-609-610-611-612-613-614-615-616-617-618-619-620-621-622-623-624-625-626-627-628-629-630-631-632-633-634-635-636-637-638-639-640-641-642-643-644-645-646-647-648-649-650-651-652-653-654-655-656-657-658-659-660-661-662-663-664-665-666-667-668-669-670-671-672-673-674-675-676-677-678-679-680-681-682-683-684-685-686-687-688-689-690-691-692-693-694-695-696-697-698-699-700-701-702-703-704-705-706-707-708-709-710-711-712-713-714-715-716-717-718-719-720-721-722-723-724-725-726-727-728-729-730-731-732-733-734-735-736-737-738-739-740-741-742-743-744-745-746-747-748-749-750-751-752-753-754-755-756-757-758-759-760-761-762-763-764-765-766-767-768-769-770-771-772-773-774-775-776-777-778-779-780-781-782-783-784-785-786-787-788-789-790-791-792-793-794-795-796-797-798-799-800-801-802-803-804-805-806-807-808-809-810-811-812-813-814-815-816-817-818-819-820-821-822-823-824-825-826-827-828-829-830-831-832-833-834-835-836-837-838-839-840-841-842-843-844-845-846-847-848-849-850-851-852-853-854-855-856-857-858-859-860-861-862-863-864-865-866-867-868-869-870-871-872-873-874-875-876-877-878-879-880-881-882-883-884-885-886-887-888-889-890-891-892-893-894-895-896-897-898-899-900-901-902-903-904-905-906-907-908-909-910-911-912-913-914-915-916-917-918-919-920-921-922-923-924-925-926-927-928-929-930-931-932-933-934-935-936-937-938-939-940-941-942-943-944-945-946-947-948-949-950-951-952-953-954-955-956-957-958-959-960-961-962-963-964-965-966-967-968-969-970-971-972-973-974-975-976-977-978-979-980-981-982-983-984-985-986-987-988-989-990-991-992-993-994-995-996-997-998-999-1000-1001-1002-1003-1004-1005-1006-1007-1008-1009-1010-1011-1012-1013-1014-1015-1016-1017-1018-1019-1020-1021-1022-1023-1024-1025-1026-1027-1028-1029-1030-1031-1032-1033-1034-1035-1036-1037-10

Table 2-12. Comparison of spatial-filter pinhole parameters for Argus and Nova.

Parameter	Argus	Nova
Laser power, TW	1.8	5.4
Pulse duration, ps	500	1000
B integral, rad	> 6	6
Filter half-angle, μ rad	240	192
Pinhole radius, μ m	480	1700
Edge loading, W/cm ²	10 ¹¹	10 ¹¹
Beam 90% half-angle, μ rad	42	40
Ripple peak/average	1.45	1.48

Filtering Against Noise and Spatial Modulation Growth. Once pinhole diameters are chosen, the entrance focal length determines spatial filtering properties. The focal length of the first filter is selected to balance front-end scattering modulation depth against filter band-edge modulation depth, assuming that the former is comparable to that we have experienced on Argus and Shiva. The remaining focal lengths are chosen to (1) provide acceptance angles small enough to reject characteristic disk-amplifier spatial noise (typical scale length 1 to 3 mm), and (2) maintain net negative effective propagation lengths through the following sections. The focal length of the last SF must be chosen to provide image relaying to the target lenses. The results of a number of code runs, to be described in the next paragraphs, indicate that the best SF strategy for satisfying all of these constraints is the one shown in Fig. 2-73, along with performance and design data.

Note that, for any chosen strategy, ΔB between SF's is always less than 3 rad and that SF acceptance angles are sufficiently small to prevent small-scale beam breakup.

Design Method. MALAPROP³⁶ is a two-dimensional, fast Fourier transform code that can simulate both near- and far-field beam profiles as a pulse traverses a laser amplifier chain. Most importantly for our purposes, it can estimate intensities on SF pinhole perimeters due to spatial noise, beam edge self-focusing,³⁷ and the nonlinear growth of both. In practice, the gain saturation of amplifiers is modeled separately.³⁸ Following a preliminary choice of SF focal lengths (and, thereby, numerical apertures or $f/\#$'s), the code is used to compute the

radius of the second SF pinhole (for a maximum intensity of 10^{11} W/cm²), then the third SF pinhole, and so forth. Near-field modulation depth at the target lens is used to judge the efficacy of the chosen $f/\#$ strategy, then the calculations are repeated for other $f/\#$ strategies. The best of these code runs is illustrated in Fig. 2-76 for the strategy of Fig. 2-73. The peak-to-average ratio does not exceed 2.0 at any lens; and at the target lens it is 1.5. This result strengthens our confidence in the performance projection of Nova.

Results. Peak and average near-field intensity profiles, as simulated by MALAPROP for 100-ps, 3-ns, and 1-ns pulses, at all lenses throughout the baseline amplifier, are shown in Fig. 2-77. Fluence is highest on the coated target lens (for coated optics) and on the fourth SF entrance lens (for uncoated optics). Peak intensities are below projected damage thresholds by a reasonable margin at these locations (Fig. 2-78). As the pulse duration lengthens, nonlinear growth, consequently the peak-to-average ratio, decreases substantially; for pulse durations longer than about 3 ns, beam propagation effects are essentially linear.

In summary, we have defined for the current Nova design an SF image-relaying strategy that appears near-optimal, that will work for Nova pulse durations, and that will fit within the planned building. Further refinements based on this strategy will result in still smoother beams, with a greater safety margin against component damage and with better focusability at the target.

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FIG. 3-15. Peak and average intensities at optical fiber lenses along the fiber chain, for 7.5-TW, 100-ps (a); 2.5-TW, 3-ns (b); and 5.0-TW, 1-ns (c) pulses. The beam evolution is shown schematically along the bottom of the figure.

Fig. 2-76. (a) Peak and average fluence as a function of pulse duration at the highest-density spatial-filter entrance lens. The data points are measured damage thresholds for several bare surfaces. (b) Peak and average fluence at the target focusing lens. Data points are measured damage thresholds for several antireflection surfaces. Present production coatings are inadequate at longer pulse durations, but research coatings are adequate.

2.4.3 Laser System Configuration

The Nova laser chain described in §2.4.1 and §2.4.2 has been configured on the space frame with proper beam relays (Fig. 2-79). Spatial-filter focal lengths and pinhole sizes have been selected, based upon spatial-filtering and pinhole-closure requirements, using the MALAPROP code (§2.4.2). Spacing between spatial filters was selected to properly relay the image of the input apodized (spatially profiled) aperture following the oscillator onto the input lens of each succeeding spatial filter. Each chain is folded at the 16-cm aperture, immediately following the 9.8- to 16-cm spatial filter. Folding mirrors are placed immediately after the spatial filter and before the disk amplifiers, to avoid damage to the mirror coatings because of beam intensity modulations.

Ghost images (back reflections from uncoated spatial-filter input lens) are avoided by designing the input lens to locate the first ghost focus at or near the pinhole of the preceding spatial filter.

The 5-cm-diam beam leaving the master oscillator room is relayed through three beam splitter

stages, until it reaches each of the 40 chains. Five chains are located on each face of the space frame, with the output beams above the space-frame centerline to create sufficient headroom for a corridor under these beams in the laser bay and switchyard.

In the final system configuration, all interstage hardware will be standardized as to diameter and length. End flanges on all components with similar beam diameters will be compatible, so that interconnecting beam tubes can be constructed of a few fixed-length sections and an adjustable-length section. The use of this standardized hardware should reduce both initial costs and maintenance labor.

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2.4.4 Pulse Generation and Driver Subsystems

Initial pulse formation, including temporal and spatial shaping, is performed at the laser front end. The front end must deliver sufficient pulse energy for 0.1- to 10-ns pulses to drive the laser chains.

Because the total system performance depends directly on accurate, repeatable front-end performance, we have emphasized reliability.

An entirely separate class-10,000 cleanroom (less than 10,000 particles/ft² larger than 0.5 μ m) is dedicated to the front end of Nova. This master oscillator room (MOR) is in the basement next to the main control room, under the beam switchyard. The controls for all the functions in the MOR will be separable from the main control room so that maintenance and shot setup can be done independently of the laser chains.

The baseline design of the MOR uses demonstrated technology only, making it a very conservative design with a minimum of technical risk. The oscillators for initial pulse formation are similar to those currently used on Argus and Shiva (see §7.1.2), but with updated electronics to improve interference immunity. Two complete master oscillators will be available to generate the main heating pulse. They can be used independently for different pulse widths or wavelengths, or they can

be synchronized to synthesize more complicated temporal pulse shapes. Additional shaping will be done with coherent pulse-stackers.³⁹

A large net gain, about 10⁵, will be required following the oscillator, to properly drive the amplifier chains for 10-ns pulses. For 0.1-ns pulses, a net gain of only about 10 is needed. The range of gains required to drive the chains over the full range of pulse durations will be provided in the MOR. The gain can be provided by five stages of amplifiers and isolators in a linear array, as in the baseline layout, or by regenerative or multipass amplifiers. Gain variation will be provided by attenuators (rotatable half-wave plates followed by a polarizer), so that amplifiers can always be either off or running at full gain. Fast Pockels cells will be used to control amplified spontaneous emission. They will be used in conjunction with a saturable dye when maximum suppression is required.

A strawman baseline for the MOR is shown in Fig. 2-80. The primary purpose of this layout is to establish the functional requirements and interfaces

Fig. 2-80. Scaled layout of the baseline master oscillator room for Nova. The crosshatched area is a diagnostic pulse system that will not be installed initially.

Table 2-13. Optical components of the Nova master oscillator room.

Component	Clear aperture, cm	Beam diam ^a $e^{-2}/10^{-3}$, cm	Gain	Energy, mJ	Intensity, MW/cm ²
Oscillator	0.5	0.12	—	(0.3)	53
Lens	2.5	0.36	0.99	(0.3)	5.9
Switchout	1.0	0.36	0.30	(0.09)	1.77
Stacker	0.7	0.34	0.01	0.0009	0.002
Amplifier	1.0	0.35	30	0.027	0.056
Isolation	1.0	0.35	0.88	0.024	0.050
Lens	2.5	0.39	0.99	0.024	0.040
Lens	2.5	0.20	0.99	0.023	0.15
Lens	2.5	1.20	0.99	0.023	0.004
Alignment sensor	2.5	1.20	0.90	0.021	0.004
Amplifier	2.3	1.20	50	0.95	0.17
Isolation	2.5	1.20	0.88	0.84	0.15
Apodized aperture	0.27	1.20/0.27	0.063	0.053	0.11
Lens	2.5	0.27	0.99	0.053	0.11
Lens	2.5	1.60	0.99	0.052	0.003
Alignment sensor	2.5	1.60	0.90	0.047	0.003
Amplifier	2.3	1.60	50	2.2	0.14
Attenuator	2.5	1.60	0.28	0.60	0.037
Isolation	2.5	1.60	0.88	0.53	0.032
Amplifier	2.3	1.60	50	24	1.50
Attenuator	2.5	1.60	0.24	5.8	0.36
Isolation	2.5	1.60	0.88	5.1	0.32
Amplifier	2.3	1.60	50	230	14
Lens	2.5	1.60	0.99	230	14
Lens	2.5	0.27	0.99	230	500
Dye cell	2.5	0.27	0.50	115	250
Lens	2.5	0.27	0.99	114	250
Lens	2.5	1.60	0.99	113	7.1
Attenuator	2.5	1.60	0.99	113	7.0
Isolation	2.5	1.60	0.88	100	6.2
Amplifier	2.3	1.60	35	3500	250
Attenuator	2.5	1.60	0.99	3500	220
Isolation	2.5	1.60	0.88	3100	190
Lens	2.5	1.60	0.99	3000	190
Lens	5.2	4.0	0.99	3000	30

^aDiameters at left of column are between e^{-2} intensity point (for Gaussian beam); those at right are between 10^{-3} points (for apodized beam).

of the MOR equipment and to provide a basis for cost and performance comparisons. The oscillators and their control racks are located in the northwest section of the room. They are in one place to simplify interconnections and to allow their ac power and ground to be isolated from the remainder of the room. Space is allocated for a third oscillator and a regenerative pulse compressor (see §7.2.3) to

provide a diagnostic pulse capability. These components are in the crosshatched area and will not be installed initially. Their table space will be used as an assembly and staging area during initial setup of the MOR.

A coherent pulse-stacker for each of the main oscillators is on the central table. Associated with each is an amplifier stage to make up the energy loss

through the stacker. For Gaussian pulses, both the stacker and amplifier stage can be bypassed without changing the propagation distance, and therefore without changing the beam relay optics.

The remaining tables contain the amplifiers, attenuators, spatial filters, and isolators required to reach the requisite drive energy for the splitter array. They are controlled from the racks on the south wall. The beam is turned vertically in the northeast corner of the room; the east-west split is made on the east wall, and the two beams exit through the ceiling into the beam switchyard. Additional features of the MOR layout are as follows:

- **Beam relaying.** The beam is totally relayed⁴⁰ from the flat output mirror of the master oscillator to the input relay plane of the splitter array. The first relay uses long focal length lenses (3.0 and 5.0 m) to avoid the need for a vacuum chamber. The next four relays are evacuated and can be used as spatial filters. These four are identical with a magnification of six and a minimum effective $f/\#$ of 75. The final up-collimator projects the last relay plane to the splitter array input.

- **Automatic alignment.** The beam lines on the three tables after the stacker table are automatically aligned (see §2.4.9), including that of the cw alignment laser.

- **Pulse synchronization system (PSS).** The PSS⁴¹ matches the propagation times from the oscillator to the target for the 40 chains. Its probe beam is injected into the main beam line just before the east-west split and is automatically aligned to the main beam lines. It can be operated independently of and simultaneously with the rest of the MOR.

- **Saturable dye cell.** The beam is demagnified sixfold prior to the dye cell to provide adequate power density to saturate the dye over the full range of desired pulse widths. An amplifier stage and an adjustable attenuator provide the needed gain flexibility after the dye cell.

Table 2-13 lists the optical components for the layout of Fig. 2-80, starting from one of the oscillators. The table includes the clear aperture of each component, the beam diameter in that component (between e^{-2} intensity points where the beam is Gaussian, and 10^{-3} where it is apodized), the gain of

the component, and the energy and power density at its output. The listed energies and power densities are for a 10-ns stacked pulse, assuming a fill factor of 0.7 over the apodized profile.

This MOR layout is a conservative design that satisfies the Nova requirements, based on current technology. It also provides a technical and cost framework against which we can evaluate alternative designs for the Nova front end.

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2.4.5 Optical Components

Laser Glass. While work on Nova optical components has progressed in several areas, the top priority has been in fluorophosphate glass development and the related technologies of edge cladding and optical finishing. In September 1978, the preliminary large-melt program was completed with the delivery from each of three vendors (Hoya, Owens-Illinois, and Schott) of two 34-cm and one 20-cm edge-clad fluorophosphate laser disks (Fig. 2-81). Some additional 20-cm disks were obtained for edge-cladding tests and development. The production of twelve 34-cm Nova preproduction disks in three quality-level phases by each vendor has begun. Table 2-14 shows the quality parameters for each phase, along with a delivery schedule. Figure 2-82 shows how the early production program blends into the full production program.

A program among finishing vendors has been carried out to determine appropriate optical-surfacing techniques for the laser glass. There appear to be no significant problems in optically finishing current fluorophosphate glasses, especially where modern, thermally controlled, continuous polishing machines are used. Flatness and freedom from visual defects (scratches and digs) are reasonably easy to obtain. Concurrently, the LLL optical shop is studying the finishing of

Fig. 2-81. Full size, 34-cm fluorophosphate laser disk, produced and tested for Nova in 1978. The small disk is a Shiva 20-cm disk.

fluorophosphate glass to determine the optimum pitch and slurry compositions for minimizing surface microroughness. The optical shop is also studying ways to decrease costs by developing processes that are completely compatible with the simultaneous finishing of borosilicate and similar, more common glasses.

The next phase of the vendor polishing qualification program will be to finish the 34-cm disks from the preproduction run. In the interim, the vendors will develop polishing methods with the previously produced 34-cm and 20-cm disks.

Preliminary results indicate that microroughness in the range of $20 \text{ \AA}$ (rms) can be achieved with techniques applicable to the finishing of both fluorophosphate and more common glasses. This ensures that common tools and finishing machines can be used to finish our laser glass.

Active Optics. The active components contained in the Nova laser chains are the Faraday isolators, containing FR-5 Faraday rotator glass, and the Pockels cells, containing KD*P crystals.

The largest Faraday rotator has a clear aperture of slightly over 22 cm in diameter and a

Table 2-14. Early production/qualification programs for Nova laser glass. Performance parameters are for 34-cm edge-clad disks.

Phase	Quantity	Delivery date	Quality			
			Damage threshold measured normal to beam with disk at Brewster's angle, J/cm^2	Δn	Loss, cm^{-1}	Edge cladding reflectivity
I	4	Sept., 1979	> 18	$< 3 \times 10^{-6}$	< 0.004	$< 0.4\%$
II	4	Dec., 1979	23	$\pm 2 \times 10^{-6}$	0.002	$< 0.25\%$
III	4	Mar., 1980	30	$\pm 1 \times 10^{-6}$	0.001	$< 0.1\%$

Fig. 2-82. Development and production schedule for Nova laser glass.

thickness of 1.5 cm. This is only slightly larger than the plates procured for Shiva and Argus, and therefore poses no technical difficulties. The material is expensive, however, and has a fairly high nonlinear index. For this reason, some long-range development work has been carried out, aimed at finding materials having a higher figure of merit and a lower cost. As discussed later, cerium-doped CaF_2 is the most promising alternative, because of its projected lower cost.

The Nova laser is designed to use 5-cm-aperture Pockels cells like those used in Shiva. For these cells, the KD*P crystal-growing technology is satisfactorily developed. However, if the practicality of 10-cm-aperture Pockels cells is demonstrated soon enough, the Nova laser will use them. To this end, a program to develop reliable growing processes for larger-aperture KD*P crystals is underway. Reasonable progress has been made in producing optically usable apertures up to about 7.5 cm. New growing-tank configurations are being implemented for the larger sizes, with a second, third, and fourth round of growth expected to start about March 1, April 1, and May 1, 1979, respectively. Each cycle takes about five months. Currently, results of the first modified run are being

analyzed. Concurrently, we are developing a liquid-electrode technology that would result in assemblies using much thinner crystals (see §7.2.7).

Passive Optics. The substrate optical material (generally BK-7) and the optical finishing and coating of the passive optics (lenses, polarizers, beam splitters, and mirrors) are generally very similar to those on Shiva. However, Nova differs in two areas: the flux loading on certain components is greater and the output optics are larger.

The flux loading on the input spatial-filter lenses requires that they be uncoated, whereas the larger output lenses can be used with coatings having damage levels presently achievable in production. The Nova laser could be operated at higher power levels if bare surface and coating damage levels can be improved. As discussed in §7.3.4, some improvements, such as barrier layers on lenses and over high-reflectance coatings, have raised the damage thresholds of lenses and mirrors. We are also pursuing improved dielectric coatings, graded-index coatings, and glassy coatings for Nova, for Argus, and for Shiva. The input lenses are curved so that the second surface essentially collimates the first reflection. This increases the manufacturing difficulty slightly and decreases the alignment

Table 2-15. Major Nova optical components. All sizes are in cm.

Component	Aperture	Diameter	Width	Length	Thickness	Quantity
Laser glass						
Rods		5		40		80
Disks	10		10.8	20.2	2.4	480
	16		17.7	31.2	3.0	320
	22		23.9	42.0	3.5	360
	34		36.4	63.7	4.5	240
Pockels cells	4.8					40
Faraday rotators	10					40
	16					40
	22					40
Thin-film polarizers (on BK-7 at Brewster's angle)	5					160
	10					160
	16					160
	22					80
Input spatial-filter lenses ($\sim f/20$)	5					40
	10					40
	16					40
	22					40
	34					40
Output spatial-filter lenses ($\sim f/20$)	10					40
	16					40
	22					40
	34					40
	50					40
Focus lenses ($\sim f/11$)	50					40
Windows	50					80
Debris shields	50					40
Turning mirrors						
100%	16	28			5	80
100%	50	60			10	40
100%	50	82			15	40
97%	50	83			10	40

tolerance, but it ensures that ghost foci will not damage other components. The output lenses are coma-corrected.

The largest of the optical components in the laser are the output turning mirrors. Of these, the first turning mirror is the most difficult to manufacture, because it is used to transmit about 3% of the beam for diagnostic and alignment purposes. Therefore, it must have good optical characteristics for transmission, as well as reflection. The design of this mirror requires a tradeoff between stiffness (thick) and low cost (thin) of high-quality optical material. The current design is a BK-7 (or equivalent) mirror, 83 cm in diameter and 10 cm thick, weighing 136 kg (300 lb). These mirrors are

used in a nearly vertical position, up to 5° off vertical. It is expected that they will be strap-mounted and uniformly supported around the edge, front, and back, within an adjustable mount.

Summary of Optical Fabrication Requirements. Table 2-15 summarizes the major Nova optical components. The quantities exclude spares and many smaller components, such as those in the master oscillator room, front end, and internal diagnostics packages. The aperture diameters are measured normal to the laser beam.

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2.4.6 Mechanical Subsystems

Mechanical engineering for the Nova laser system focused on overall system design and prototype development. A change in the building configuration has positioned the target room horizontally adjacent to the laser, instead of beneath it. This minimizes radiation effects at alignment and diagnostic sensor locations, and allows room for reasonable sensor geometries. Studies of irradiation geometries, mirror locations, and beam path arrangements have resulted in a baseline configuration design. The following paragraphs describe the space frame and beam line arrangement. Also discussed are the engineering features of a prototype with 34-cm-aperture disk amplifiers and the design of a plasma shutter, located in the final spatial filter to provide chain isolation.

Space Frame. The evolving design of Nova is based on our experience in operating the Shiva system. The Nova baseline design naturally looks different from Shiva in many areas. The laser chains have spatial filters sized and located for optimal relaying, the output beam aperture is larger, and the amplifiers are box shaped and have larger apertures. The front-end driver, splitter, and folding arrays have compact geometries to use space more efficiently. The arrangement for stacking chains on the space frame is optimized to best suit the turning mirrors and the associated diagnostics in the switchyard and target rooms.

The space frame will serve as a stable support for all optical components. As shown in Fig. 2-83, the frame comprises five major units. These units are to be designed and installed in two phases. In-

itially, the target and final mirror frames, half of the switchyard frames, and the entire east laser frame will be installed. The second phase will include additions to the switchyard, the addition to the Shiva frame, and the modification of the Shiva frame. Hardware will first be installed in the new east wing of the laser building. Then, in the west wing, the Shiva system will be modified to incorporate newly developed ideas at minimum cost.

The design criteria for all frame units are the same as they were on Shiva. Thermal and vibration stability are the dominant requirements. Seismic resistance, accessibility, cleanliness, damping, and strict attention to system requirements are secondary, but essential, criteria. Data to be used as design input for the Nova frame design were gathered from the Shiva space frame.

Vibration data were recorded at the space frame foundation, at the top of the frame in two locations, in the air-handling room behind the laser bay, where the fans are located, and on a ground stake behind the Shiva building. Most data at these locations were recorded using three perpendicular quartz accelerometers. So far, 50 records of data have been reduced. The results are compiled as two graphs showing the acceleration spectrum, the integrated displacement spectrum, and the rms displacement (see Fig. 2-84).

Using these measurements as input data, preliminary calculations using SAPIV have shown that the structural cross-room stiffness, as used on the Shiva frame, can be eliminated by making the side walls, which carry the components, wider and stiffer. Eliminating this stiffness will enhance access and will make maintenance easier. Currently, there

Fig. 2-84. Frequency response of the acceleration (a) and displacement (b) data obtained, measured on the top row of the Shiva space frame, perpendicular to beam propagation. The largest displacement amplitudes occur between 2 and 5 Hz, which correspond to peaks in the driving laser spectrum. The rms displacement at this location on the space frame is only 3.04 μm .

are seven cross-room bulkheads. If only the end stiffeners are kept, and the center five removed, the first natural frequency of the frame will be lowered more than threefold, putting it in an undesirable range. Widening the side wall frame and using a combination of diagonals, plates, and extra supports will avoid this consequence and will allow the

new frame, and the extension and modification of Shiva, to be free of these space-limiting cross-room bulkheads.

To make the Nova system symmetrical, as shown in Fig. 2-85, the inside of the north and south Shiva frames must be widened by 30 in. On each laser space frame, the beams are arranged in four

Fig. 2-85. End view of laser space frame, showing five beams (shaded circles), stacked vertically with their drivers, on each face. The equipment is easily accessible from an aisle with no obstructing structure.

vertical rows, five beams to a row (Fig. 2-85). The driver for each beam is either above or below the main beam. There are three service aisles. Vertical spacing between beams is 30 in., enough to accommodate disk amplifiers with 34-cm apertures and spatial filters with 50-cm output apertures.

Two turning mirrors steer each beam to the target. One is in the laser bay at the end of each beam, and the second is in the target room pointing toward the target. These mirrors are connected with beam pipes and are mounted on stable box-like frames, called plenums (Fig. 2-86). The plenums

serve as stiff structural housings for the mirrors and act as beam enclosures. This construction simplifies the crowded condition of crossing beams. Each first turning mirror not only reflects light, but also transmits a diagnostic beam to detectors mounted directly behind it. These mirrors and detector packages are also mounted on or inside plenums. Plenums will have horizontal baffles to control convection currents and will be built of plate steel. Access to mirrors will be provided by removable covers on the plenums. A standard structure, designed for openness and stability, supports the plenums and target chamber.

Beam-Line Components. Work described in §2.4.1 has resulted in a chain design having both optimal aperture sizes and the optimal number of components. Chain optimization also specifies a linear spacing to achieve proper image relaying (see also §2.4.2 and §2.4.3). Forty chains are optimally arranged on the space frame to satisfy all of the operational, geometric, and construction constraints.

The total straight-line length of the chain exceeds the length of the laser bay. This necessitates folding the chains. One driver serves five beams. Each driver beam is split at 5 cm into five beams; then these are folded at 16 cm. These beams are then mounted on the space frame as shown in Fig. 2-85. The major components that make up the laser chain are listed in Table 2-16 and are discussed in the following paragraphs.

● **Disk Amplifiers.** The disk amplifiers currently being used on Shiva are the starting point for the design of the Nova amplifiers, which are more sophisticated than any of their predecessors. Furthermore, the Nova amplifiers will be simpler to manufacture and assemble, and will incorporate improvements to increase gain and lifetime.

The Nova square amplifier design is more efficient than the round Shiva amplifiers, as discussed in §2.2.1. Fewer flashlamps are used and they are placed so that they pump directly into the disk faces. A prototype 34-cm, two-disk amplifier has been constructed and tested (see Figs. 2-63, 2-87, and 2-88).

The large, 34-by-64-cm elliptical disks, weighing 35 kg each, are mounted in stainless-steel holders, which support the disks and shield the edge coating. This subassembly is hung from the sides of a box, which acts as a structural support and sealed enclosure. Clear glass plates can be placed on the

Table 2-16. Major components for the Nova chain. Quantities are totals for 40 beams.

Component	Quantity
10-cm disk amplifier	100
15-cm disk amplifier	40
16-cm disk amplifier	60
20-cm disk amplifier	40
22-cm disk amplifier	60
34-cm disk amplifier	120
5.0-cm rod amplifier	52
<i>f</i> /20 spatial filter, 5 cm × 10 cm	20
<i>f</i> /32 spatial filter, 10 cm × 17 cm	20
<i>f</i> /20 spatial filter, 17 cm × 23 cm	20
<i>f</i> /20 spatial filter, 23 cm × 36 cm	20
<i>f</i> /26 spatial filter, 36 cm × 53 cm	40
<i>f</i> /36 spatial filter, 5 cm × 10 cm	20
<i>f</i> /32 spatial filter, 10 cm × 16 cm	20
<i>f</i> /20 spatial filter, 15 cm × 21 cm	20
<i>f</i> /20 spatial filter, 21 cm × 36 cm	20
10-cm Faraday rotator	20
16-cm Faraday rotator	20
22-cm Faraday rotator	20
5-cm Pockels cell	16
50-cm 1st turning mirror	40
50-cm 2nd turning mirror	40
16-cm folding mirror	80
Total	908

top and bottom of the box as covers to separate the clean disk cavity from the less-clean flashlamp cavity. These covers also help channel gas for good thermal control. Flashlamps, with reflectors, are mounted in metal covers, which are then placed over the glass shields and bolted to flanges on the box. The flashlamps are arranged in a side-by-side, flat geometry, in contrast to the cylindrical geometry of the Shiva amplifiers. Each flashlamp is backed up by a silver-plated, single-cusp reflector, and the inside walls of the box have silver reflectors.

The simple construction of this design, requiring few complex assembly fixtures, has proved to be cost effective and easy to fabricate.

● **Spatial Filters.** Evacuated spatial filters control beam propagation in the laser chains. These

Fig. 2-87. Design of prototype 34-cm, two-disk box amplifier.

lens-pinhole-lens devices (Fig. 2-89) smooth the beam, magnify it between amplifier sections, and relay it through the amplifier chains to the target chamber.

The Nova system will employ five spatial filters in each chain. The bodies will be constructed from sections of 300-series stainless-steel tubing, with a maximum length of 11 ft. On the large filters, the diameter of tubing will decrease near the pinhole.

All the filters will be maintained at 10^{-6} to 10^{-7} Torr with one to four 28-l/s Vac-Ion pumps, depending on the filter size. Ten vacuum pumps will be powered with 5 kV supplied by one 10-station dc power supply.

The aperture ratios of the spatial filters vary from $f/20$ to $f/36$. Because the lengths of the units range up to 2184 cm (71.5 ft), four-point support is required. This makes precise alignment as a unit difficult. Therefore, the spatial-filter assembly will be roughly aligned on the beam axis, and the final adjustments made by moving the lenses. A lens-adjusting mechanism has been designed that will provide lens positioning accuracy of $\pm 2 \mu\text{m}$ over a range of ± 1 cm in the x and y (transverse) and ± 2 cm in the focus direction. A bellows seal allows all adjustments to be made under full vacuum.

The need to choose one of four pinhole sizes requires movable pinholes. The manipulator system provides stepper-motor-driven movement, ± 2.5 cm, in the transverse direction.

The final spatial filter in each chain will contain a plasma shutter (Fig. 2-90). This device ejects a critical density of aluminum plasma across the beam path at the pinhole immediately after the beam pulse passes. The plasma prevents the pulse from reflecting back into the chain.

The plasma shutter incorporates an electrical energy storage system (including switches, a triggering device, and a coaxial conductor) to deliver an electrical pulse through the vacuum pressure barrier to the shutter cartridge. The current design comprises an eight-element capacitor bank in a cylindrical array, mounted on an aluminum structural housing. The aluminum housing forms the coaxial electrical conductor. An array of shutter cartridges is placed around a rotatable circular holding ring. A linear actuator, operating through a vacuum sealing bellows and in cooperation with a pawl and ratchet mechanism, indexes and repositions the holding ring assembly to replace the shutter cartridge after each shot. A spherical-shell plasma catcher collects the plasma jet to prevent plating onto the lenses.

Fig. 2-88. Thirty-four-centimeter, two-disk box amplifier.

The plasma passes across the beam path and enters the aluminum shell, where it condenses. The minute amount of vapor that does escape down the beam path is inhibited by a system of permanent magnet deflectors and deposition surfaces.

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2.4. Power Conditioning

The responsibilities of the pulse power engineering group for the Nova laser system fall into three major categories, as outlined below and discussed in detail in following paragraphs.

- **Flashlamp Power System.** This subsystem includes the flashlamps, capacitor banks, power supplies, switches, and distribution system. It will also include the new compensated pulsed alternator, a possible replacement for much of the capacitor bank (see §7.2.4).

- **Optical Isolation System.** Isolation includes the elements in the Nova chain that minimize amplified spontaneous emission, prevent oscillation within the chain, and protect laser components against damage from target-reflected and opposing-beam light. These elements include Faraday rotators (discussed below), Pockels cells, fast-closing plasma shutters, and fast-rotating shutters. The rotating shutters were first developed in 1975⁴²; work has now restarted on these elements to bring their performance in line with Nova requirements.

- **Pulsed-Power Control System.** The Nova power conditioning control system must reliably perform many process control and diagnostic functions. Reliability is difficult because of the electrical noise produced when the capacitor banks discharge at 20 kV and 400,000 MW. Of necessity, the control interface circuitry is located at points within the pulsed-power system where noise levels are highest. Signal isolation will be achieved by use of a serial fiber optic data bus currently being tested.

The functions of the control system include system status monitoring and data retrieval. Prior to a system shot, diagnostic and testing routines are

carried out to verify that no flashlamps, capacitors, cables, or other pulse-power components are damaged. Further, during the actual bank charge sequence, right up to the final firing time, the control system must alert the operator in the event of a malfunction, thus providing the option of aborting the shot. Finally, after a shot, the control system must organize and display accumulated performance data for postshot engineering evaluation. These requirements will be met on Nova by using a well-isolated, digital-based control system similar to Shiva's.

Staging of Nova Pulsed-Power System. A summary of the Nova pulsed-power system is shown in Tables 2-17 and 2-18, which describe the 40-chain design ending in three 34-cm disk amplifiers. The laser is designed around 20-kV, 30-kJ circuits, whereas the bank is designed around 22-kV, 37.5-kJ circuits to provide an adequate design margin. All of the circuits for the Nova addition are based on 22-kV, 12.5-kJ capacitors, which are placed in 2- or 3-can circuits, depending on the load. These capacitors are discussed in greater detail below.

To use Shiva hardware, the system is designed as a mix of Shiva cylindrical amplifiers and Nova box amplifiers. The new amplifiers use 22-kV, 12.5-kJ capacitors in 25- or 37.5-kJ circuits. The Shiva amplifiers are relocated, but the capacitors, power supplies, and other components are reused.

We plan to use 1-MVA power supplies to charge the majority of the bank. The supplies are basically scaled-up versions of the present 100-kVA supplies used on Shiva. Our standard three-phase voltage-doubler design is impedance-limited against a short circuit, which is appropriate for driving flashlamps. Because costs increase as $(\text{kVA})^{3/4}$, there is a cost advantage in scaling up to larger supplies. In addition, these larger supplies are designed to be located in the substation, outside the main building, thus saving valuable building space.

The front end of the laser (rods and small rotators) will be charged using the standard 100-kVA supply, which is a better match to that load.

Components will be located to avoid the unnecessary complexity experienced on Shiva in the laser bay. Several components will be located outside the laser bay: dummy loads will be in the energy storage area on circuit boards; PLC will be in easily accessible racks near the switches in the bank. The components remaining in the laser bay are simplified junction boxes and their cables. A few

Table 2-17. Specifications for the Nova pulsed-power system in the new laser bay. The system contains all high density capacitors; the charge voltage is 22 kV.

Component	Number		Lamps		Name of circuits		Bank energy, kJ	
	Per arm	Total	Size, in.	Number	Per component	Total	Per circuit	Total
2.5-cm rod	—	7	15	42	1	7	25	175
5.0-cm rod	2	45	15	270	1	45	25	1,125
10-cm FR ^a	1	20	—	—	1	20	25	500
10-cm disk	2	40	44	320	4	160	37.5	6,000
16-cm FR ^a	1	20	—	—	2	40	25	1,000
16-cm disk	2	40	44	480	6	240	37.5	9,000
22-cm FR ^a	1	20	—	—	4	80	25	2,000
22-cm disk	3	60	44	960	8	480	37.5	18,000
34-cm disk	3	60	44	1440	12	720	37.5	27,000
Total				3512		1792		64,800

^aFR = Faraday rotator.

diagnostic interfaces will be required to monitor elements such as shutter positions, but most power conditioning hardware will be in the bank or at the substation.

Flashlamp Power System. The control and distribution of flashlamp drive energy is provided by

the flashlamp power system. The flashlamp capacitor bank is charged from the grid in 60 s, then discharged into the flashlamps in 500 μ s, at 400,000 MW. Although the total energy is large, it is a reasonable extension of our experience on Shiva. Figure 2-91 shows the Nova capacitors and circuits

Table 2-18. Specifications for the Nova pulsed-power system in the Shiva laser bay. This system comprises a mix of high-density and Shiva capacitors, charged from different supplies. The new capacitors are charged to 22 kV; the Shiva capacitors are charged to 20 kV.

Component	Number		Lamps		Name of circuits		Bank energy, kJ	
	Per arm	Total	Size, in.	Number	Per component	Total	Per circuit	Total
5-cm rod	2+splitter	45	15	150	1	45	25	625 Nova, the rest Shiva
10-cm FR ^a	1	20	—	—	1	20	Shiva	Shiva
10-cm disk	2	40	Shiva	Shiva	8	320	Shiva	Shiva
16-cm FR ^a	1	20	—	—	2	40	25	1,000
16-cm disk	1	20	Shiva	Shiva	12	240	Shiva	Shiva
	1	20	44	240	6	120	37.5	4,500
22-cm FR ^a	1	20	—	—	4	80	25	2,000
22-cm disk	1	20	Shiva	Shiva	16	320	Shiva	Shiva
	1	20	44	320	8	160	37.5	6,000
	1	20	44	320	8	160	37.5	6,000
34-cm disk	3	60	44	1440	12	720	37.5	27,000
Total				2470		2225		47,125
						(900 Shiva)		

^aFR = Faraday rotator.

Fig. 2-91. (a) Twenty-five-kilojoule Nova bank circuit comprising two 12.5-kJ, 22-kV capacitors. (b) Original 18-kJ Shiva bank circuit comprising six 3-kJ, 20-kV capacitors. The Nova design saves space and is less expensive.

together with the comparable Shiva components, illustrating the evolution of LLL pulse power technology.

In the process of developing large-bore xenon flashlamps for Shiva and Argus, we have accumulated considerable data on lamp lifetime. The specification, inspection, and testing of these lamps are now standard practice. During 1978, we increased our industrial base by identifying and qualifying two new sources of cerium-doped quartz-lamp envelopes.

Capacitor Banks. The 40-arm Nova system demands 112 MJ from the new bank and 25 MJ from the Shiva bank—a total of 137 MJ of stored energy. The layout of the bank and its grounding satisfies safety requirements and minimizes noise coupling to other subsystems in the laser. The system design, similar to that of Shiva, minimizes damage that might result from either internal bank faults or load faults.

Each flashlamp circuit is driven by a single capacitor-bank module. The module comprises two or three high-density capacitors (12.5 kJ, 22 kV) that provide 25 or 37.5 kJ of energy to the load. The 25-kJ circuits drive the rod amplifiers, which have six 15-in.-long flashlamps in series, and the Faraday rotators. The 37.5-kJ circuits drive the flashlamp circuits in the Nova box amplifiers.

One of the design improvements over the Shiva system is the development of these higher-density capacitors. The 12.5-kJ, 22-kV capacitors have been developed in cooperation with three vendors, using new dielectric systems. A comprehensive test program has been undertaken to qualify this new design and the data have been very encouraging. These high-density capacitors have lifetimes of 300,000 shots and dc lifetimes greater than 2500 h. An oscillatory or fault-pulse life of 500 shots, at 85% reversal, is part of the requirement, thus ensuring heavy-duty construction to tolerate very high current pulses. The cost of these capacitors has been quoted by the vendors at 4¢ per joule (at 1978 prices), in large quantities. This is a 30% improvement over the best Shiva capacitors. High-density capacitors save significant space, because two Nova capacitors replace about eight Shiva capacitors, as shown in Fig. 2-91.

Pulsed-Power Control System. The Nova power conditioning control system architecture is similar to that of Shiva. This similarity takes advantage of hardware designs and computer programs that were

developed for Shiva but are adaptable to Nova. During 1978, a preliminary design for the Nova control system was formulated. It is based on extending the control computer bus throughout the energy storage area and the laser amplifier room. Figure 2-92 depicts how the distributed bus system interconnects more than 400 devices that must be controlled or monitored. Redundancy ensures high reliability and facilitates the activation phase, when redundant components can be applied to simultaneous parallel tasks.

The primary design requirements for noise immunity and voltage isolation have led us to consider using fiber optics. The bandwidth of fiber optic cables is sufficient to allow for serialized transmission of computer bus signals, without introducing significant delays.

Each device that is controlled or monitored by the control system is associated with a device interface that converts bus signals to discrete outputs (electrical or optical) or encodes device parameters into a format for transmission on the serial bus. A set of 10 general purpose, modular control-system elements is being designed that can be assembled in different combinations to form the 400 needed device interfaces. This modular approach concentrates the design and assembly effort to ensure a noise-immune system.

The planned system incorporates programmed event timers within the device interface. Appropriate timing delays are loaded in the device interfaces well before shot time. About 10 ms before a system shot, the control computer will issue a master trigger signal, synchronized with the master oscillator and the rotating ASE shutters. Each timer, once triggered, runs independently while the control computer monitors the operation of the system. The computer does, however, retain ultimate control of the system. It can, in the event of an abort condition, prevent the switchout of the laser pulse and return the energy storage system to the safe condition.

Power Conditioning System Prototype. Before Nova production orders can be issued, designs must be evaluated to ensure noise immunity, fault control, reliability, adequate characterization of failure modes, mechanical form, and cost effectiveness. To achieve these goals, we are building a 1-MJ segment of the Nova bank in a test facility that will test switches, circuits, cables, resistors, and the large power supply controls designed for Nova. The new

designs are being fabricated in small quantities and tested under actual operating conditions. The test-bank hardware will be reusable on the Nova system. The expected cost savings realized by this approach will more than offset the cost of the test bank.

During 1978, we developed components in preparation for the prototype system design. Purchase, fabrication, and activation of the prototype facility are planned for 1979.

The design, development, and testing of the prototype control system elements will take place in several phases:

- Phase A: develop and integrate a fiber optic bus.
- Phase B: upgrade existing control system interfaces.
- Phase C: develop and integrate new device interfaces.
- Phase D: develop and integrate control-room elements of the control system.

Figure 2-93 illustrates phase A, where the high-voltage power supply can be controlled with either Shiva or Nova components. This configuration allows for comparative testing of the new Nova controls and the well-characterized Shiva control elements. Extreme noise conditions can be readily generated using controlled faults (such as replacing a flashlamp with a spark gap).

Phase B includes the implementation of fiber optic interfaces for the safety interlock, ignition trigger, and diagnostic systems. The redundant Shiva interfaces remain and are used for comparative testing. Phase C is the development and testing of new devices and their control interfaces, as shown in Fig. 2-94. The control and display functions needed for each type of device will be installed and tested. Some of these options require dedicated display panels, whereas others can use a shared graphical CRT and keyboard. Phase D will address these needs and will ensure that adequate controls

and status information are available to the operator. Prototype control panels will be developed and tested as part of the overall system.

Reference

42. L. P. Bradley, W. L. Gagnon, and B. M. Carder, "Fast Optical Shutters for Nova, a High-Power Fusion Laser" (UCRL-75699), prepared for the 7th Symposium on Engineering Problems of Fusion Research, Knoxville, Tenn., Oct. 1977.

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2.4.8 Control Systems

System Development. The control systems for Nova, including the power conditioning controls discussed in §2.4.7, will rely on common software and hardware components, which will be developed during 1979 and 1980. By developing these common elements in advance of the various control and data

acquisition systems themselves, we can reduce duplication and produce a well-integrated control system.

To support these early efforts, we have planned a development facility to centralize all system software development and both hardware and software documentation. When the Nova laser is finally operational, the computer will be integrated into the control system as the primary documentation, data analysis, and data base storage system. The development facility will employ a DEC VAX 11-780 computer system, which is compatible with the existing Shiva DEC computers. Delivery and operation are scheduled for the last quarter of FY 1979.

Development of a Control-Oriented Programming Language. As part of the controls systems planning for the Nova facility, the implementation of the Shiva control system was reviewed. This review identified the need for a good control systems programming language. A study of existing control-oriented languages, including industrial and government programming languages and the Department of Defense's planned high-order

language (HOL), concluded that none was adequate. Several, however, could be extended to meet our needs. The most promising candidate was a communications-oriented language (COL) designed by Bolt, Beranek and Newman, Inc. (BBN). We have contracted BBN to implement a compiler for COL that will run on the Shiva computers (PDP-11/70 and VAX). This compiler is due to be installed for use in Nova development in FY 1980.

The COL language is a modern block-structured language with strong type-checking. It is similar to PASCAL. COL will include features to handle shared memory, interlocks, protected data structures, exception handling, and modular compilation of code. It allows close control over computer resources, thus promoting efficient implementation and generating highly optimized codes. The COL language will be the primary programming language for Nova and for upgrades to the current Shiva control system.

2.4.9 Alignment and Beam Diagnostics

Current plans for Nova alignment and beam diagnostics are based on the subsystem structure described in the 1977 annual report.⁴³ Locations of sensors and motor-driven components are shown in Fig. 2-95 for the present baseline design. The specific capabilities of each sensor are indicated by a C for centering, a P for pointing, and a D for diagnostics.

During 1978, we reduced the number of calorimetry stations and further consolidated the diagnostic and alignment tasks. For example, a single sensor behind the first turning mirror at the output of each chain will perform the tasks now done on Shiva by three separate packages, namely, the PFC (pointing, focusing, and centering), IBD (incident-beam diagnostics), and RBD (reflected-beam diagnostics) sensors. It will collect data for chain alignment tasks (such as positioning pinholes and centering the beam in various chain apertures) by looking directly back into the chain. It will perform target-related alignment functions, using reflections from the second turning mirror, an auxiliary mirror, and the first turning mirror, as shown

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Fig. 2-95. A representative Nova chain. The path to the target starts with a single beam leaving the oscillator-preamplifier area. This beam is split into two, one for each of the two laser bays. The figure shows one beam entering the east bay, where it is split into four, then twenty, beams. Centering (C), pointing (P), and diagnostic (D) sensors are indicated by capital letters. Each insertable cross hair reference is designated by an X, and each actuator for moving a gimbal, pinhole, or other component is identified by a dot.

Fig. 2-96. Schematic of a single multifunction sensor, which performs alignment and diagnostic tasks on both the forward-going and the reflected beam with the aid of an auxiliary mirror. Discrimination between incident and reflected beams is achieved by introducing a small angle difference with the auxiliary mirror and by using the insertable shutter. Dots identify actuators.

in Fig. 2-96. Similarly, the multifunction sensor can perform beam diagnostic functions, using both forward and reflected light. Discrimination between incident and reflected light will be achieved by introducing a small angle difference with the auxiliary mirror and by opening and closing a shutter in front of the auxiliary mirror.

Sensor Design. During 1978, we more fully defined requirements for various sensor packages and, in some cases, began optical design to meet these requirements. The 50-cm-aperture alignment and diagnosis sensor is the best example of this work.

To image cross hairs and the beam in any part of the chain, the output alignment and diagnostics sensor requires a large effective focus range, as illustrated in Fig. 2-97. In addition, imaging the full range of spatial-filter pinhole sizes in the baseline chain calls for two different magnifications for far-field imaging. Figure 2-98 shows an optical schematic for meeting these requirements, using an initial $f/2$ down-collimating telescope, followed by a second, slower telescope and two insertable lenses.

Fig. 2-97. Required position of the sensor package and focus lens as a function of the distance to the target. The curves are for the first and second turning mirrors. The curves for the first turning mirror are for the sensor package and focus lens. The curves for the second turning mirror are for the sensor package and focus lens. The curves for the first turning mirror are for the sensor package and focus lens. The curves for the second turning mirror are for the sensor package and focus lens.

Optical configurations for viewing targets of various sizes and for viewing beams over a range of planes offset from best focus require a seventh lens, as shown in the optical schematics of Fig. 2-99.

The schematics of Figs. 2-98 and 2-99 are embodied in the alignment and diagnostic sensor package, shown in Fig. 2-100. The optics, as well as calorimeters, a photodiode, and the video camera, are in the middle level of the package. Components

for diagnostic photography are in the lower level, and the top level is an interchangeable module. This top module can house, for example, a radial-shear interferometer or a streak camera interface for use on selected beams.

Direct Sensing of Beam Positioning in the Target Chamber. We now plan to place a charge-coupled device (CCD) diode array in the target chamber, in place of a spherical surrogate target.

Fig. 2-98. Optical configuration for viewing targets of various sizes and focus over a range of phase offset from best focus. Lenses 3 through 6 are also required for chain alignment (Fig. 2-95.).

Whereas a spherical reflecting surrogate allows one to infer beam position and focus by viewing the reflected light with a sensor outside the chamber, a CCD array is itself a sensor. The CCD array will provide a direct mapping of beam positions and sizes in the target region. (CCD arrays will also be used as primary detectors in many of the alignment and diagnostic sensors, because of their compactness, durability, and wide dynamic range.)

Several factors, in addition to the improved performance of commercially available CCD arrays, make the CCD approach more favorable on Nova than it would have been on Shiva. The baseline Nova focusing lenses are $f/11$ lenses (they were $f/6$ on Shiva), and the targets envisioned for irradiation in Nova experiments are several times larger than those on Shiva. Thus, the $30\text{-}\mu\text{m}$ cell size and 12-mm diagonal dimension of a standard CCD

chip are a near-perfect match to the resolution and range requirements for Nova beam positioning on target. As a backup approach, the output alignment and diagnostic sensor described above will retain the capability of obtaining output pointing and focusing data, using reflections from a spherical surrogate. However, for normal operation, we anticipate the use of a CCD chip.

Reference

43. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), §2.3.5.

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2.4.10 Target System Design

Target Chamber. The Nova target chamber will be designed to contain a scientific feasibility experiment, which will produce a yield of $\leq 5 \times 10^{18}$ 14-MeV neutrons. In addition, x rays, target debris, and alpha particles will be produced. Neutrons deposit little of their energy in the chamber, but the first wall liner must absorb all of the x-ray and debris energy, in addition to the laser light scattered from the target. We anticipate up to 2 MJ of x rays in the 0.1- to 10-keV range and target debris with 100 eV of energy.

The possible effects of the x rays and debris produced by the target include material ablation, early-time shock and late-time thermal degradation of strength, and late-time pressure loading of the chamber. We also had to consider x-ray-induced spall of the fused-silica debris shields that protect the vacuum windows. A spherical vessel of 2-m radius and a first wall of a highly damage-resistant carbon composite satisfy the design requirements. A summary of the effects considered is given in Table 2-19. The dominant source of shock and stress in the chamber is the impulse imparted by x-ray absorption by the inner wall surface.

The chamber material will be aluminum alloy, which was selected after consideration of its cost, its structural properties, and its response to high vacuum and radiation. Attached to the chamber will be a 60-cm-thick water shield, which will reduce neutron activation of the steel space frame and concrete building.

The Nova chamber must contain and support cryogenic targets. To avoid melting frozen DT targets, the pressure in the chamber must not exceed 10^{-6} Torr and should approach 10^{-7} Torr. To achieve this goal, the surface of the vessel must have a low outgassing rate (about 10^{-8} Torr·l/s·cm²), the vacuum ports must be large (30 to 40 cm), and the vacuum pumps must have high capacities (about 10^4 l/s). The main pumping systems will probably consist of cryopumps, turbomolecular pumps, traps, and roughing pumps, similar to the Shiva and Argus vacuum systems.

The design goals for the vacuum and waste disposal system are as follows:

- To attain a base pressure of 5×10^{-7} Torr in a bare chamber.
- To attain a working pressure of 10^{-6} Torr with cryogenic targets.

Table 2-19. Effects of x rays on the first wall of the Nova target chamber.

Effect	Carbon first wall at R = 2 m	Quartz shield at R = 4.5 m
Maximum credible yield (gain = $800; 10^{19}$ n; 6.3-MJ x rays)		
Material removed	2 μ m	0.75 μ m
Stress, kbar	3.5	< 0.1
Spall probability	No	No
10 X maximum credible yield (gain = $800; 10^{20}$ n; 63-MJ x rays)		
Material removed	5 μ m	2 μ m
Stress, kbar	10	5-10
Spall probability	No	Yes

- To pump down from atmospheric pressure to 10^{-5} Torr within 30 min.

- To collect radioactive debris in gaseous, liquid, and solid phases.

- To process waste material for safe disposal.

The target will be irradiated by 40 laser beams from two opposed clusters of 20 beams. A close-packed array of lenses is mounted on each end of the target chamber, as shown in Fig. 2-101. Each lens is remotely adjustable along three axes, over a range of 2 cm and to an accuracy of 5 μ m. Individual motions are computer-controlled to provide speed and flexibility in focusing the 40 beams. The design of target positioners and viewers will be based on Argus and Shiva designs with an added capability for cryogenic targets.

Other irradiation geometries are being considered, particularly an open cone of beams having an included angle of about 80° . With this geometry, greater flexibility in target irradiation techniques is possible.

Target Area Layout. The general arrangement of the laser bays, switchyard, and target room is shown in Fig. 2-102. The laser beams will be routed by turning mirrors to the concrete target room on the north side of the building, which contains the target chamber, second turning mirrors, and support structures. Six-foot-thick walls will provide shielding from the neutron and secondary gamma pulses produced by the targets.

Clean-room conditions will be maintained in the target area, and temperature will be controlled

Fig. 2-101. Nova target chamber design. The chamber will support a room-temperature or cryogenic target at 10^{-6} Torr. The 40 laser beams will be simultaneously focused in two bundles to an accuracy of $5\ \mu\text{m}$, using remotely powered lens positioners and 5.5-m $f/11$ lenses.

to $\pm 0.5^\circ\text{C}$. A bridge crane will be provided for general installation and servicing, but special equipment will be designed for precise or often-repeated operations, such as target insertion.

Because of the radiation pulse expected in the target room at shot time, most electronic components will be in shielded areas in the diagnostics loft or switchyard. Line-of-sight pipes will penetrate the target-room shielding walls. Similarly, all beam diagnostic sensors will be located in the switchyard, where the radiation pulse is low enough for their reliable operation.

Radiological Analysis. Design, construction, and operation of the Nova laser will be conducted to ensure that identifiable hazards are mitigated or eliminated, in accordance with currently accepted safety standards. Pertinent radiation protection standards that will be followed to eliminate risks to

health and safety include those promulgated by the U.S. Department of Energy (DOE) and contained in the DOE Manual Chapters; 10 CFR (Code of Federal Regulations) parts 20, 50, and 100; and radiation protection standards stipulated in the LLL Health and Safety Manual.

Radiation doses to personnel will be kept at a level "as low as reasonably achievable" (commonly abbreviated ALARA) in accordance with DOE and LLL policies on radiation. We have established operating limits on exposure, as shown in Table 2-20. Our analysis indicates that an annual series of 500 maximum credible shots, of 10^{19} neutrons each, will result in maximum exposure levels well below design limits.

The expected exposure from 250 breakeven and 500 scientific feasibility experiments, together with the shielding specifications, are summarized in

Fig. 2-102. Nova target room design. The target room walls will be made of 6-ft-thick concrete, shielding personnel from shots producing up to 10^{20} 14-MeV neutrons.

Table 2-21. (With this shielding configuration, in combination with appropriate target-chamber materials, we can achieve a useful shot rate without excessive cool-down periods.) The radiation dose from skyshine is almost tenfold less than the direct radiation just outside the shielding; it becomes about the same at 50 m and predominates thereafter.

Expected gaseous radioactivity and tritium releases to the environment for Nova operations are presented in Table 2-22. The radiation levels at the site boundary are well within accepted limits.

Pulsed Radiation Effects on Instruments. High-yield Nova experiments will expose diagnostics equipment to neutron and secondary gamma doses large enough to damage components or compromise data. Components susceptible to damage include TV vidicons, CCD's, photographic film, calorimeters, calorimeter amplifiers, and photo-

diodes.⁴⁴⁻⁴⁷ The thin films and glass used in turning mirrors, lenses, and debris shields are also vulnerable. Experiments are being conducted to validate the tactics used to protect the data and components.

The prompt-radiation environment inside the target room (in this calculation, a 100-by-75-by-90-ft room) for a 10^{17} -neutron shot is summarized in

Table 2-20. Radiation exposure limits for Nova operations.

Category	Dose equivalent, mrem/yr	
	Design	Acceptable
Operating personnel	500	5000
Site-boundary personnel	50	500
Offsite average population	17	170

Table 2-21. Calculated prompt-radiation dose equivalents outside the Nova target-room shielding.

	Breakeven experiments	Scientific feasibility experiments
Neutrons per shot	10^{17}	5×10^{18}
Number of shots per year	250	500
Shielding materials:		
Local water shield, m	0	0.6
Target room concrete:		
Wall thickness, m	1.83	1.83
Roof thickness, m	1.22	1.22
Dose equivalents, mrem/yr:		
At nearest site boundary	< 1	< 1
Immediately outside shielding walls (direct plus skyshine)	< 125	175

Fig. 2-103. The calculations assume a 3-cm-thick aluminum-alloy target chamber with no local shielding. The tissue doses are calculated at various vertical distances from the target.

Occasionally, radiation doses are stated in terms of rads silicon. The neutron and photon conversion factors (kermas) calculated for tissue and silicon are presented in Fig. 2-104. Obviously the radiation environment in the target room is sufficiently severe to paralyze any diagnostics sensor that incorporates film or active electronics. To minimize these effects, we explored two options in detail: 1) locally shield the sensors, or 2) isolate the sensors from the target room altogether by partitioning the room into two separate cells.

The radiation environment, in terms of tissue doses, at a potential film-package location within the target room is given in Table 2-23. Reducing the gamma flux to a tolerable level would require a 10-cm-thick lead box around each sensor. Because of the fabrication cost, massive structural supports, and inconvenience of servicing involved in this option, complete isolation appears to be a preferable

solution. The sensors, if removed to the adjacent switchyard room, would be exposed only to the radiation that leaks through the forty 60-cm-diam holes in the wall.

A profile of tissue doses on the axis of a 60-cm-diam hole, near the center of the switchyard room, is shown in Fig. 2-105, for a 10^{19} -neutron shot. The average radiation environment in the switchyard room would be about 0.2 rem per shot. This energy will be deposited in microseconds, because the neutrons are multiscattered and degraded in energy before reaching the components in the switchyard. Therefore, the rate of energy deposition will be about 10^5 rad/s.

This dose rate was simulated in a series of experiments, using a high-intensity flash x-ray machine that produces radiation pulses characteristic of 5-MeV, thick-target, electron bremsstrahlung.^{48,49} The electron bremsstrahlung spectrum has been calculated assuming monoenergetic (5-MeV) electrons incident on a 45-mil (the most common thickness) tantalum converter (anode). Figure 2-106 shows the x-ray spectrum

Table 2-22. Potential doses at the nearest LLL site boundary from release of effluents in Nova operations.

Operation	Type of effluent	Release rate, Ci/yr	Potential dose, mrem/yr
Filling targets with DT	Tritium	< 500	< 1
Nova fusion shots	Induced radioactivity in air	< 100	< 1

Table 2-23. Prompt-radiation dose equivalents at a film-package location 6.6 m from a 5×10^{18} -neutron Nova shot. Shielding shells with and without lead are considered.

Contribution	Dose equivalent, rem	
	Neutron	Gamma
Direct, through:		
3 cm Al + 60 cm H ₂ O + 3 cm Al	1370	108
3 cm Al + 60 cm H ₂ O + 3 cm Al + 5 cm Pb	535	9
Scattered by:		
Air + H ₂ O	419	25
Air	171	3-6
Air + turning mikrons	993	36

transmitted through the 1/2-in.-thick aluminum plate normally used between the converter and the irradiated targets. The mean photon energy is about 1.05 MeV, with a peak intensity at about 350 keV. This is at the low end of the 1- to 5-MeV range expected in the switchyard area, but energy deposition in this range is not a strong function of the energy level.

Exposures range from a few roentgens at 3 m to 50,000 R at the faceplate, as shown in Fig. 2-107.⁴⁸ For silicon, in this energy range, exposure to 1 R results in an absorbed dose of about 0.87 rad. The radiation pulse width is 45 ns (FWHM), as shown in Fig. 2-108; therefore, the exposure of 50,000 R produces a dose rate of approximately 10^{12} rad/s in silicon absorbers. This high exposure rate is available only over a few square centimeters.

rate expected at the sensor location from the largest Nova shot.⁴⁴

Photographic film (Royal-X-Pan), I-Z spectroscopic plates, and high-speed infrared film will be usable in the gamma environment of the switchyard during a shot producing 5×10^{18} neutrons.⁴⁵

Silicon target vidicons (RCA 4532) survived 20 rad with less than 25% of saturation levels.

Recovery was immediate, with only a narrow band of one half frame lost. Because 20 rad is about one hundred times the expected switchyard exposure, we anticipate no problems with these vidicons.⁴⁵

BK-7 glass substrates with dielectric coatings were exposed to the entire series of shots. They were inspected at 14 krad and showed no visual effects. At 400 krad, there was some discoloration, but we expect that these components would be replaced for reasons other than radiation damage long before they accumulated such a large dose.⁴⁵

A calorimeter amplifier for target diagnostics survived exposures of about 40 to 50 krad per shot, with a large transient at the time of the shot, but with complete recovery in a few seconds. At levels to be encountered at the target-chamber wall (5 krad integrated, 10^{11} rad/s), the preamplifier would typically saturate, then return to the proper output with a 1- to 2-s time constant. Because the calorimeter curve is usually reconstructed by extrapolating backward, minimal errors are introduced by the loss of a few seconds of data.⁴⁶

Another calorimeter amplifier, intended for laser beam diagnostics, initially failed at 10 rad, because of a high current in the CMOS circuitry. After we added a current-limiting resistor, exposure to 1500 rad produced no degradation of performance.⁴⁷

A calorimeter designed for laser beam diagnostics showed a 10-mJ energy deposition at 200 rad. This is about the minimum detectable energy for this type of calorimeter. At 1500 rad, the recorded energy was about 0.2 J. This was due primarily to the difference in exposure between the input and reference sensors, which, in turn, was a result of about a 3-cm difference in distance from

Table 2-24. Expected doses and dose rates for Nova components.

Component	Period of operation			Instrument location		Maximum expected dose ^b		Tested survival dose, (γ)	
	During shot	Immediately after shot	Between shots	Target bay	Laser bay ^a	Rate, rad/s	Dose per shot, rad	Rate, rad/s	Dose per shot, rad
CCD camera	X		X		X	2×10^8	0.4	10^{12}	3×10^3
Silicon vidicon	X		X		X	2×10^8	0.4	5×10^8	>20
Photodiode (IBD)	X				X	2×10^8	0.4	1.5×10^9	70
Film	X				X	—	0.4	—	~1
Fiber optics	X				X	—	0.4	—	1.3×10^3
Calorimeter amplifier (laser)		X			X	2×10^8	0.4	3×10^{10}	1.5×10^3
Calorimeter amplifier (target)		X		X		1×10^{12}	5×10^3	10^{12}	5×10^4
Calorimeter	X	X			X	—	5×10^3	—	5×10^4
Focus lens	X		X	X		—	1.5×10^3	—	$>1.4 \times 10^4$
Turning mirror	X		X	X		—	4×10^2	—	$>1.4 \times 10^4$

^aIncluding the switchyard.^bTotal of neutron and γ radiation. The flash x-ray machine produces only γ radiation.

the source. Both the field gradient and the field in the Nova switchyard will be much less than in the experiment, so we consider this effect negligible. In high-field regions, calorimeters will be designed so that the input and reference sensors are equidistant from the source.⁴⁷

Both an EG&G FOD-100 avalanche photodiode and a UDT pin photodiode generated large signals when used in the photovoltaic mode and subjected to a few rads. There was no apparent damage up to 70 rad, which saturated the detectors. These detectors could be used in a compensated configuration to remove background, as long as saturation levels are not reached.⁴⁷

These experiments measured only the effects of x rays. Additional work may be required to establish the vulnerability of Nova electronics to neutrons.

Residual Radioactivity. After a high-yield shot, neutron-induced radioactivity in the target-room air, target-chamber structure, space frame, concrete, optical components, and target materials, as well as the presence of fission products and actinides, would restrict personnel access to the target room until the radioactivity has decayed to a safe level.

Most fission products and actinides, which will be produced only if the target contains uranium, will be removed from the chamber by an automatic

wash-down system, leaving induced radioactivity as the principal source. Induced radioactivity will arise mainly from the target chamber, space frame, and concrete building. Both the aluminum chamber and the concrete walls activate primarily through production of ²⁴Na, which has a half-life of 15 h. Accordingly, every two days of cool-down produces a tenfold reduction in the field. The small residual gamma-radiation tissue doses inside the target room, assuming a 60-cm-thick water shield on the chamber, are shown in Table 2-25.

If we were to surround the chamber with a 5-cm-thick lead shield (weighing about 60 tons), we would significantly reduce the residual gamma level (resulting from the activated target chamber), as shown in Fig. 2-109 and Table 2-25. The fields in the region of the lenses, which cannot be shielded, are not significantly reduced by the lead, but no diagnostics are located in this area.

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Table 2-25. Radiation environment (in rem/h) inside the Nova target room from the radioactivity induced in a 3-cm-thick aluminum vessel by a 5×10^{18} -neutron shot. Dose rates are given with and without a 5-cm lead shield surrounding the vessel. Detector locations are shown in Fig. 2-109.

Detector	Location			After 0 h		After 10 h		After 100 h		After 9000 h	
	x	y	z	No Pb	With Pb	No Pb	With Pb	No Pb	With Pb	No Pb	With Pb
1	0	0	0	3.64 E+02	360	11.0	11.0	0.172	0.170	2.32 E-05	2.29 E-05
2	0	0	400	2.56 E+01	2.42 E+01	0.772	0.729	0.012	0.001	1.54 E-06	1.59 E-06
3	0	0	700	4.42	2.64	0.133	0.080	2.08 E-03	1.25 E-03	2.82 E-07	1.69 E-07
4	300	0	0	9.84	0.187	0.297	5.63 E-03	4.64 E-03	8.81 E-05	6.27 E-07	1.19 E-08
5	400	0	0	4.77	0.158	0.144	4.77 E-03	2.25 E-03	7.46 E-05	3.04 E-07	1.01 E-08
6	700	0	0	0.418	0.030	0.013	9.18 E-04	1.97 E-04	1.44 E-05	2.66 E-08	1.94 E-09

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Author

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2.4.11 Target Diagnostics

Our work on the definition and design of target diagnostics systems for Nova⁵⁰ is that of addressing the requirements to:

- Operate in the hostile environment created by high-yield Nova targets.
- Take advantage of new techniques made possible by the high signal levels expected of Nova targets.

We must meet these requirements in order to:

- Provide laser pulse-target interaction and absorption data at Nova's high density and yield.
- Make detailed comparisons of target performance with design calculations and predictions.

As discussed in §6, we now have high-level diagnostics to spatially and temporally resolve contemporary laser-target experiments. More advanced diagnostics must be designed specifically for Nova. Recent experiments to test the response of various instrument systems to Nova-like radiation environments are described in §2.4.10.

Target diagnostic instruments will be located in a loft on the north side of the Nova target room (see Fig. 2-115 in §2.4.12). The 6-ft-thick wall of the target room will provide the major radiation shielding for the instruments, which will access the target chamber through line-of-sight tubes. Table 2-26 lists various techniques for shielding and isolating the instruments.

Our primary diagnostics will comprise optical, neutron, and x-ray measurements. Optical diagnostics of incident, reflected, and scattered laser light will provide a measure of energy balance, that is, the effectiveness with which the laser pulse

Table 2-26. Various techniques for shielding and isolating target diagnostic instruments.

-
- Graded Z collimation and shielding
 - Low pass x-ray filtering with reflection elements (mirrors, Chevron MCPs)
 - Focusing crystal geometry with focal plane collimation
 - "Thin" detectors (thinned back-illuminated CCD arrays, xerographic film)
 - Distance
-

energy is coupled to a target. Incident and reflected laser-beam diagnostics, together with additional target-area optical instruments, will provide these data.

The concept of neutron imaging was introduced last year.⁵¹ For high-density targets, imaging of the thermonuclear neutrons emitted from the reacting compressed DT fuel provides a direct measure of target performance. Because of the high densities, charged particles generated in the reacting volume do not escape from the target, whereas the highly penetrating 14-MeV neutrons do. Neutron imaging with a neutron pinhole will be possible with the high neutron yields expected.

Figure 2-110 shows the results of simple calculations to find the limits of this technique. The neutron yield required to provide 100-neutrons-per-image resolution element is plotted against target-to-collimator distance for various resolutions (pinhole sizes), assuming:

- A 40- μ m diameter for the compressed fuel region.
- An 80- μ m field of view for the collimator camera.
- A 100-mm-long collimator "pinhole."

The minimum acceptable object distance arises because the field of view in the target plane through the narrow collimator becomes too small at short distances. The curves indicate that, with sufficient magnification to make the detector problem tractable, neutron images with 5- μ m or better source resolution are possible for yields at or above 10^{16} /shot. We are also considering techniques based on multiple or coded apertures that may offer geometrical and operational advantages for 14-MeV neutron source imaging.

We have identified some technical issues associated with the neutron imaging experiment. In a high-yield shot, substantial shielding will be required for an acceptable signal-to-noise ratio.

Fig. 2-110. Usable object distances with various pinhole sizes for a neutron pinhole camera. Resolution in the object plane is given essentially by the pinhole size, because the magnification is large. The "pinhole" is really a collimator (taken to be 10-cm long for these calculations); thus, there is a minimum object distance below which the camera does not have a sufficient field of view in the object plane. The necessary field of view is taken here to be twice the compressed core size. With neutron yields in the 10^{16} to 10^{17} range, about 5- μ m resolution is reasonable.

Manufacturing and testing development will be necessary for the "pinhole," which will be several micrometers in diameter and 100 mm in length, in copper or tungsten. Alignment of the collimator to the source will be difficult, because the diameter is only a few light wavelengths. Finally, the neutron image detector must be developed. Candidate systems include:

- Fluor/fiber optics/gated-image intensifier.
- Fluor/tapered light pipes/photomultipliers.
- Activation techniques.
- Polymer track detectors.

Nova targets will be irradiated with laser pulses ranging in intensity from 10^{12} to 10^{15} W/cm². Consequently, the x-ray photon emission from targets will span the range from sub-keV to several hundred keV, the same range as in current target-irradiation experiments. However, radiation fluxes will be so high that the detectors must be placed farther from the target with sufficient collimation and shielding to allow acquisition of clean signals and to protect the instruments from damage.

We will deploy instruments for making spatially, temporally, and spectrally resolved x-ray measurements. Versions of our Dante diagnostics system (Fig. 2-111) will provide low-energy x-ray spectral data with sub-100-ps time resolution.⁵² For x rays above about 10 keV—at which energy we are unable to use the high-energy cutoff phenomena of critical-angle reflection from a grazing-incidence mirror that is the basis of the Dante system—we use the filter-fluorescer concept (Fig. 2-112) to produce clean, well-defined spectral cuts.^{53,54} Grazing-incidence x-ray microscopes⁵⁵ will continue to be a mainstay for spatial imaging. X-ray streak cameras⁵⁶ and fast diodes will provide high time resolution for temporally resolved measurements. X-ray calorimeters will be used to monitor total x-ray emission.

For the high-energy x-ray measurements with the filter-fluorescer system, the use of the fluorescer allows the detectors (scintillators and phototubes) to be placed out of the direct x-ray and neutron line of sight, and, therefore, to be adequately shielded. For other types of x-ray instrumentation, we envision using a plane grazing-incidence mirror as a disposable first element of the system (Fig. 2-113). In this way, x-rays of interest can be directed toward a well-shielded and protected instrument located out of the direct radial line of sight to the target. The replaceable mirror will sustain the debris and radiation damage. For a 20-MJ yield experiment, the several megajoules of radiative flux and debris make it imperative to use these techniques to ensure survivability of instruments and reliable acquisition of data.

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Fig. 2-111. Schematic of the Dents Diagnostic system and characteristics of several components. The Dents experiment is useful primarily between about 100 eV to several keV. The system components include an L-edge filter, a low-Z mirror (at a critical angle to the optical path), a windowless x-ray diode (XRD), and a fast oscilloscope with a frequency response greater than 1 GHz. The combined response of the filter, mirror, and detector produces a narrow spectral channel with a clean high-energy cutoff.

Fig. 2-112. Schematic of filter-fluorescer diagnostic instrument, which is used to measure x-ray spectra above 10 keV. The combination of a K-edge filter and a K-edge fluorescing foil makes it possible to measure a relatively narrow and well-defined portion of the spectrum of x rays. Because of the high fluxes expected with Nova, we will be able to use fast photodiodes in place of the photomultipliers used on Shiva.

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2.4.12 Buildings

The Nova buildings are an integral part of the total Nova project. They consist of the laser laboratory addition to the existing High Energy Laser Facility (HELFF), Building 391, shown in Fig. 2-2, and the construction of a 55,000-ft² office building for 200 employees, adjacent to and connected with the present Laser Fusion office, Building 381.

The major contracts for construction of Hise conventional facilities are being administered by the San Francisco Operations Office of the DOE. Albert C. Martin and Associates, Los Angeles, Calif., and Kaiser Engineers, Oakland, Calif., are the architect-engineers (A-E) and construction managers, respectively.

During 1978, Title I design of the laboratory building was completed, and Title II design was begun, with construction scheduled to begin in March, 1979. The office building's conceptual design was completed in late 1978. We plan to complete the office building Title I early in 1979 to take

advantage of cost savings from the concurrent construction of both facilities.

Laboratory Addition. The Nova laboratory will be an addition to the existing 66,000-ft² HELFF, which now houses the Shiva laser system. The new laboratory will add approximately 115,000 ft² to the structure. Table 2-27 shows the distribution of the extra space. The various programmed experimental

Table 2-27. Space distribution of Nova laboratory addition.

Area	Gross area, ft ²
Target room	5,000
Laser bay	12,800
Optical switchyard	6,300
Master oscillator room	1,700
Energy storage	25,300
Control room	4,500
Diagnostics area	3,300
Support laboratories	19,500
Target fabrication	4,100
Target staging area	3,500
Building services	22,900
Total	108,900

Fig. 2-115. Cross section, looking west, of the proposed Nova laboratory.

and service areas are shown in Figs. 2-114 and 2-115. Detailed descriptions of those areas that were significantly modified or formed during the past year are presented. Reference 57 previously described the building.

- **Target Room.** The Nova target room will be built to the north and east of the existing Shiva target room. The new target room will be 50 ft wide by 100 ft long (east-west direction), with 64 ft of clearance under a 20-ton bridge crane. Its floor will be 20 ft lower than that of the laser and optical switchyard. The room has space for the target chamber, chamber shielding jacket, final turning mirrors, and support equipment for planned high-flux target experiments. Because the room must be a third-level radiation containment vessel, all openings will be sealable and contain sufficient shielding traps to reduce neutron loss. Construction is entirely of reinforced concrete, 6 ft thick at walls between the target chamber and any area occupied during experiments. The roof is 4 ft thick as is the mat floor, which is the foundation for the target room.

The air-handling system, which maintains the room as a Class 10,000 clean room with a controlled temperature of $74 \pm 1/2^\circ\text{F}$, is inside the target

room complex for containment. It is shielded to reduce the radiation exposure of the mechanical equipment to levels that will allow routine maintenance without hazard.

- **Control and Diagnostics.** The 4500-ft² control room has been relocated to the lower floor level from the first floor, and the south diagnostic loft shown in previous floor plans has been eliminated. Control room facilities can be divided into "Q"-cleared control and computer areas and similar areas with "P" access. The diagnostic loft area is located to the north of the target room, as previously described.⁵⁷

- **Target Fabrication.** Laboratories for the production of Nova targets are located below the laser switchyard adjacent to the target room. Targets with significant quantities of tritium will be prepared in a separate tritium target production facility (TTPF).

- **Optical Switchyard.** This Class 10,000 clean room area will be 106 ft long by 59 ft wide. It will serve as a laser diagnostics area and beam switchyard to direct laser beams from the east and west laser bays into the target room. Its floor will be structurally isolated from the rest of the building, minimizing the vibrations transmitted from the

Fig. 2-116. Proposed Nova office building.

mechanical equipment. The space frame for supporting turning-mirror and optical diagnostics will rest on columns from the basement floor. Like the laser bay, the optical switchyard can be upgraded to a Class 1000 clean room area by improving administrative control. Temperature will be maintained at $74 \pm 1/2^\circ\text{F}$. Air supply ducting is to be contained above a suspended ceiling that will have flush lighting and HEPA filters, distributed to provide a uniform high-velocity, vertical-laminar-flow environment.

A pair of 5-ton radio-remote-controlled bridge cranes will be installed. Large doors at the east end will permit large components to enter the laser bay without compromising temperature, cleanliness, or security. Surface finishes in the optical switchyard will minimize dust and dirt retention.

- **Building Services.** Mechanical and electrical support equipment will be in several locations to service the special requirements of the various laboratory areas. Since the last report,⁵⁷ we

relocated mechanical equipment on the mezzanine that supports the optical switchyard, and the laboratories south of the switchyard to maintain acceptable vibration and acoustic isolation of the switchyard space frame.

Office Building. Conceptual design of the Nova office building (Fig. 2-116) was completed during 1978. The building will provide a high-quality working environment with effective and convenient communication and traffic flow, both internally and to the other facilities within the laser program complex. The design incorporates a strong architectural and functional link with the existing office building by use of a connecting "Q"-cleared passageway at the second-story level.

Functional organization was the major element considered in the selection of this design. The interior plan (Fig. 2-117) combines the support functions into a central core area. The first level contains:

- The main entrance lobby.

Fig. 2-117. Plan views of the second floor (top) and first floor (bottom) of the proposed Nova office building.

- A 180-seat briefing room that is convertible for “controlled” (red-badge) or “limited” (green-badge) classified meetings.

- Several “controlled” offices.

- A small conference room.

Dual CAIN booths will be placed in the entrance lobby and on the east side of the building. The second level of the central core has two large

conference rooms as well as an area for mechanical and electrical equipment. A two-story open courtyard, which is centrally located adjacent to the briefing room and stairs, will be a convenient place for informal discussions. Conference rooms, drafting areas, and computer terminal areas have been dispersed to provide local accessibility and improved communications. Building-service and

Table 2-28. Estimated construction costs, including site improvements and utilities.

Item	Cost, \$
Laboratory addition, 115,000 ft ²	21,436,000
Office building, 55,000 ft ²	4,650,000
Target room conversion	520,000
Engineering, design, and inspection	2,861,000
Standard equipment	665,000
Total	30,132,000

equipment-receiving areas have been addressed to provide access and ease of maintenance.

Energy conservation, security, and acoustic isolation were considered throughout the design process. Current proposals include the use of waste heat from the Nova laboratory complex to heat the office areas, and the use of bronze reflecting glass to conserve energy and maintain a strong architectural tie with Building 381.

Cost and Construction Schedule. The A-E have prepared current cost estimates (Table 2-28) for the Building 391 addition as part of the building Title II submission. Estimates for the Nova office building, which are based on preliminary Title I design, were developed from site preparation costs and construction costs of comparable office buildings. As reported previously, construction of the laboratory and office building will use fast-track (phased) techniques to reduce the overall construction period and cost.

Reference

57. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978).

Author

R. Foley

2.4.13 Project Planning and Control System

The Nova project planning and control (PPC) system has these major objectives:

- Ensure the development of accurate and optimum cost and schedule baseline plans.
- Have project-oriented controls that highlight cost and schedule deviations.

- Provide a consistent accounting system that satisfies the requirements of the project office, LLL, and DOE.

- Have a visible cost-control structure at all levels of the work breakdown structure (WBS) by using graphic reports.

- Provide computer automation to rapidly update cost and schedule changes.

We achieved these objectives by developing a computer-based PPC system that uses the special computer graphics capabilities available at LLL. We worked closely with the DOE San Francisco office to develop and refine the format of graphic reports that show cost and schedule performance against established project baselines. To ensure accurate baseline estimates, an estimating procedure and manual⁵⁸ specific to the Nova project was developed.

The Nova PPC system, which is consistent with the LLL accounting system, is designed within the framework of the Nova WBS shown in Figure 2-118. A single prime account, 7520, was established for Nova, and subaccounts were assigned as shown; for example, subaccount 32 is used for level-3 costs associated with the target chamber. Nova extends the LLL accounting system to levels 4 and 5 for procurements by assigning a Nova control number to all purchase orders. Procurement baselines are established at level 4 or 5, and procurements are tracked at level 5 by noting deviations from estimated amounts.

We established formal procedures to ensure that baseline cost estimates are accurate. The *Nova Project Cost Estimating Manual*⁵⁸ was prepared by a consultant for use by the level 2 lead engineers and by the Project Office administrative staff. The consultant conducted training sessions to explain the use of various cost estimating techniques. Standard forms for collecting cost and schedule estimates were designed to interface with computer programs that analyze the data.

We developed automated procedures to analyze the cost estimates and establish project budgets and baselines to level 3 of the WBS. These procedures:

- Apply learning (a quantity-based price adjustment) where applicable to the procurement estimates.
- Calculate labor costs.
- Apply the appropriate inflation-related escalation to all estimates. After each estimating and

Fig. 2-118. Nova work breakdown structure, down to level 3. Project costs are planned, tracked, and summarized using the cost account codes shown for each Nova cost center.

2/14/79 baseline	173.645
Estimate at completion	173.653
Variance over(•) under (+)	-0.008
Contingency	21.355
Total est at completion	195.000

Level 0, total project
January, 1979

Fig. 2-119. Scheduled commitment of project funds. This schedule serves as a baseline, and performance is measured against it. The estimated commitment of funds totals \$173.6 million. Figures are included for budgeted commitments for work scheduled (BCMWS), budgeted commitments for work performed (BCMWP), and actual commitments for work performed (ACMWP). The schedule variance (BCMWP-BCMWS) shows whether funds are being committed at the rate planned. The cost variance (BCMWP-ACMWP) shows the difference between actual and planned costs for the work actually done.

pricing cycle, budget review sessions are conducted by the Nova project manager with the lead engineers to determine where budget adjustments are needed to achieve the highest laser performance, to stay within budget, and to prepare for effective

operation of the completed facility. The automated procedures include the generation of a time-phased obligation plan, which is consistent with the schedule of expected funding and probable contingency expenditures. Time-phased performance

Level 1, total project
 January 1979
 Planned % complete 2.70%
 Actual % complete 2.51%

2/14/79 baseline	173.845
Estimate at completion	173.853
Variance over (-) under (+)	-0.008
Contingency	21.355
Total est at completion	195.000

FY 1979

Fig. 2-120. Scheduled commitment of project funds for FY 1979. BCMWS's are displayed for FY 1979 with the latest monthly data for the ACMWP and the corresponding BCMWP. Planned percent complete is computed as BCMWS/estimate at completion, and actual percent complete as BCMWP/estimate at completion.

measurement baselines are generated automatically from the budget plan for financial commitments as well as for costs.

To measure performance, the Nova PPC system displays cost and schedule deviations from baseline values both numerically and graphically. The graphical displays down to level 2 will be produced through mid-1979, when this capability will be extended to level 3. Performance is measured against both commitment and cost baselines. The commitment baseline is useful early in the project, during design and procurement; the cost baseline is useful later, during delivery and assembly. Examples of performance measurement graphs are shown in Figs. 2-119 and 2-120.

During 1978, the actual and budgeted data for work performed were prepared by hand for the computer plotting portion of the system; the baselines were automatically extracted from com-

puter data bases derived from the cost estimates. The tracking portion of the Nova PPC system, which will be operational in 1979, automatically updates plotting data bases with actual and budgeted work performed. Figure 2-121 shows the relation between the Nova PPC budget-analysis and performance-measurement processing.

During the year, we emphasized development of a computerized PPC system in the areas of budget analysis, cost tracking, and performance measurement and did not emphasize the automation of schedule control. In fact, the performance measurement-graphs display schedule deviations that show whether planned dollar commitments and costs at delivery are occurring when specified by the baselines.

However, the PPC system will be expanded during 1979 to include a detailed schedule analysis for both the laser system and the building.

Milestone charts will be prepared for both special and conventional facilities. The Nova laser procurement plan has scheduled milestones for requisition submittal, contract award, and delivery for each level 4 or 5 WBS item. These milestones—along with the design milestones preceding requisition submittal and assembly milestones that follow delivery—are now operator input for each level-2 system, and the system interfaces are identified and accommodated. Such milestone network analysis and charting will be more fully automated during 1979.

Reference

58. P. E. Ostwald, *Nova Project Cost Estimating Manual*, Dept. of Mechanical and Industrial Engineering, University of Colorado, Boulder.

Author

F. Holcomb

2.4.14 Documentation

The final report for Nova construction, planning, and design (CP&D) was published in 1978.⁵⁹

The report, which is the last in a series of three, documents the system baseline as of early 1978 and lists most Nova-related documents. We have also established a Nova file and document library.

Reference

59. *Nova CP&D Final Report*, Lawrence Livermore Laboratory, Livermore, Calif., LLL-MISC-111 (1978).

Authors

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2.5 Argus Improvements

2.5.1 Performance

Argus became the principal target irradiation facility for the Y program in the latter part of 1976. Since then, the laser system has been continuously improved and upgraded to its present high quality. The milestones for improvements in laser performance were:

- June, 1976—3 TW of focusable power.
- Dec., 1976—Partial implementation of relay imaging; 4.5 TW of focusable power.
- Dec., 1977—Full implementation of relay imaging; 5 TW of focusable power; improved beam quality.
- Dec., 1978—5 TW/2 kJ of focusable power/energy, ultraclean beam quality.

The improvements in beam quality are summarized in Fig. 2-122, which shows that the 4:1 peak-to-average beam modulation experienced in 1976 has been reduced to 1.2:1. Because the peak intensity points of the beam produce damage, the reduced modulation has resulted in a commensurate reduction in the likelihood of damage to the coated optics in the laser chain.

2.5.2 Effect of Optical Damage

The high-energy, high-power implosion experiments conducted on Argus over the past year have been the primary motivation for improving beam quality and system reliability. Figure 2-123 shows the system performance (focusable energy vs pulse

Fig. 2-125. Changes made to the optical system of Argus during the changeover from a 20- to a 28-cm spatial filter.

2.5.3 Preventative Maintenance and Reliability

Although beam-induced damage to the optical components of the laser chain limits the focusable power of the system, component failures have limited the shot rate. We instituted a strict program of regularly scheduled preventative maintenance on Argus to minimize component failure and system downtime, while delivering a better quality beam. There have been only three days of unscheduled maintenance since the preventative maintenance program started in September 1978.

Each major area of the Argus system has a schedule of items to be checked weekly, monthly, quarterly, and semiannually. A portion of the master preventative maintenance schedule is shown in Table 2-29. Each area has a list of items that must be checked on each week's maintenance day. Adherence to this schedule has improved system reliability by reducing component failure rate, as shown in Table 2-30.

The optics damage category in the table needs explanation. Realizing the effect of damaged components (particularly in the rod systems) on the output beam quality, we no longer tolerate as much damage as we did before. Therefore, we replace many more components than before. Because many of these components are spatial-filter lenses, there has been an associated increase in the number of vacuum system problems.

Not all of the improvement can be attributed to preventative maintenance. As discussed above, improving the systems and components has also led to more reliable operation.

We are continuing to improve the preventative maintenance schedule to further minimize downtime and to improve beam and shot quality. The statistics show that the total number of shots per year can be increased if the number of component failures and shutdown days are reduced (Table 2-31). We took the following steps to improve reliability and increase the shot rates:

- Obtained component failure statistics to identify major problem areas.
- Implemented the most operationally effective solution to each problem.
- Rigorously adhered to a preventative maintenance schedule.
- Took parts inventories and ordered necessary spare parts.
- Initiated a training program.

The major problem areas that we identified and the operational solutions that we used are discussed below.

Oscillator Switchout Combination. Although the present oscillator-switchout combination is much more reliable than its predecessor, we experienced many failures during the year. A better engineered unit that is more immune to noise is in

Table 2-29. Sample weekly and monthly items on the Argus preventative maintenance schedule.

Weekly	Monthly
Spare parts: <ul style="list-style-type: none">Check quantity of parts on hand - reorderCheck status of parts on order	
Power conditioning: <ul style="list-style-type: none">Inspect capacitor banks and power statusInspect dump resistors and relaysClean up bank area	<ul style="list-style-type: none">Check fanout diodes and B fusesCheck operation of power suppliesInspect ignitrons and ignition chassisCheck for leaking capacitorsInspect HV silicon wire (amplifies to junction box.)Perform maintenance on spares
Laser area: <ul style="list-style-type: none">Check timing pulse settingReplace burned out lightsAdd water to lamp cooling systemsCheck for component damageCheck that all data were properly loggedLook for abnormalities and trends in data	<ul style="list-style-type: none">Check calibration, gain, and timing of all scopesPerform computer-scanner maintenanceCheck Neslab in-line filtersMeasure temperature and pressure of N₂ cooling gasCheck CW laser power supply performanceClean and realign CW laser

Table 2-30. Argus component reliability improvement after instituting preventative maintenance.

System	Decrease in failure rate, %
Oscillator and switchout	51
Pockels cells	0
Power conditioning	23
Alpha rod	49
HP computer/diagnostics computer	60
Flashlamps	68
2.5-cm/4-cm rods	79
CW laser (Laser bay/target room)	67
Optics damage	-667 (increase)
Vacuum systems	-67 (increase)

final assembly and is scheduled for installation in early 1979. The new oscillator should be almost failure-free.

Pockels Cell Driver. The electrical pulse, or gate, that turns on the cell drifts in time relative to the arrival of the laser beam. We designed and built an improved Pockels cell driver that is immune to noise and is jitter-free. This new driver, which is scheduled for installation in early 1979, will virtually eliminate the drift problem and provide stable Pockels cell operation.

Alpha Rod Amplifier. This component's failure modes included prefire, failure to fire, and leakage of the highly corrosive index-matching fluid used to achieve high gain by eliminating parasitic oscillation. Corrections to eliminate prefire and failure to fire are discussed below in the power conditioning subsection. We eliminated the leakage by

- Using water for the index-matching fluid.
- Modifying the end plates of the amplifier.
- Using new, leak-proof O-ring seals.

This component has not failed since these changes were made in September 1978.

Flashlamps. Many flashlamp failures occurred, especially in the rod amplifiers. We attribute the relatively good record for flashlamps in disk amplifiers to the PILC system and to off-line early-failure testing of the flashlamps. A fixture for off-line testing of the flashlamps in the rod amplifiers is being designed. Once this device is in use, all flashlamps will be tested before installation, thereby reducing the failure rate.

Table 2-31. Number of shutdown days and component failures per year—Argus experiments.

Number of full system shots	362
Target shots	244
Number of working days	249
Number of shot days	154
Number of shutdown days (upgrades, etc.)	78
Number of component failures	483

Laser Diagnostics Computer. The computer used for laser calorimetry failed several times during the year. Replacement parts are now available for all components, and a new trigger-and-monitor chassis was added, along with a system clock. The software was rewritten to eliminate dead spots and errors in the system, and to improve control and data manipulation during noise bursts. With these and other changes, the computer reliability improved markedly, but it is still not totally reliable.

Debris Shields. Keeping enough debris shields in stock for the scheduled target shots is an aggravating and costly operational problem on Argus. These shields prevent target debris from reaching and damaging the target lenses.

Originally, the debris shields were made from optical-quality glass, finished to 1/10 wave and coated with a nonstrippable AR coating. An additional cryolite coating, which is strippable, was placed over the hard AR coating on the side of the shield facing the target. These shields transmitted virtually all of the light striking them, with no discernable degradation in wave-front quality. After a fixed number of shots, the shield was removed from the target chamber and cleaned of target debris by stripping the cryolite from the shield. The shield was then recoated with cryolite, at a cost of about \$40, and was again ready for use.

During a high-power series of shots, however, the hard coatings on 90% of the debris shields sustained damage. Repair of the damage required stripping the hard coatings, refinishing the glass surfaces, and then recoating. Repair of the shields took approximately three months. The cost of repair was approximately \$700 for a 20-cm shield and \$1200 for a 28-cm shield. We circumvented this damage problem by deleting the hard coating from the shields and coating both sides with cryolite. The degradation in transmission from 100 to 98-99% per shield has been acceptable.

Power Conditioning. Long-overdue maintenance of the Argus power conditioning system was done during a three-week shutdown in late January. Unused equipment and cables were pulled out of the bank; power supplies were calibrated and checked out; and the system was brought back to operational readiness.

The system was operated for several months and delivered many shots, but operational problems continued to be troublesome.

In July, during a shutdown for the changeover to 28-cm optics, we:

- Replaced the α rod power supply with an LLL 20-kV supply.
- Replaced the two A ignitrons with dual D ignitrons.
- Converted the 4-cm rods to 20-kV operation.

● Built new bank modules and installed another LLL 20-kV supply and dual D ignitron switch.

The new amplifiers initially suffered internal arcing because of shield glass, but this was quickly corrected. The debugged system began operating in August.

We eliminated other operational problems by installing 5-kV isolation, similar to the Shiva design, in the control systems of the power supplies.

The last serious problem to be overcome was the α rod's failure to fire reliably. Shortly after the Shiva-type rod amplifiers were added to Argus, we noted poor triggering reliability. The problem stemmed from the large spacing between the lamps

and the reflectors, a feature unique to the rod amplifier design. Because a momentary overvoltage in the air gap between the lamp trigger electrode and the reflector forces the lamps to trigger, the large spacing reduced the voltage at the electrode to the point where triggering was marginal. We solved the problem by locating a small rod close to each lamp along its length. Connected at each end of the amplifier to the reflectors, the rods provide a higher voltage gradient between the lamps and the reflector. The amplifiers have triggered reliably over a wide range of bank voltage since the modification was made.

2.5.4 Summary

The reliability and performance of the Argus laser system as a target shooter have been continuously and dramatically improved during the last two years. Redesign and better engineering of critical components have played a role in these improvements. Also, improvements have resulted from:

- Careful monitoring of system characteristics.
- Scheduled maintenance.
- Quality assurance.
- Realistic spare-parts inventories.
- Intensive care by qualified personnel.

Authors

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Section 3

**Target
Design**

SECTION 3

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SECTION 3

TARGET DESIGN

3.1 Introduction

The target design activity includes the Plasma, Code Development, and Design Groups. These groups develop the theories of beam plasma interactions, implosions, and thermonuclear microexplosions; build plasma and implosion/burn computer codes; and use these theoretical computational tools to design targets and to simulate experiments.

In 1978, we concentrated on the implosion of DT to 10 to 100 times liquid density. By late 1978, we used the Shiva laser to successfully implode a target to high densities. We achieved compression of the DT to ≥ 50 times liquid density, $n\tau = 3 \times 10^{14} \text{ cm}^{-3}\text{-s}$, and 0.5-keV temperature.

We also used Shiva to irradiate simple exploding-pusher targets, achieving record neutron yields of 3×10^{10} . In these experiments, the DT was compressed to about liquid density, $n\tau = 3 \times 10^{12} \text{ cm}^{-3}\text{-s}$, and 5-keV ion temperature.

We achieved important advances in understanding the plasma and atomic physics of laser-plasma interaction. Non-LTE code calcula-

tions of laser-irradiated high-Z disks show good agreement with diagnostic measurements of laser light absorption, thermal energy transport, and x-ray spectra.

Heretofore, our work in the reactor target area has focused on the development of maximum performance targets that minimize the driver requirements for practical fusion reactors. Realization of these target performance levels depends on the development and mastery of highly sophisticated implosion technology and, in the case of lasers, good luck with respect to still incompletely understood laser-plasma interactions.

In 1978, we attempted to determine the conservative limits on the driver requirements. We based this analysis on our implosion experiments, our understanding of implosion and thermonuclear physics, and, in the case of lasers, conservative assumptions about the laser-plasma interaction.

The resulting conservative estimates of target gain vs driver energy are shown in Fig. 3-1. We expect to achieve these conservative target performance levels first and then we will follow a learning curve leading to the optimistic target performance levels. The Nova facility will play a key role in climbing up the initial stages of this learning curve. For conservative planning of the ETF and the first demonstration reactor, drivers that satisfy the conservative requirements should be chosen. These requirements are shown in Table 3-1.

Table 3-1. Requirements for estimated target gain vs driver energy.

Parameter	Conservative	Optimistic
Driver efficiency, %	>6	>1
Wavelength (or ion voltage)	$<0.3 \mu\text{m}/5 \text{ GeV U}$ $/10 \text{ MeVp}$	$<2 \mu\text{m}/20 \text{ GeV U}$ $/20 \text{ MeVp}$
Energy, MJ	3-5	>1
Peak power, TW	200	>100
Pulse rate, per second	8	4

These conservative requirements may be met by proposed heavy-ion accelerator designs that have projected efficiencies of 20 to 30%. If short wavelength coupling is as efficient as projected, short wavelength lasers such as KrF may also qualify. We plan to explore the scaling of short wavelength coupling in frequency-converted Nova experiments. Light ions would also be a candidate if the beam can be focused across several meters (from the reactor wall to the target) to an intensity of $\sim 10^{14}$ W/cm².

In the following articles, the design, code development, and plasma groups describe important advances in greater detail.

Author

J. H. Nuckolls

3.2 Exploding-Pusher Targets

3.2.1 Introduction

We have made extensive use of numerical simulation codes to model laboratory experiments and thus observe the dynamical behavior of exploding-pusher targets. We have performed both one-dimensional (spherically symmetric) and two-dimensional (cylindrically symmetric) calculations for a wide variety of target parameters and laser conditions. Many variations in these models have been explored with the calculations resulting in models that give good agreement with the quantities observed in the laboratory.

We discuss the behavior of a specific target designed for a laser system with 30-TW peak power and a Gaussian pulse of 80 ps FWHM. We selected the glass target ball to be 400 μ m in diameter, with a 1.7- μ m wall and 2-mg/cm³ DT gas fill. An estimated 35-to-40% absorption may be achieved by selectively placing each of many beams with adjustable polarizations on the target at positions that maximize the effect of resonance absorption. However, symmetry becomes degraded if absorption is optimal. The results discussed here are based on spherically symmetric calculations that are a good approximation when the target illumination is moderately symmetric.

3.2.2 Laser Light Absorption and Hot Electron Generation

An important aspect of exploding-pusher performance is the mechanism by which the laser light

is absorbed. Initial explanations for the absorption were based on the classical collisional mechanism, inverse bremsstrahlung. However, a simple analysis of this process shows that this absorption mechanism becomes inefficient as the outer portion of the target is heated with high-intensity laser light.¹ As the laser energy is absorbed, the plasma is heated, which results in the plasma density decreasing by hydrodynamic expansion. In addition, at high laser intensities the ponderomotive force reduces the scale length at the critical surface. The inverse bremsstrahlung absorption is

$$f_{ib} \propto ZL/\lambda_0 \theta_e^{3/2}, \quad (1)$$

where L , the scale length of the underdense shelf, becomes small and effectively shuts off the classical absorption. Figure 3-2 shows absorbed laser power as a function of time, as well as the division between inverse bremsstrahlung and the collective absorption mechanisms. Classical absorption is reduced very early in the laser irradiation, so only a small fraction of the total absorption goes by this mechanism. Hence, it is of negligible consequence in driving the implosion.

Fig. 3-2. Collisional processes dominating the absorption of high-intensity, short pulse irradiations of exploding-pusher targets. At early times, inverse bremsstrahlung (yellow) is efficient because the plasma is relatively cool. Expansion and heating of the corona, together with the high laser intensities, provide an ideal atmosphere for efficient resonant absorption (blue). The laser pulse is Gaussian with an 80-ps FWHM.

The dominant absorption mechanism, from Fig. 3-2, is seen to be the collisionless plasma processes, with a combination of resonant absorption and parametric decay being the more important components. The resonant absorption fraction is

$$f_{ra} \propto (L/\lambda_L)^{2/3} \exp(-4/3 L/\lambda_L), \quad (2)$$

where L is the density scale height at the critical surface. A sharp density gradient ($L \gtrsim 1 \mu\text{m}$) is required for efficient absorption. This density gradient occurs naturally in these plasmas at the high laser intensities encountered here, $I_L \approx 10^{16} \text{ W/cm}^2$. We have experimentally confirmed that the ponderomotive force (light pressure) causes a steepened profile at the critical surface² and that numerical simulations are in excellent agreement.³ Figure 3-3 shows the calculated electron number density profile at the peak intensity of the laser pulse. Indeed, a density jump of about a factor of six occurs, placing the edge of the lower density shelf at about 1/4 of the critical density. Figure 3-3 also shows the average electron-temperature and ion-temperature

Fig. 3-3. A sharp variation in the density of the plasma at the critical position where the critical electron density is located, produced by high laser intensity. At maximum laser power (it equals θ) the ponderomotive pressure is comparable to the plasma pressure at the critical surface. The average electron temperature profile shows a nearly constant value for radii larger than the critical radius. This is characteristic of the high suprathermal electron population in the underdense plasma. At positions inside the critical surface the temperature shows a gradient formed by the dominant background (thermal) electron distribution.

Fig. 3-4. The suprathermal electron temperature dependent on the laser intensity at the critical surface, I_L . Maximum temperature is generated at the peak of the pulse when the largest fraction of the energy is absorbed. Hence, the target will be driven most strongly by the effective distribution of the FWHM of the pulse. This is about 15 ps.

profiles at this time. Exponentially decreasing ion temperature as a function of radius is characteristic of hydrodynamic expansion in the underdense plasma. The average electron temperature increases to a high value just outside the critical density and remains nearly constant throughout the underdense region. (Of course, the high electron temperature and low density reinforce the suppression of inverse bremsstrahlung absorption.) It is well known that resonant absorption generates energetic electrons that scale with the laser intensity and wavelength.⁴ For the target material (glass) and plasma conditions under consideration here, the characteristic temperature of the suprathermal electron distribution is given by

$$T_{\text{hot}} \approx T_{\text{avg}} + 3 \times 10^{-6} (I_L \lambda_L^2)^{0.425}. \quad (3)$$

Figure 3-4 shows laser intensity and calculated T_{hot} as functions of time. Most of the laser energy is absorbed near the peak of the pulse when the laser power is greatest. Thus, the effective hot electron temperature (which will most affect the target) is very nearly the maximum value. Of course, we are assuming that the target dimensions and laser pulse parameters are properly matched to make use of the majority of the pulse.

3.2.3 Thermal Transport Inhibition and Hot Electron Transport

Computer modeling of implosion experiments has shown the necessity of a reduced heat conductivity.⁵ We do not know the exact nature of the reduction mechanism. Previous modeling has concentrated on severely inhibiting the thermal electron distribution; however, there is no a priori

reason to believe that thermal distribution alone is affected. Inhibition of the suprathermal distribution may also reduce the heat flow to some degree. The experiments only show that heat flow, as described by diffusion theory, must be reduced from its classical value.

Nevertheless, we use the inhibition of the thermal group to model the reduction, and it appears to

Fig. 3-5. Conversion of the suprathermal electron energy to the background electron distribution by Coulomb collisions. This conversion is most efficient at early times when the hot electron temperature is low. As the laser intensity is increased, the electrons become more energetic, thus having a longer mean-free-path. This results in less energy being coupled to the target. The figure plots the fractional suprathermalization in each of the four regions: blue is the material between the critical density and the middle of the shell, red is the pusher, green is the opposing pusher, and orange is the opposite atmosphere. The effective thickness (electrons per cm^2) is shown for each region. The relationship of the three times, relative to the peak of the pulse with hot electron temperatures and number densities of the pusher, is shown in the table.

t , ps	ϕ_{hot} , keV	n_e , cm^{-3}
-100	2.8	2.1×10^{22}
-50	13	1.2×10^{23}
0	22	3.7×10^{22}

The number density increases at the outset because of ionization. By -50 ps the glass is completely ionized and the shell begins to expand, thus dropping the number density and thickness.

explain our observations. Classical transport of the absorbed energy by the thermal electron distribution would give too high an implosion velocity and, thus, too high a neutron yield.⁶ At least two important mechanisms could provide the required thermal reduction—namely, self-generated thermoelectric magnetic fields and two-stream instability. We will not discuss the former mechanism here; numerical simulations show it to play a lesser effect in the inhibition of heat flow in the radial direction. Rather, the two-stream mechanism⁷ may explain, at least partially, the large reduction required, of the order of 0.03. The large reduction factor in the conductivity effectively prevents all thermal energy available at the critical surface from contributing to the implosion process.

The energy to drive the implosion is therefore delivered by the suprathermal electron distribution that is generated at the critical surface and which occupies all of the coronal volume. Figure 3-4 shows the temperature of this distribution to be 15 to 20 keV for a significant fraction of the laser pulse. The high energy tail of this hot electron distribution can readily penetrate the thin glass. The suprathermal distribution includes electrons with energies much less than 15 to 20 keV, and some of the lowest energy electrons are stopped in the glass, depositing their energy by collisions with the background electrons. The more energetic electrons penetrate the whole of the target and emerge on the other side. These electrons may then be heated again by the laser and returned to the target. Figure 3-5 schematically demonstrates the thermalization of a portion of the hot electron distribution by the outer 1/2 of the glass shell, the inner 1/2 of the shell, and like components on the opposite side of the target. *(The DT fuel does not appreciably affect the thermalization of electrons from the suprathermal distribution, because the background electron density is almost two orders of magnitude less than that of the glass.)* The figure shows a significant fraction of the electrons to be stopped at early times in the laser pulse where the suprathermal temperature is low, while, at the peak of the pulse, the bulk of the hot electron energy is decoupled from the target.

It is convenient to describe the two glass regions as distinct parts because their roles in the implosion are different; this will be shown in the following subsection.

3.2.4 Explosion/Implosion of the Shell and Setting of the Fuel Adiatat

The hot electron penetration and partial thermalization of the shell heat the glass in a somewhat isothermal manner. Figures 3-6(a), (b), and (c) plot the average electron temperature, pressure, and density as functions of position within the shell for selected times. These three profiles are characteristic of exploding pushers and approximate the isothermal expansion of the implosion. The position of the peak pressure remains essentially stationary at the initial shell position. Roughly 1/2 of the shell moves inward and is called the pusher, and 1/2 moves outward becoming the atmosphere. Except for the initial shock, the density of the pusher is always decreasing as the fuel/pusher interface is accelerated inward. Figure 3-7 shows the temporal behavior of the midpoint of the shell, where the electron temperature increases from the suprathermalization (which generates the driving pressure), resulting in the shell's expansion and, thus, reducing its density.

The isothermal-like behavior of the pusher, when coupled with increasing electron pressure, causes fairly constant acceleration of the fuel/pusher interface during most of the increase in velocity. Figure 3-8 plots the interface velocity as a function of time. This velocity increases linearly with time until the pressure in the pusher becomes comparable to the pressure of the fuel. Equilibration of the pressure across the fuel/pusher interface is demonstrated in Fig. 3-9 for selected times near the stagnation phase of the implosion process. Deceleration of the pusher completes the implosion process, culminating in stagnation.

Optimal exploding pusher targets require that the laser power rise rapidly to its peak value while the pusher is exploding. The tremendous increase in pressure within the shell causes the interface to be rapidly accelerated, thus generating a strong shock that propagates through the fuel. Shock theory is used to predict the temperature of the gas that has been heated by the passage of the shock front. Because the DT gamma is 5/3, the shock front propagates through the fuel at a velocity of about 4/3 (that of the interface) until convergence effects become dominant. The front reaches the center of the sphere many tens of picoseconds before the extrapolated fall line of the interface. After reflection

Fig. 3-6. Average electron temperature, pressure, and density as functions of position with the shell at selected times. (a) Suprathermalization creates a nearly uniform temperature profile in the later stages of the heating phase ($T \geq 0$ ps). Early in time the hot electrons do not penetrate the shell sufficiently to heat the inner portion of the pusher. (b) As the heating becomes uniform and the electron temperature increases, the pressure reaches a maximum at the center of the shell. This is the driving force that effectively splits the glass into two equal parts. (c) The density behaves in a manner similar to that of the pressure profiles. Initially the shell density was 10^3 times that of the gas.

Fig. 3-8. Acceleration of the fuel/pusher interface. The acceleration is nearly constant at $5 \times 10^{-3} \mu\text{m}/\text{ps}^2$ ($5 \times 10^{17} \text{ cm}/\text{s}^2$) for the majority of the early part of the implosion. The acceleration changes signs as the fuel pressure equals the pusher pressure. There follows a rapid decrease in velocity as the kinetic energy of the pusher is converted mainly into thermal energy of the DT fuel.

at the center, the shock propagates outward to intercept the incoming pusher near the time of maximum compression. Figure 3-10 shows the shock trajectory to behave in the same parabolic-like fashion as the fuel/pusher interface, but with a larger acceleration constant and different convergence effects. The DT fuel behind the shock front is left in a state of higher entropy. This shock preheating, together with a small contribution from electron conduction from the pusher, sets the fuel adiabat. Compression of the fuel now proceeds with

Fig. 3-10. Fuel/pusher interface and shock positions. Both demonstrate a parabolic nature in time. The higher shock velocity allows it to converge on the center and reflect back to the still inward-moving interface. Collision of the shock and interface results in the stagnation of motion. A compression factor of $(200/53)^3 \approx 54$ was achieved for this target.

the inward motion of the pusher, doing PdV work in a nearly isentropic process.

3.2.5 Compression and Adiabatic Heating of the Fuel

Following the passage of the main shock wave, the DT fuel is placed at an elevated temperature, pressure, and density. Figure 3-11 follows the thermodynamic behavior of a mass point in the DT fuel plotted in the p-ρ plane. Shock heating is signified by the rapid rise in pressure with a fourfold increase in mass density. Further increases in pressure and density follow an adiabat that roughly parallels the adiabat of the zero-temperature isentrope. These increases result from the PdV work performed on the gas by the interface acting as a piston. The compressional part of the curve more or less satisfies the adiabatic condition of no heat being added to the fuel by additional shock waves or thermal conduction from the pusher.

An important point in understanding the energy flow, and, hence, the thermodynamic nature of the fuel, is the energy coupling between the pusher and the fuel as a function of time. Figure 3-12 shows the mass density, electron temperature, and ion temperature as functions of time for the same mass point mentioned above. This mass element was selected to be representative of the average over the fuel volume. The electron temperature leads the ion temperature at early times,

Fig. 3-9. Pressure equilibrium across the fuel/pusher interface. Equilibrium is achieved only at the outflow time between +50 and +100 ps.

Fig. 3-11. Compression of the fuel. Compression may proceed in many ways. The P vs ρ diagram shows the ideal path along the zero temperature isentrope. Exploding pushers operate along a higher entropy adiabat. The vertical rise in the pressure at constant density occurs early in time and corresponds to the shock and thermal wave probe. The compression then follows a path parallel to the degenerate adiabat. The slope is $\approx 5/3$ which satisfies the condition for adiabatic compression of an ideal gas.

This is because the coupling between the fuel electrons and the pusher electrons (and to some extent the suprathermal electrons) is moderately good, while the coupling to the fuel ions is very poor. When the shock wave passes through the mass point, the ions are heated but the electrons are only slightly affected. Thus, the ion temperature and pressure are greater than those of the electrons. PdV work is then performed on the gas with the ions reflecting the increased temperature and pressure. Electrons are cooled by thermal conduction. The electron-ion coupling in the fuel improves through the course of the compression and is seen as a slight rise in the electron temperature near peak compression. Figure 3-12 then shows the cooling of the fuel by hydrodynamic expansion of both the fuel and the pusher.

DT reactions take place for a short period as the pusher and compressed fuel stagnate (see Fig. 3-12). Ninety percent of the reactions are seen to take place in about 90 ps, approximately twice the time required for the average ion at the peak temperature

to cross the compressed fuel radius without collisions.

3.2.6 Energy Coupling and Partitioning

The coupling of 1.06- μm laser light to exploding-pusher targets is poor. We have measured absorptions greater than 20%, with theoretical predictions up to 40%. Exploding-pusher targets have moderately good coupling to the fuel. For the target discussed here, about 4.5% of the absorbed energy appears as ion thermal energy in the fuel. Figures 3-13 and 3-14 show the cumulative energy balance as a function of time. The envelope of Fig. 3-13 is the total absorption—approaching 40%. Energy partitioning is shown for the three parts of the target with the largest portion appearing in the outer half of the glass shell. Details of the atmosphere are not presented here, but it is important to note that about 50% of the absorbed energy appears as “fast” ions; that is, about 500 J leave the target volume on a time scale comparable to that of the laser pulse. The remaining 50% is primarily in hot electrons from which about 50% of the energy will be coupled to the pusher, the fuel, or both. Not more than 25% of the absorbed energy, less than

Fig. 3-12. Temporal behavior of the fuel mass point used for Fig. 3-11. This shows the electrons to be heated by the suprathermal electrons and clearly follows the laser pulse. Coupling to the ions is very poor because of the low density and temperature. As the compression of the fuel proceeds from the time of the peak of the laser pulse, the ions are heated by PdV work. Stagnation of the pusher against the compressed fuel takes place shortly before +200 ps. The maximum in the ion temperature corresponds to the peak DT reaction rate. Hydrodynamic expansion results in the fuel being cooled, which quenches the reaction. The reaction time is about 90 ps.

Fig. 3-13. The total energy content of the three regions of the target. This adds up to 46% of the incident laser energy. The majority of the absorbed energy, ~ 750 J, resides in the outer $\frac{1}{2}$ of the glass shell. The target energy budget has about 6% of absorbed energy in the fuel.

250 J, is available for heating the pusher and compressing the fuel.

Figure 3-14 shows how the energy is divided into its different forms within the pusher. The majority of the energy resides in the electron thermal energy that creates the driving pressure. (Only about $1/10$ of this amount is carried in ion thermal energy because there are ten times as many electrons as ions.) Following the peak of the laser pulse, the pusher exhibits an increase in its kinetic energy resulting from the shell's expansion.

Concomitantly, Fig. 3-14 also shows the energy content of the fuel to be increasing. The rise in energy coincident with the laser pulse is largely the result of the suprathermal component that is just passing through; it is included only to keep the energy budget balanced and is not really part of the fuel itself. The motion of the fuel accounts for the majority of the energy content for a few tens of picoseconds following the laser pulse. As the isentropic compression progresses, beginning at about $+100$ ps, more and more of the kinetic energy of the

pusher is transferred to the the ion internal energy of the fuel. As we have noted, the fuel electrons do not participate in the fuel compression and heating to a large degree. The ion temperature reaches a maximum at stagnation time, near $+200$ ps. The useful energy is about 45 J. Approximately 20% of the total pusher energy is coupled to the fuel's ion internal energy.

In summary, exploding-pusher targets have poor laser absorption and good coupling between the pusher and the fuel. There is also poor transfer of the absorbed laser energy, resident in the suprathermal electron distribution, to the thermal electron population of the pusher. The high overhead requirements of long mean-free-path electrons, as well as the absorption mechanism, preclude a more efficient performance for this target design. Of course, the low compressed densities (only about normal DT density) are the most significant limitations of exploding pusher targets. Consequently, for practical ICF drivers, the ρR is always too small for efficient fuel burn.

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3.3 Intermediate-Density Shiva Targets

We are examining electron-coupled, double-shelled targets with an exploding outer shell^{8,9} as an option for imploding DT to intermediate density with Shiva. Code simulations indicate that it may be feasible to diagnose implosions to 100 times liquid density. Two preliminary implosion experiments performed on Shiva in November are discussed in §5.7. Characteristics of the target and some design problems are discussed in this subsection.

3.3.1 Target Description

The exploding outer shell target is illustrated in Fig. 3-15. A DT-filled, thick-walled, spherical inner ball is surrounded by a larger thin-walled outer shell of comparable mass. Laser illumination explodes the outer shell in the usual exploding-pusher sense, i.e., the shell is quickly heated all the way through so that thermal expansion causes half the material to move inward and half to move outward.

Fig. 3-15. Double-shelled target with exploding outer shell.

Suprathermal electrons and the inward-moving material cause ablation and compression of the inner ball which, in turn, pushes the DT fuel to high density. The inner ball is called the ablator/pusher.

The characteristics of the exploding outer shell target lie between those of the exploding pusher and those of ablatively driven targets. The outer shell has the symmetry and stability of the exploding pusher, but the thick inner shell allows a cooler, higher-density fuel implosion.

3.3.2 One-Dimensional Implosion Dynamics

An easily fabricated design that uses a glass ablator/pusher and a plastic exploding shell is shown in Fig. 3-16. With 2 TW of peak absorbed power from a 400-ps FWHM Gaussian pulse, the one-dimensional calculation yields 2×10^7 neutrons and gives DT compression to 45 times liquid density. We assumed resonant absorption with an 11-keV suprathermal temperature (T_{hot}) and conduction inhibition by the two-stream instability.

The general features of the implosion dynamics are shown in Fig. 3-17, where the position vs time of several locations in the target material are plotted. The laser pulse reaches peak power just before the imploding half of the outer shell impacts the inner ball. Before this time, suprathermal electrons that are exploding the outer shell are also ablating the outside surface of the inner ball. Thus, the inner

Fig. 3-17. Implosion dynamics. After an initial ablation by hot electrons, the fuel ball is driven by the impact from the exploded outer shell.

Absorbing a given laser power with a relatively large outer shell reduces preheating of the fuel and pusher in two ways. First, reduced light intensity lowers the suprathermal electron energy and range. Second, the increased volume of the target lowers the number density of suprathermal electrons at the surface of the ablator/pusher. Further, preheat protection requires that the ablator/pusher wall thickness be many times the range of the suprathermal electrons. If the wall is too thick, the impact shock will not penetrate early enough to be effective. The compromise improves with increasing ablator/pusher Z and density.

Variations in the suprathermal electron physics affect the strength and timing of the two shocks in the ablator/pusher. For example, an increase in T_{hot} strengthens and advances the ablation shock but delays and weakens the impact shock. If the second shock arrives after the fuel and pusher have stagnated and mixed, then no useful work will have been done by the outer shell.

A design selected for reduced sensitivity to T_{hot} is shown in Fig. 3-19. The ablator/pusher is glass with a thin coating of gold. The relatively thick, low-density glass controls the propagation time of

portion of the ball (which pushes the DT fuel) is driven by two shock waves. The first arises from the ablation pressure of the suprathermals and the second from the impact pressure of the outer shell material. Depending on the particular design, the first shock may be overtaken by the second, either in the ablator/pusher or in the DT, or it may rebound from the center before the second shock arrives.

The shell material that impacts the ablator/pusher is a hot, low-density plasma. Most of the energy that drives the second shock is transferred by thermal electron conduction. As discussed below, this conduction transfer is an advantage for symmetrization. However, it makes the target performance sensitive to conduction inhibition.

As the outer shell is thickened with the absorbed energy held fixed, the temperature of the plasma hitting the ablator/pusher decreases and its density increases. Figure 3-18 shows the neutron yield and maximum DT density vs outer shell thickness for a copper ablator/pusher and a glass ablator/pusher. In general, one-dimensional performance improves with increasing shell thickness because the hydrodynamic transfer of energy to the pusher improves. However, the impact shock is delayed. The lower- Z , glass ablator/pusher does not withstand preheating as well, and its performance drops as the implosion timing deteriorates.

Fig. 3-18. Neutron yield and peak DT density vs exploding shell thickness for glass and copper ablator/pushers. In both cases, 2.2 TW peak power was absorbed from a Gaussian 1- μm laser pulse by collective processes with $T_{\text{hot}} \sim 11$ keV. Dimensions are i.d. and thickness.

the first shock. The thinner, high-Z, high-density gold layer provides most of the suprathermal electron attenuation. The impact shock arises in the gold and catches the ablation shock in the glass layer. Thus, a single strong shock drives the DT fuel. Variation of T_{hot} changes the position in the glass where the two shocks merge, but only weakly affects neutron yield and maximum DT density.

Figure 3-20 shows a plot of the neutron yield and peak DT density vs gold plate thickness for a series of one-dimensional calculations. The design is like that in Fig. 3-19 but with a larger, thinner outer shell. The neutron yield peaks when the impact shock catches the ablation shock at the fuel/pusher interface. This situation gives the highest fuel adiabat and the lowest pusher adiabat, maximizing energy transfer to the fuel. For thicker gold layers, the shocks merge in the glass pusher, giving reduced sensitivity to T_{hot} .

3.3.3 Two-Dimensional Implosion Dynamics

We have conducted cylindrically symmetric, two-dimensional simulations to assess implosion

degradation caused by deviations from spherical symmetry.

The dominant large-scale asymmetry in driving a spherical shell with the two-sided Shiva beam arrangement is the absorption in large polar caps on the top and bottom of the target. The code LITAR indicates that resonant absorption can be made uniform to $\pm 30\%$ up to 50° away from the poles. Thereafter, absorption decreases rapidly toward the equator.

The implosion symmetry of the ablator/pusher is enhanced by exploding the outer shell. Both electron conduction and hydrodynamic expansion tend to symmetrize the pressure applied to the ablator/pusher. Electron conduction is improved by using low-Z material in the outer shell. However, magnetic fields that may be generated between the shells would degrade the implosion symmetry by reducing electron conduction.

The impact pressure and temperature applied to the ablator/pusher are initially highest in polar caps, similar to the laser absorption caps. However, hydrodynamic flow tends to move hot plasma around the ablator/pusher towards its equator. When the streams of plasma from the opposite poles of the exploding shell meet head-on at the

Fig. 3-21. The calculational mesh at the time of peak x-ray emission from the ring shock with and without magnetic fields. (a) Lagrangian mesh 60 ps after laser peak when x-ray emission from the ring shock is at maximum. Note material flow toward the equator on the r axis. Magnetic fields not included in calculation. (b) Lagrangian mesh 130 ps after laser peak when x-ray emission from the ring shock is at maximum. The calculation includes thermo-electric magnetic fields.

hydrodynamic flow helps maintain the pressure on the equatorial region of the ablator/pusher during the subsequent implosion.

A snapshot of the calculational mesh at the time of peak x-ray emission from the ring shock is shown in Fig. 3-21(a) for a calculation that does not include magnetic fields. The corresponding mesh plot for a calculation with magnetic fields is shown in Fig. 3-21(b). The ablator/pusher was a 130- μm -i.d. glass ball, 5 μm thick, with an 11- μm -Teflon coating. The shell was 450- μm -i.d. Parylene, 2.3 μm thick. We assumed two-sided f/1 illumination with angle-dependent resonance absorption for p-polarization. Each side received 3.6 kJ of laser light in a 1-ns FWHM pulse. We assumed that half of the light was lost to backscatter, 3% went to inverse bremsstrahlung, and 11.5% went to resonance absorption with $T_{\text{hot}} \approx 7$ keV. In both calculations, thermal electron conduction was inhibited by the two-stream instability.

The mesh distortion caused by flow toward the equator is apparent, both with and without magnetic fields. The formation of the shock is a hydrodynamic consequence of asymmetric laser light absorption and is not qualitatively affected by conduction inhibition, magnetic fields, or suprathermal electron physics assumptions. On the other hand, the magnetic field has clearly affected the symmetry of the ablator/pusher implosion. By reducing thermal conduction away from the poles of the target, the magnetic field maintains a higher pressure on the poles, causing the premature implosion shown in Fig. 3-21(b).

3.3.4 Discussion

With spherical symmetry, the exploding outer shell target appears capable of achieving DT compression to 100 times liquid density. There are significant uncertainties in laser absorption for longer pulse lengths, in the hot electron spectrum, and in the amount of conduction inhibition between the shells. However, simulations indicate that reasonable adjustments of target parameters can compensate for these uncertainties. Furthermore, target shots with available diagnostics should readily lead to an optimized one-dimensional design.

Whether two-dimensional asymmetries are manageable is less clear. We have not yet established the accuracy to which we can calculate two-dimensional suprathermal electron transport

and magnetic field generation. Both processes directly affect implosion symmetry. Furthermore, we have no direct experimental diagnostic to measure the magnetic field between the colliding shells. Finally, the Rayleigh–Taylor instability should be carefully analyzed.

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G. McClellan

3.4 Beam-Target Interaction in Heavy-Ion Fusion

Heavy-ion targets and laser targets have many common features. Both rely on the same basic principles of compression, ignition, and thermonuclear burn. The critical difference is the way in which the beam energy is coupled to the target.

Beam-target interaction in laser fusion has proved to be a very challenging problem. It is therefore natural to be concerned about beam-target interaction in heavy-ion fusion. Much of this concern seems to arise from the feeling that a beam capable of target ignition is in some sense “intense” and is, thus, qualitatively different from the low-intensity beams with which we are familiar in nuclear science. Intensity must, of course, be quantified and, in several respects, heavy-ion fusion beams are not truly intense. For typical target and beam parameters, the electron density in the target is roughly nine orders of magnitude larger than the density of beam ions. Furthermore, beam ions in the target are separated by about 1000 Debye lengths, so that one might expect the beam ions to behave independently. These statements are simply a manifestation of the fact that, for heavy-ion fusion, each beam particle carries a large energy (~ 10 GeV). This can be contrasted with light-ion (proton) or electron-beam fusion, where the expected particle energy is 1 to 10 MeV, or with laser fusion, where each photon carries an energy of about 1 eV.

However, heavy-ion beams must be considered intense in some respects. Collective effects are important in the propagation of the beams in the accelerator and through the combustion chamber to the target.

Two classes of ion beam physics must be considered: nuclear and electromagnetic. Recent accelerator designs have focused on accelerating heavy ions to a maximum energy of about 20 GeV. At this energy, the calculated range of a heavy ion is much less than a nuclear collision length, so only a small fraction of the incident ions will produce nuclear reactions.¹⁰ Furthermore, nuclear processes are unaffected by the state of matter in the target, so measurements of cross sections with low-intensity beams are directly applicable. The only area of conceivable uncertainty involves electromagnetic phenomena.

Electromagnetic interaction of low-intensity ion beams with ordinary matter has been reasonably well understood for about 60 years. The calculated energy loss of heavy ions in matter (or range) is in excellent agreement with experiments.^{11,12} However, experiments with heavy-ion beams at the appropriate energies, intensities, and matter temperatures have never been performed. Some additional relevant experiments might be performed at existing heavy-ion accelerators, but it has not yet been possible to attain fusion-intensity beams. The continuing experiments in light-ion fusion are also relevant to heavy-ion energy deposition and may provide early verification of ion stopping predictions in hot matter.

To achieve fusion conditions, it is necessary to deposit $\lesssim 2 \times 10^7$ J/g in the target.¹³ Thus, for a given target size, less total energy is required if the range of the incident ions is short. On the other hand, there are significant accelerator design considerations that push one in the direction of high ion kinetic energy and, therefore, long range. Any anomalous effect that shortened the range of the ion would be welcome. Conversely, if the range of the ions was significantly larger than calculated, it would increase the cost of the heavy-ion accelerator. Recent estimates show accelerator costs increasing as (output energy)^{-0.4}. Thus, if the range was 25% too long, one could compensate by increasing the output energy by 25% to achieve $\lesssim 2 \times 10^7$ J/g, thereby increasing the cost of the accelerator by about 10%. This represents the worst case, since it might be possible to redesign the target or ac-

celerator to reduce the cost penalty. Fortunately, fundamental physical arguments indicate that the range will not be significantly larger than calculated.

As an ion passes through matter, it loses energy through binary Coulomb collisions with plasma electrons lying near its trajectory. It also loses energy by exciting the plasma lying far enough from the beam to preclude a simple description in terms of binary collisions. The distance at which the transition to the plasma regime takes place is normally taken to be a Debye length λ_D .

For heavy-ion fusion, typical conditions in the beam deposition region of the target are an electron density of $10^{23}/\text{cm}^3$ (solid density) and a temperature of about 200 eV. These conditions give $\lambda_D = 3 \times 10^{-8}$ cm. Thus, there are very few electrons in λ_D^3 so that collisions out to λ_D must be unscreened binary collisions.

In performing the usual calculations¹⁴ for a 10-GeV heavy ion, we find that more than half of the expected energy loss results from binary collisions. Thus, one can place a lower limit on energy loss that is independent of a detailed understanding of plasma physics. This lower limit differs from the total calculated energy loss by less than a factor of two.¹⁵

The range could be significantly longer than calculated only if the ions were accelerated by some mechanism. To compete with the binary collisions, the accelerating field would have to add ~ 20 GeV to a heavy ion in about 1 cm (range ~ 1 g/cm² $\Rightarrow$ 1 cm at a density of 1 g/cm³). The Z of the ion is certainly less than 100, requiring a minimum electric field of 2×10^8 V/cm over a distance of about 1 cm.

Because the only source of energy is the ion beam, it would have to accelerate itself by some chain of events. In any case, 2×10^8 V/cm fields are rather inconceivable. Joule heating results in a power dissipation per unit volume given by E^2/η , where E is the electric field and η is the resistivity of the plasma. Following Spitzer,¹⁶ we calculate $\eta \approx 10^{-3}$ ohm cm for a high- Z plasma and $\eta \approx 10^{-5}$ ohm cm for a low- Z plasma. Thus, a 2×10^8 -V/cm field produces $\lesssim 10^{19}$ W/cm³ in a high- Z plasma and $\lesssim 10^{21}$ W/cm³ in a low- Z plasma. Because the total power deposited by the beam is only about 3×10^{15} W/cm³, the Spitzer resistivity would have to be wrong by more than three to five

orders of magnitude before such fields could be energetically possible.

If the beam strikes matter at all, it appears that it will stop as predicted. If the beam carries a large amount of momentum, it is conceivable that it can sweep the target material out of its way. Very simple calculations show that the effects of momentum deposition by a heavy-ion beam are negligible compared to the thermal pressure developed by energy deposition.

In conclusion, it seems unlikely that fusion-intensity ion beams will have significantly less energy loss than predicted.

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to long-pulse-length irradiation of high-Z targets. In such cases, the underdense plasma becomes quite large, and many more physical processes compete to determine the coupling. Major issues are stimulated scattering and filamentation, absorptive processes that lead to hot electron generation, and plasma processes that inhibit the electron energy transport. Our major accomplishments this year include:

- Development of a first stimulated scattering package.

- Construction and use of a new hydrodynamics-wave optics code to study Brillouin scatter in realistic density and temperature gradients.

- A theory of the competition between filamentation and Brillouin scatter.

- Predictions of hot electron generation by the $2\omega_{pe}$ and Raman instabilities in large underdense plasmas.

- Calculation of B field generation by two different instabilities.

Because our new results are discussed in detail in subsequent articles, we concentrate here on giving an overview of LLL's understanding and progress in the area of laser plasma coupling.

Stimulated Scattering and Filamentation. One of the most important issues is the role of stimulated scattering¹⁷ and filamentation¹⁸ in large regions of underdense plasma. In discussions of stimulated scattering, it is instructive to introduce a quality factor. To do this, consider a simple model for Brillouin backscatter in which the underdense plasma is treated as a uniform plasma with density n_p and length L . If we further assume that the ion waves responsible for the scatter are heavily damped, the spatial gain coefficient for backscatter is readily shown to be¹⁹

$$K_{BS} = \frac{k_0}{4} \frac{n_p}{n_{cr}} \left(\frac{v_{os}^2}{v_e} \right) / D, \quad (4)$$

where $D = (1 + 3\theta_i/z\theta_e)\nu_i/\omega_i(1 - n_p/n_{cr})$. Here k_0 is the free-space wave number of the light, n_{cr} is the critical density, v_{os} is the oscillation velocity of an electron in the electric field of the incident light in free space, v_e is the electron thermal velocity, $\theta_e(\theta_i)$ is the electron (ion) temperature, and ν_i is the ion wave damping rate normalized to ω_i , the ion wave frequency. The quality factor Q_{BS} is then defined as

3.5 Laser Plasma Coupling

3.5.1 Introduction

This year, we have focused our attention on extending our understanding of laser plasma coupling

the number of growth lengths in the length L of the plasma, i.e.,

$$Q_{BS} \approx 1/4 \frac{n_p}{n_{cr}} \left(\frac{v_{os}}{v_e} \right)^2 k_0 L/D. \quad (5)$$

The denominator D is often estimated to be ~ 1 , because the ion waves tend to become very heavily damped as a result of either self-consistent ion heating or other nonlinear effects. The quality factor depends on the intensity multiplied by the amount of plasma traversed ($n_p L$). Gradients do not essentially change this discussion. For example, if the ion waves are not heavily damped, density and expansion velocity gradients lead to a very similar quality factor¹⁷ with L/D simply replaced by an effective gradient length in the underdense plasma. For recent long-pulse-length experiments on disks and microspheres, Q_{BS} is estimated to range from about 5 to 10, which illustrates why significant Brillouin scattering was expected. Measurements²⁰⁻²² indeed indicated that a sizeable fraction ($\sim 50\%$) of the incident light was Brillouin-scattered.

This year, we have improved our calculations of stimulated scattering in a number of ways. First, we developed a Brillouin scattering package based on particle simulations. Initial calculations with this package have compared reasonably well with some experiments. Second, we developed a new hydrodynamics-wave optics code to extend our simulations of Brillouin scattering to more realistic temperature and density profiles. This code will help us improve the scattering package. Finally, we have made some predictions of Raman scattering in large underdense plasmas. We do not expect this scattering to be large, but it can provide a valuable diagnostic for the plasma temperature in the underdense region.

Many features of stimulated scattering need to be better understood: What is the angular distribution of the Brillouin-scattered light? Under which conditions is the scattered light very peaked in the backward direction? It is also very important to better understand how filamentation competes with Brillouin scattering. From theory, we find that filamentation has nearly the same growth length as Brillouin backscatter in plasmas with nearly equal ion and electron temperatures, a condition found in

some experiments. In addition, filamentation could be favored because hot spots in the incident beam provide a large perturbation from which to grow.

Absorption into Hot Electrons. We have also extended our understanding of the collective absorption processes in long-pulse-length experiments. We conducted particle simulations to provide estimates of the hot electron generation near $1/4$ the critical density, an effect not currently included in target simulations. Fractional absorptions of ~ 5 to 10% are predicted with a heated electron temperature up to twice as large as the heated temperature expected from resonance absorption at the critical density. We also continued to improve our modeling of the hot electron temperature that results from heating at the critical density. We modified our hot electron temperature package to include dependences on both the ion-electron temperature ratio and the angle of incidence of the light. We also examined how resonantly heated electrons are modified by reheating, by relativistic mass variations, and by self-generated magnetic fields.

An improved understanding of hot electron generation is strongly coupled with an improved understanding of filamentation in the underdense plasma. Again, a simple estimate of one possible nonlinear state is instructive. Assume that the light filaments in the low-density underdense plasma where the electron temperature is the hot temperature, θ_h , produced by absorption near the critical surface. Invoking pressure balance $[(v_{os}/v_e)^2 \approx 1]$, we expect the intensity of the filamented light to be $I \lambda_0^2 \approx 2.5 \times 10^{15} \theta_h$, where I is in W/cm^2 , λ_0 in μm , and θ_h in keV. Simulations²³ show that light with this intensity will produce a heated temperature of $\theta_h \approx 1.2 \times 10^{-5} \theta_B^{0.25} [(I \lambda_0^2)^{0.39}]$, where θ_B is the thermal (background) electron temperature at the critical density. If we assume that θ_B is typically about 1 keV, these two equations suffice to determine the characteristic hot electron temperature to be expected: $\theta_h \approx 60$ keV. Hence, one indication of strong filamentation may be the appearance of heated electron temperatures in the range of 100 keV.

Electron Transport Inhibition. Finally, we have made progress in better understanding the mechanisms that impede electron transport. One commonly used model invokes ion acoustic turbulence generated by the heat flow instability to limit the flux of thermal electrons. Microwave experiments conducted at UC-Davis give evidence for

the generation of ion turbulence through this mechanism, but show that the heat flux carried by the suprathermal electrons is not significantly impeded by this turbulence. Thermal electron heat flow is found to be strongly modified, essentially because thermal electrons are heated by the enhanced dc resistivity associated with ion turbulence.

The hot electron flux can be more strongly impeded by self-generated magnetic fields. This year, we examined several new mechanisms for generating these fields. We found that the anisotropic velocity distribution of electrons heated by resonance absorption typically produces megagauss magnetic fields through the Weibel instability. These fields tend to channel the hot electron flow. In addition, we discovered a new parametric instability that produces fluctuating magnetic fields near the critical density.

Summary. In conclusion, our understanding of laser plasma coupling in long-pulse-length experiments is progressing but is, at best, semiquantitative. For example, our initial modeling of high-Z disk experiments²⁴ typically underestimated the hot electron temperature by a factor of about 2 and overestimated the number of hot electrons by a factor of about 2 to 3. Calculations of the amount of Brillouin scatter were about right for those experiments, but significant uncertainties about the angular distribution of this scatter exist. Iterations with experiments to date have improved the modeling, but the parameter space is large enough to require much more iteration. The plasma group is actively involved in helping to design new experiments to test and improve our modeling.

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3.5.2 Absorption in the One-Quarter Critical Density Region

Nonlinear saturation mechanisms of high-frequency instabilities that occur at or below quarter-critical density in laser plasma interactions are currently of experimental interest.²⁵⁻²⁸ Increasing evidence for a high-energy electron component²⁹ has focused attention on these instabilities, including the $2\omega_{pe}$ process, the decay of the incident electromagnetic wave into two plasma waves, and the stimulated Raman scattering (SRS), in which the incident light decays into an electromagnetic wave and a plasma wave. These high-frequency instabilities, though less absorptive than mechanisms at critical density, generate high-energy electrons that may contribute to preheat and core-corona decoupling. We have simulated this density region using the computer model ZOHAR,³⁰ and find that ion dynamics determine the saturation of these high-frequency instabilities over a large parameter range.

Referring to previous work,^{30,31} we will describe briefly Case A, a simulation with the ion motion frozen and parameter choices guided by laser plasma interaction experiments with an Nd:glass laser. The simulation system consists of a plasma slab with a linear density gradient in the x or open-sided direction and periodic in the y direction. The light, normally incident from the left, produces an oscillatory velocity, $v_0 = 0.1c$ (10^{16} W/cm² for Nd:glass). The background electron temperature is 1 keV, and the density gradient scale length corresponds to 25 vacuum wavelengths (λ_0) from vacuum to critical density (ρ_c). The $2\omega_{pe}$ instability occurs first with a growth rate of $0.01 \omega_0$, approximately half the maximum³² $k_0 v_0/4$ (Fig. 3-22, Case A). Modes 3 and 4 ($k_y \approx k_0$) are the most unstable, as predicted by theory.³³ For these parameters,

Fig. 3-22. Longitudinal field energy vs time for four simulations with $v_0 = 0.1c$ and $25\lambda_D$ density gradient scale length: Case A, $T_e = 1$ keV and immobile ions; Case B, $T_e = 1$ keV, $m_i/m_e = 3600$, and $ZT_e/T_i = 4$; Case C, $T_e = 1$ keV, $m_i/m_e = 100$, and $ZT_e/T_i = 4$; Case D, $T_e = 10$ keV, $m_i/m_e = 100$, and $ZT_e/T_i = 4$.

$k_0\lambda_{De} \lesssim 0.1$, and higher electron plasma wave numbers are limited by Landau damping. Raman backscatter has slower growth because of its higher gradient threshold,³⁴ and emerges after $650\omega_0^{-1}$. For this restricted problem, saturation is caused by electron trapping with $\sim 20\%$ absorption into a 70-keV Maxwellian ($\ln f(E) \propto -E/70$ keV out to 450 keV).

Before SWS dominates the simulation, the $2\omega_{pe}$ peak decay wave oscillation velocity is greater than five times the thermal velocity. Therefore, ponderomotive forces exceed thermal forces and ion motion must be included. Case B incorporates the ion motion into Case A with $m_i/m_e = 3600$ and $ZT_e/T_i = 4$. Initial growth is the same, but initial saturation occurs below the level reached in Case A.

at the same time (Fig. 3-22, Case B). Large-amplitude ion fluctuations, driven up by the ponderomotive forces from the electron plasma waves and concentrated just below the quarter-critical region with both x - and y -dependent variation (Fig. 3-23), arrest the growth of the $2\omega_{pe}$ decay waves by coupling them to short-wavelength, more strongly damped fluctuations.³⁵ The largest ion fluctuation is in mode 6 ($k_y = 1.8k_0$), with $\delta n/n$ reaching $\sim 20\%$.

This process is reminiscent of the oscillating two-stream instability and plasmon + phonon decay with finite-wavelength pump, but it is simpler because several plasma waves with low-frequency beats already exist. That is, the parametric instability feedback mechanism, in which beating plasma waves are driven up by the ion perturbation and the pump, is unnecessary and the ion fluctuations here grow more immediately.

Simple estimates clarify the saturation mechanism. A standing plasma wave (k, ω) produces an ion perturbation δn at $2k$, which, in turn, couples it to a heavily damped plasma fluctuation at $3k$. Equating the resulting damping rate³⁵ to the instability growth rate predicts $\delta n/n \approx 1/2$, which is within a factor of two of the observed value. Using two coupled equations for wave energy and density fluctuation, we find ion inertia essential to model the relaxation behavior.

At initial saturation, the density profile shows negligible change. However, an outward impulse

Fig. 3-23. Ion density contours for the simulation of Case B, Fig. 3-22, at initial saturation, $\omega_0 t = 650$. The quarter-critical surface is at $k_0 x = 26$ and the contours are $0.05 n_0$ apart.

has been delivered to the ions, causing a density depression to form, which then evolves into a density step as the plasma below quarter critical expands and blows off. We have not attempted to run a realistic mass ratio simulation long enough to observe profile steepening. To study this later evolution, we use an ion-to-electron mass ratio that is artificially low but still separates the electron and ion time scales. For Case C, similar to Case B but with $m_i/m_e = 100$, initial saturation occurs earlier and at a lower level (Fig. 3-22, Case C). The profile then steepens to $L \approx 5\lambda_0$, which is sufficient to stabilize the instability.³³ To present easily visible profiles in Fig. 3-24, the y-averaged density at initial saturation ($\omega_{qt} = 360$) and the subsequently steepened profile ($\omega_{qt} = 750$) are from a simulation similar to Case C, except that $T_i = T_e$ to minimize Brillouin scattering in the plot. Brillouin scattering occurs in all simulations in which ion motion is included. But its relatively long-wavelength ion-decay waves and its presence throughout the underdense plasma (in contrast to Fig. 3-23) combine with its slow growth rate to distinguish it from the instabilities studied here. In Case C and its $T_i = T_e$ variant, the high frequency instabilities and the profile do have the same behavior as functions of time.

This steepened profile then inhibits the high-frequency instabilities, even after the short-wavelength ion turbulence subsides. Eventually the profile relaxes and the instabilities recur. As another example of the electrostatic energy as a function of time, a low-mass-ratio simulation with 10-keV electron background (Case D) is shown in Fig. 3-22. For the parameter range we have considered, the peak longitudinal field energy and the time between bursts of varying clarity differ, but the qualitative description holds.

Direct experimental evidence consistent with this complex saturation mechanism has been observed in CO₂ laser plasma interaction experiments by Baldi, Samson, and Corkum.²⁵ They report profile steepening by a factor of three through the quarter-critical region as the $2\omega_{pe}$ instability turns off. Also, they observe enhanced ion fluctuations that may be identified with those described here.

Because the importance of density profile modification to $2\omega_{pe}$ was first reported,³⁰ a theoretical description in terms of solitons has been proposed.³⁶ Our low-mass-ratio simulations easily satisfy the condition given for validity of the theory, $v_0/c \ll 5(m_0/n_0)^{1/2}$. If we apply Eqs. (15) through

(16) of Ref. 36 to Case C, the predictions are too small. Their v_w/v_{th} is 0.7 vs ~ 3 at initial saturation, and their density fluctuation is 2% compared to 25% for the highest mode at $\omega_{qt} = 400$. Furthermore, the absorption is 0.025% as compared with $\sim 1\%$ in this simulation.

Even qualitatively, the soliton approach assigns the ions too limited a role. Because Ref. 36 includes only a single decay pair and averages over the short-wavelength beat, the driving force for the ion fluctuations responsible for saturation is omitted. These ion fluctuations are two-dimensional as opposed to the ion perturbation in Ref. 36, which depends only on x , the density gradient direction. The theory envisions decay plasmons always self-trapped in local density depressions given by the hydrostatic response to the ponderomotive pressure of the decay waves. In the simulations, the decay plasmons have already been damped before a density depression forms. When $2\omega_{pe}$ resumes, the ion density (averaged over y) has become monotonic in x , thereby excluding plasmon trapping. Even in small mass-ratio simulations, ion inertia causes obvious delays and overshoots in the ion response at both short and long wavelengths.

We now discuss the implications of $2\omega_{pe}$ saturation for some recent experiments.³⁷ We use

Case D, the simulation with the 10-keV background temperature, on the assumption that heating at critical density is flooding the quarter-critical region with hot electrons.³⁷ Whereas steepening at critical density enhances resonance absorption, steepening at quarter-critical limits $2\omega_{pe}$ and Raman scattering. Absorption (averaged over instability bursts and quiescent interim periods) is 6% in Case D. (Absorptions of 1 to 10% encompass other simulation results.)

Electron heating, correlated with these recurrences, results in a 75-keV Maxwellian out to 450 keV. This is somewhat hotter than the spectrum produced by resonance absorption for the same simulation conditions.³⁸ However, this result needs qualification. Thirty percent of the electron energy is above 0.5 MeV in a 10-keV simulation with the pump incident at 40° and with particle boundary conditions that model suprathermal reheating. Above 10 keV, Landau damping limits heating from $2\omega_{pe}$ and Raman scattering at 10^{16} W/cm², although "hot spots" in the beam or filamentation may produce local, discrete regions of intensity large enough to overcome plasma wave damping.²⁸ Experimentally, high-energy electrons appear when plasma conditions are hospitable to parametric instabilities.²⁶

The emission of $3\omega_0/2$ light has long been used as a diagnostic of the quarter-critical surface.²⁷ In our simulations, both $3\omega_0/2$ and $\omega_0/2$ emission occur at low levels. For Case D, 1% of the incident power emerges as $\omega_0/2$ light, peaked at a slab exit angle of 31° . Less than 0.1% of the incident power is in $3\omega_0/2$ emission. However, these fractions do not imply that SRS is dominating $2\omega_{pe}$. Raman scattering produces $\omega_0/2$ directly, while $3\omega_0/2$ light is a subsequent combination of a decay plasma wave and a light wave at ω_0 , or higher-order combinations, e.g., of three plasma waves. If Raman scattering were dominant, the energy in the heated particle distribution would at least equal the energy in $\omega_0/2$ production. Even assuming that half of this $\omega_0/2$ light is resonantly absorbed at its critical surface, enough $\omega_0/2$ is still not emitted. Also, self-steepening through the quarter-critical region limits SRS more than $2\omega_{pe}$.³²⁻³⁴ Another possibility is that the $2\omega_{pe}$ decay plasma waves at $\omega_0/2$ couple to electromagnetic waves by tunneling, a process that may be thought of as inverse to resonance absorption.

Thus, simulations indicate that $2\omega_{pe}$ is probably dominant near quarter-critical. Important

components in the saturation are damping by short-wavelength ion fluctuations and profile self-steepening. The $2\omega_{pe}$ instability exhibits relaxation behavior that limits its efficiency as a light absorption mechanism and displays characteristic experimental signatures.

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3.5.3 Relativistic Wave Breaking of Resonantly Driven Electron Plasma Waves

The coupling of laser light through density gradients into electron plasma waves (resonance absorption³⁹⁻⁴²) has been found to be an important absorption process.⁴³ Some important features of this coupling depend on the amplitude to which the plasma waves can be driven. This amplitude is

usually determined by a nonlinear process called wave breaking,⁴⁴ in which electrons are resonantly accelerated by the driven plasma wave. Here, we show that this wave-breaking amplitude can be reduced by relativistic effects, and we estimate when this effect is important for resonance absorption of laser light. We compare detailed numerical calculations with previous theory⁴⁵ and with particle simulations.

To describe the resonant driving of electron plasma waves we adopt the well known capacitor model.^{40,41} In this model, an oscillating driver electric field of the form $E_d \sin \omega_0 t$ (simulating a component of the laser light field near the critical density n_{cr}) is applied to an inhomogeneous plasma. By oscillating electrons along the direction of the density gradient, this driver field produces charge fluctuations that resonantly drive an electron plasma wave at the critical density. The field of the plasma wave grows in time, becoming more and more peaked near the critical density, until electrons are resonantly accelerated through the intense, localized wave. This is wave breaking. From a more microscopic point of view, it occurs when electrons, which were initially at different locations, cross one another because of their oscillation in the field of the electron plasma wave.

Relativistically, the mass of the electron becomes a function of the oscillation velocity v_w of an electron in the electric field E_w of the plasma wave. Hence, the electron plasma frequency becomes dependent on wave amplitude, which detunes the resonant driving of the wave by the imposed oscillating field. This detuning does not limit the growth but simply shifts the resonance to a higher density. The important effect is that, because the electric field is a function of position, the amplitude dependence of the electron plasma frequency introduces an additional spatial variation. This enhances the effective density gradient and allows neighboring electrons to cross one another at a lower amplitude of oscillation.

To investigate this relativistic effect in its simplest context, we describe the plasma as cold and adopt a one-dimensional Lagrangian description in which the position of each electron (x) is its initial position (x_0), plus a displacement ξ (x_0). Poisson's equation then readily gives the electric field

$$E = 4\pi n_0 e \xi + E_d \sin \omega_0 t.$$

where the first term is the self-consistent plasma field and the second is the imposed driver field. The dynamics are then completely described by

$$\begin{aligned} \frac{dp}{d\tau} &= -\frac{x_0}{L} \xi - \frac{v_d}{c} \sin \tau \\ \frac{d\xi}{d\tau} &= \frac{p}{\sqrt{1+p^2}}, \end{aligned} \quad (6)$$

where p is the momentum ($\gamma \xi$, $\gamma = \sqrt{1+p^2}$) normalized to c , the velocity of light, τ is the time normalized to ω_0^{-1} , and ξ is the displacement normalized to c/ω_0 . Here $v_d = eE_d/m\omega_0$ is the oscillation velocity of an electron in the imposed driver field. This description is exact until electron crossing occurs; i.e., until wave breaking.

These equations were solved on a computer to give $p(x_0, \tau)$ and $\xi(x_0, \tau)$. It is instructive to look at a particular example in which $v_d/c = 0.0346$ and $\omega_0 L/C = 17.32$. Some plots of momentum vs time for electrons at three different initial locations are shown in Fig. 3-25. The momentum of an electron at the critical density [Fig. 3-25(a)] grows linearly in time, as expected for a resonantly driven oscillator, and then saturates as the field becomes large enough to detune the resonance. As shown in Figs. 3-25(b) and (c), the momenta of electrons at somewhat higher density continue to grow, demonstrating the shift of the resonant point to higher density. Finally, wave breaking first occurs at $n \approx 1.15 n_{cr}$, when $\omega_0 t = 57.4$.

The amplitude of the momentum at breaking is $P_b/c \approx 0.77$, and the wave amplitude is $eE/m\omega_0 c \approx 0.70$. We note that the momentum and wave amplitude are actually larger at somewhat lower density, showing that the maximum fields do not occur at the location of wave breaking. This result emphasizes that the breaking amplitudes are lowered by the additional gradient introduced by the relativistic mass variation.

A heuristic derivation of the relativistic wave breaking amplitude emphasizes this point. The relativistic mass variation lowers the plasma frequency by $\sim 3/16 (v_w^2/c^2) \omega_{pe}$, where it is assumed that $v_w \ll c$. Hence, the relativistic correction corresponds to a density change of $n_{rel} \approx 3/8 (v_w/c)^2 n_{cr}$ in the distance over which the wave is peaked, which is about $X = eE_w/m\omega_0^2$ at breaking.

Hence, $L_{rel} \approx 8/3 c^2/v_w \omega_0$. Using this scale length in the well-known nonrelativistic prediction gives

$$\frac{P_b}{c} = 1.7 \left(\frac{v_d}{c} \right)^{1/3}, \quad (7)$$

which is quite close to the result of Drake and Lee⁴⁵ $[1.45 (v_d/c)^{1/3}]$.

We computed the amplitude of the momentum at wave breaking for a variety of conditions and then compared it with theory. Figure 3-26(a) shows P_b/c as a function of v_d/c for a fixed L ($\omega_0 L/c = 10$); Fig. 3-26(b) shows P_b/c as a function of L for a fixed v_d ($v_d/c = 1.1 \times 10^{-4}$). The solid and broken lines denote the predictions from nonrelativistic⁴⁰ and relativistic⁴⁵ theory, respectively.

Fig. 3.26. Momentum of an electron at the location and time of initial wave breaking as a function of (a) driver field amplitude (v_d/c) for ($\omega_0 L/c = 10$) and (b) density scale length ($\omega_0 L/c$) for $v_d/c = 1.1 \times 10^{-4}$.

Clearly, the relativistic mass variation significantly lowers breaking amplitudes over a large range of parameters. The relativistic theoretical prediction [$P_0/c \approx 1.45 (v_d/c)^{1/3}$] is in reasonable semiquantitative agreement with the detailed numerical results. It is interesting that the theory seems least accurate when L is large.

We have checked our numerical calculations with the results from particle simulations. We used a standard one-dimensional, electrostatic particle simulation code, extended to include relativistic dynamics. In the particle simulations, wave break-

ing was simply inferred from the onset of streamers in phase space. Because it was most convenient in the particle simulations to measure the maximum electric field amplitude up to the time of wave breaking, we compared this measurement with the maximum fields predicted by numerical integration of Eq. (6). As shown in Table 3-2, we found that the particle simulations are in good agreement with the solution of the differential equations.

To conclude, we estimate when the relativistic mass variation reduces the amplitude of plasma waves resonantly driven by intense laser light. If we

Table 3-2. Particle simulations (in which it was most convenient to measure the maximum electric field up to the time of wave breaking).

$\frac{v_d}{c}$	$\frac{\omega_0 L}{c}$	$\left(\frac{eE_{\max}}{m\omega_0 c}\right)_{\text{simulation}}$	$\left(\frac{eE_{\max}}{m\omega_0 c}\right)_{\text{diff eq.}}$
1.732×10^{-3}	0.866	0.053	0.055
1.732×10^{-2}	8.66	0.52	0.54
3.464×10^{-2}	17.32	0.94	0.94
8.66×10^{-2}	43.3	1.71	1.59

neglect thermal corrections,⁴⁶ the relativistic prediction is less than the nonrelativistic prediction when

$$\frac{v_d}{c} \geq \frac{9}{\left(\frac{\omega_0 L}{c}\right)^3}. \quad (8)$$

To relate the capacitor model to resonance absorption of light, we note that

$$E_d = \frac{E_L \Phi(\tau)}{\sqrt{2\pi \frac{\omega_0 L}{c}}}, \quad (8a)$$

where E_L is the electric field of the light in free space, and $\Phi(\tau)$ is the well-known resonance function with a maximum value of ~ 1 for $\tau = (\omega_0 L/c)^{1/3} \sinh \approx 0.6$. Hence, relativistic mass corrections are significant when

$$\frac{v_L}{c} \approx \frac{23}{\Phi(\tau)} \left(\frac{\omega_0 L}{c}\right)^{-5/2}, \quad (9)$$

where

$$v_L = eEL/m\omega_0.$$

Equation (9) shows that for strongly steepened profiles, $(\omega_0 L/c \approx 1-3)$, v_L/c must be of the order of 1 for the relativistic corrections to matter (intensity of order 10^{18} W/cm² for 1- μ m light).

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3.5.4 Plasma Density Profiles in the Presence of Supersonic Flow

Absorption of electromagnetic radiation by an inhomogeneous plasma can be strongly affected by the plasma density profile at the critical surface (where the electron plasma frequency equals the electromagnetic driver frequency). The steady state density profile is determined by a balance between the pondermotive force (caused by the high-frequency driver) and the thermal pressure. The addition of plasma flow completes a simple picture for the plasma density profile in an electromagnetic-plasma interaction. The spherically symmetric, stationary, steady state MHD equation of motion is given by:

$$(C_s^2 - v_r^2) \frac{dn}{dr} = - \frac{ne^2}{2m_e M \omega_0^2} \frac{d}{dr} \langle E^2 \rangle + \frac{nv_r^2}{r}.$$

Numerical solutions to nonstationary, nonplanar, one-fluid equations show that supersonic flow ($v_r \gtrsim C_s$) forms different density profiles than does the step profile seen in cases with subsonic flow (or any flow velocity in planar solutions). Solutions to the nonstationary, cylindrical-like, one-fluid equations are seen in Fig. 3-27.

Measurements⁴⁷ of the plasma density profile have been conducted in the U.C.-Davis PROMETHEUS device at microwave powers of $v_0/v_e \gtrsim 0.4$. Using the rapid change in the electron temperature in a decay discharge plasma to generate temporary supersonic flow, we have measured plasma density profiles in both subsonic and supersonic flows.

In the subsonic regime, the familiar step density profile is formed. The steady state steepened density scale length

$$L = n_c \left(\frac{dn_c}{dx} \right)^{-1}$$

initially decreases with microwave power to a minimum of $60\lambda_{De}$ at 100 W ($v_0/v_c \approx 0.1$). At higher power, the scale length increases (see Fig. 3-28). This increase may result from the observed increase in the thermal temperature at the critical density. A noticeable second density modification is seen at $n_c/2$, the electromagnetic turning point.

Fig. 3-30. Density profiles with superimposed field with $v_0/v_e = 0.4$. Multiple shots for A, B, with C and D, E, and F at, respectively.

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3.5.5 Resonant Absorption Caused by dc Magnetic Fields Parallel to the Density Gradient

We have shown that a dc magnetic field in the plasma can increase resonant absorption. However, previous work⁴⁸ has concentrated on a magnetic field applied perpendicular to the density gradient. This field couples the incoming electromagnetic waves into upper-hybrid (electrostatic) waves that

The step-like shape does not form in supersonic flow. Instead, a large, overdense density bump grows in the underdense plasma. This structure is similar in form to the numerical solution seen in Fig. 3-27 (see Fig. 3-29). This profile appears to be long-lived, although many ion times later some change is seen that might indicate that the supersonic profile is not a steady state. Indeed, using the nonstationary, one-fluid equation, it can be shown that no steady state solution exists. The cavity that is formed (width $\approx 30\lambda_{De}$) behind the overdense bump acts to trap the electrostatic field. At increased microwave power ($v_0/v_e > 0.3$), large amplitude turbulence develops above and below the initial density. We are now making measurements to determine whether this turbulence affects energy transport, or heating, or both at the critical surface (see Fig. 3-30).

are responsible for the absorption. On the other hand, only electromagnetic waves can be coupled by a magnetic field applied parallel to the density gradient. Here, we want to show that these secondary electromagnetic waves can serve as new electromagnetic drivers to drive the electrostatic waves that are responsible for additional absorption. In other words, the electrostatic waves are driven indirectly by the incoming electromagnetic light, and they can be plasma waves, upper-hybrid waves, or a combination of both. If treated separately, the maximum absorption is about 20%, as a result of plasma waves, and about 73% as a result of upper-hybrid waves. However, if the two effects are combined, a maximum absorption of about 90% can be achieved.

This new absorption mechanism resulting from the indirectly driven electrostatic waves is well separated from absorption caused by the directly driven electrostatic waves⁴⁸ in the s-polarization case. Therefore, we find that the maximum absorption is about 90% ($b_x \approx b_z$ curve in Fig. 3-31), even in the s-polarization case in which one generally does not expect high absorption. Because the polarization state will be changed after the electromagnetic wave enters the magnetized plasma, s- and p-polarizations refer to the incoming state of the light. The combination of indirectly driven absorption and directly driven absorption will also be studied for completeness.

We have derived⁴⁸ the following linearized high-frequency equation for the light wave ($E_h \propto e^{i\omega t}$) propagating in a magnetized plasma:

$$\nabla \times \nabla \times \vec{E}_h - (\gamma_e k T_e / mc^2) \nabla (\nabla \cdot \vec{E}_h) - k_0^2 \epsilon \vec{E}_h + i\vec{b}_0 \times (\nabla \times \nabla \times - k_0^2) \vec{E}_h = 0, \quad (10)$$

where

$$\epsilon = 1 - \frac{4\pi n_e e^2}{m\omega^2}, \quad \vec{b}_0 = \frac{e}{m\omega c} \vec{B}_0, \quad \vec{B}_0 \parallel \vec{B}_0$$

is the externally imposed dc magnetic field, and the subscript h(L) designates high- (low-) frequency quantities.

We assume $E_h = [\hat{x}E_x(x) + \hat{y}E_y(x) + \hat{z}E_z(x)]e^{-ik_0 y}$, where $\alpha_0 = \sin\theta$ and θ is the angle of incidence, $n_r = (x/L)n_c$, and $\vec{b}_0 = \hat{x}b_x + \hat{y}b_y + \hat{z}b_z$. Using Faraday's law and $T_e = 0$, from Eq. (10) we obtain

$$\epsilon_R E_x = -\alpha_0 (1 - b_0^2) B_z + i(n_r/n_c) (b_z E_{dy} - b_y E_{dz}), \quad (11)$$

where $\epsilon_R = \epsilon(1 - b_0^2) - b_y^2 - b_z^2$, $E_{dy} = E_y + ib_x E_z$, and $E_{dz} = E_z - ib_x E_y$. One can see that E_x is resonant at the point $\epsilon = (b_y^2 + b_z^2)/(1 - b_0^2)$. Equation (11) is a general equation for E_x driven by the sum of all the driver terms. The first term on the right side drives plasma waves, and the second term drives upper-hybrid waves if they are treated separately. In general, all the drivers, B_z , E_{dy} , and E_{dz} , are coupled and described by a set of coupled equations.

To independently study the indirectly driven electrostatic waves, we consider the s-polarization case (incoming light polarized in the z direction). If $\vec{b}_0 = \hat{x}b_x$, we can describe the driver B_z in Eq. (11),

Fig. 3-32. Maximum absorption as a function of $\sin \theta(\alpha_0)$ by optimizing b_x for the solid line and by setting $b_x = 0$ for the dashed line. Here $b_y = b_z = 0$. The p and 45° (dashed) curves result from directly driven plasma waves; the s curve results from indirectly driven plasma waves; the 45° (solid) curve is a result of the combination of both.

which drives the plasma waves, as from Eqs. (10) and (11)

$$\epsilon \frac{d}{dx} \left(\frac{1 - b_x^2}{\epsilon - b_x^2} \frac{dB_z}{dx} \right) + k_0^2 (\epsilon - \alpha_0^2) B_z = - \frac{k_0 b_x \epsilon}{n_c} \frac{d}{dx} \left(\frac{n_0 E_z}{\epsilon - b_x^2} \right). \quad (12)$$

Equation (12) shows that B_z exists even in the s-polarization case if $b_x \neq 0$.

For indirectly driven upper-hybrid waves, we consider normally incident, s-polarized light with $b_0 = \hat{x}b_x + \hat{z}b_z$. Again, from Eqs. (10) and (11), we obtain an equation for the driver E_{dy} in Eq. (11) as

$$\epsilon_R \frac{d^2}{dx^2} E_{dy} + k_0^2 \left[(1 + b_x^2) \epsilon^2 - 2b_x^2 \epsilon - b_z^2 \right] E_{dy} = \frac{ik_0^2 b_x n_0 \epsilon_R}{n_c} E_z. \quad (13)$$

Fig. 3-33. Same interpretation as in Fig. 3-32, except $b_y = \sin \theta = 0$, the absorption is changed to b_z , and plasma waves are changed to upper-hybrid waves.

Again, Eq. (13) shows that E_{dy} exists if $b_x = 0$.

We solve Eq. (10) for the parameters $v_e/c = 0.1$ and $k_0 L = 10$, where $v_e = \sqrt{kT_e/m}$. We find that the absorption is almost independent of plasma temperature. In Figs. 3-32 and 3-33, the solid lines give the maximum absorption vs α_0 and b_z , respectively (parameter b_x is optimized), for the case $b_y = b_z = 0$ ($b_y = \alpha_0 = 0$). The three polarization cases, p, 45°, and s, are given.

Fig. 3-34. Same interpretation for the labeled and the unlabeled parameters as in Fig. 3-31 for p-polarization. Lowest curve results from the directly driven plasma waves; the b_z curve is a result of the combination of the directly driven plasma and upper-hybrid waves; the $b_x \approx b_y$ curve is a result of the combination of the directly driven plasma waves and the indirectly driven upper-hybrid waves.

The absorption for s(p)-polarization is given in Figs. 3-31 and 3-34, respectively. Each curve is labeled by the optimized parameters; the other parameters are set to be zero.

The maximum absorption in Figs. 3-31 and 3-34 is determined by the condition that the electromagnetic drivers in Eq. (11) are in phase and by $(k_0 L)^{2/3} \epsilon_T \approx 0.5^1$, where ϵ_T is a function of α_0 , b_x , b_y , and b_z , and where it is the effective dielectric constant at the turning point of the electromagnetic drivers. However, in general, the explicit expressions for the phase condition and ϵ_T are difficult to find analytically.

In summary, we have demonstrated a new type of resonant absorption caused by the indirectly driven plasma and upper-hybrid waves that are generated when a dc magnetic field is applied parallel to the density gradient. Maximum absorption for s polarization is now 90%.

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3.5.6 Heated Electron Distribution

Functions from Resonant Absorption vs Angle and ZT_e/T_i

The 1975 annual report⁴⁹ described the results of two-dimensional kinetic simulations (ZOHAR⁵⁰) that predicted the self-consistent absorption of laser light with angle via resonant absorption⁵¹. The continuation of this work was discussed in the 1976 and 1977 annual reports,^{52,53} which described the heated electron temperatures as functions of laser light intensity and wavelength and the background electron temperature.⁵⁴ The formula describing that dependence has been used in target simulations.

In 1978, we have used ZOHAR to examine the dependence of the heated electron temperature on ion temperature—as expressed in the functional $ZT_e/(3T_i)$ —and the angle of incidence. We then entered the fitted results into target codes. Z is the ion charge state, T_e is the electron temperature, and T_i is the ion temperature. Figure 3-35 presents the data of ZOHAR simulations, where T_{hot} from resonant absorption is a function of $[1 + 3T_i/(ZT_e)]$. As may be seen, T_{hot} is a reasonably good fit with

$[1 + 3T_i/(ZT_e)]^{0.25}$. The reason for this dependence is probably that the ion pressure increases the density gradient length at critical, and, thus, increases the distance through which the resonantly driven electric field accelerates the electrons.⁵⁵ A fit to the simulation data is

$$T_{hot} = T_e + 3.6 \times 10^{-6} T_e^{0.04} [1 + 3T_i/(ZT_e)]^{0.25} \times \left\{ I_0 [\lambda_0 / (1.06 \mu m)]^2 \right\}^{0.42}, \quad (14)$$

or

$$T_{hot} = 10^{-5} T_e^{0.25} \left\{ I [\lambda_0 / (1.06 \mu m)]^2 \right\}^{0.39} \times [1 + 3T_i/(ZT_e)]^{0.25}. \quad (15)$$

The temperatures are in keV, I is the laser irradiance in W/cm², and λ_0 is the laser wavelength in μm . For our target simulation model, T_e is the average energy of the electrons. Both formulas fit the data within the error bars. The upper equation has the advantage that T_{hot} never is less than T_e , and the next formula can be defended by analytic theory.⁵⁵

The dependence on angle was presented graphically in last year's annual report⁵³ and has also been seen experimentally.⁵⁶ As predicted by Kruer,⁵⁵ T_{hot} varies as the fraction absorbed to the 0.4 power as may be seen from the simulation data of T_{hot} vs angle⁵⁴ and absorption vs angle.⁵¹ Consequently, the latter half of Eq. (14), or Eq. (15), is simply scaled by the fraction absorbed vs angle curve to the 0.4 power. T_{hot} also depends on macroscopic magnetic fields and $Z^{0.25}$ (as pointed out by Manes et al.⁵⁷). Interpretation of this latter experimental observation is the subject of continuing work.

Fig. 3-36. Model of plasma flow.

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3.5.7 Stimulated Brillouin Scattering in Realistic Plasma Flow Profiles

The magnitude of stimulated Brillouin scattering (SBS) depends rather sensitively on the detailed structure of plasma density, temperature, and flow profiles. In turn, the presence of SBS modifies these profiles as a result of momentum deposition and ion heating. In previous annual reports,⁵⁸ these topics were discussed in conjunction with plasma simulation code results. In the past year, we have been

concerned with long time-scale (i.e., 0.2 to 1 ns) disk experiments on materials of various atomic numbers. We found that SBS plays a significant role in the overall energy balance. Accordingly, we have begun to investigate these experiments analytically and numerically. In this subsection, we discuss the effect of ion heating and flow effects (i.e., supersonic vs subsonic flow). We show some examples of these effects using the code AURUS (described in §3.5.14).

For our analytic treatment, we take as a model a slab of plasma of length L , with uniform density and uniform speed V (toward the laser). This geometry is shown in Fig. 3-36. It is important to note that the exponentiation time for SBS is much shorter than other times of interest, such as the ion heating or hydrodynamic times. Thus, we are interested in the time-asymptotic state of the instability. The slow time and space equations for the wave amplitudes may be obtained in the usual way.⁵⁹ The time-asymptotic state is found by simply letting $\partial/\partial t \rightarrow 0$. Thus, our model equations are

$$c \frac{\partial a_0}{\partial x} = -\gamma_0 a_s \tilde{n}, \quad (16)$$

$$c \frac{\partial a_s}{\partial x} = -\gamma_0 a_0 \tilde{n}, \quad (17)$$

$$\left[\nu + c_s (1 - M) \frac{\partial}{\partial x} \right] \tilde{n} = \gamma_0 a_s^* a_0. \quad (18)$$

Here, a_0 is the amplitude of the incident laser beam normalized to its free space value [$a_0^2(x=0) = 1$, $a_0^2(x=L) = T$, the transmissivity]; a_s is the

similarly normalized, backscattered wave [$a_s^2(0) = R$, $a_s^2(L) = \epsilon$, the noise level], $\tilde{n}$ is the fractional density fluctuation, c_s is the speed of sound, M is the Mach number, ν is the ion damping rate, and γ_0 is the maximum linear growth rate.⁵⁹ To this set, we add the ion heating equation,

$$n \left(\frac{\partial T_i}{\partial t} - \frac{Mc_s \partial T_i}{\partial x} \right) + \frac{\partial Q}{\partial x} = \nu \frac{E^2}{8\pi}, \quad (19)$$

where T_i is the ion temperature and Q is the heat flux. We assume that Q is flux-limited, so that

$$Q = -f n m_i \left(\frac{T_i}{m_i} \right)^{3/2} \sin \left(\frac{\partial T_i}{\partial x} \right). \quad (20)$$

Defining $\xi = T_i/ZT_e$, $T = \omega_{s0}t$, $z = kx$, where $\omega_{s0} = k(ZT_e/m_i)^{1/2}$ and $k = 2k_0$, Eq. (19) may be written⁶⁰

$$\left(\frac{\partial}{\partial \tau} - M \frac{\partial}{\partial z} - f \left| \frac{\partial^{3/2}}{\partial z} \right| \right) \xi_i = \nu/\omega_s \tilde{n}, \quad (21)$$

where

$$\omega_s = \omega_{s0} \sqrt{1 + 3\xi}. \quad (21a)$$

SBS heats ions through the ion damping rate ν , which has four components: (1) collisional damping, (2) linear Landau damping, (3) nonlinear Landau damping, and (4) wave breaking. Collisional damping, even for high- Z plasmas, is generally negligible. Linear Landau damping depends on the temperature ratio ξ . Initially, this ratio is very small, and the linear Landau damping is correspondingly low. However, as nonlinear Landau damping and wave breaking cause the SBS to heat the ions, $\xi \rightarrow 1$, and linear Landau damping becomes dominant.

In linear Landau damping, an ion with velocity V exchanges energy with a wave if $k \cdot V \approx \omega$. In nonlinear Landau damping, the ion may interact with two waves such that $\Delta k \cdot \nu \approx \Delta \omega$, where Δk and $\Delta \omega$ are the beat k and ω , transferring energy from one mode to the other. Thus, a single ion

mode may drive up a spectrum of lower frequency modes, concomitantly heating up the ions at an approximate rate:

$$\nu_{NL}/\omega_s \approx 0.3 \tilde{n}^2. \quad (22)$$

Ion trapping is the usual mechanism dominant in particle simulation codes. Here, ion waves steepen and break in a nonlinear manner, transferring energy directly to the ions. This occurs if

$$\tilde{n} > 1/4 \left(1 - \sqrt{3T_i/ZT_e} \right)^{1/2} \quad (23)$$

and gives a heating rate

$$\nu_{TR} \approx \min(\gamma_0, \omega_s). \quad (24)$$

In the weakly damped case, the ion fluctuation level can be estimated⁵⁹ as

$$\tilde{n} \approx \sqrt{2} \frac{V_0}{V_e} \frac{\omega_0}{\omega_{pe}} \frac{1}{(1-M)}. \quad (25)$$

From Eqs. (24) and (25), we see that trapping occurs if

$$\frac{V_0^2}{V_e^2} \geq 0.03 \frac{n}{n_c} (1-M)^2. \quad (26)$$

Below this level, nonlinear Landau damping is dominant.

The steady state temperature can be calculated from Eqs. (16-18) and (21):

$$M\xi + f\xi^{3/2} = (1-M)\tilde{n}^2 + c/c_s (a_0^2 - T) + M\xi_0 + f\xi_0^{3/2}. \quad (27)$$

The constant of integration is determined from the requirement that as $x \rightarrow \infty$, ξ goes to the initial temperature ratio ξ_0 .

We now consider the effect of Mach number. M is a function of various parameters, including heat flux inhibition and ponderomotive force. Generally, if heat transfer is reduced from the classical value, M decreases. In recent simulations of high- Z disk experiments, we found that a good match was attained using strongly inhibited heat flow, resulting in a primarily subsonic plasma.⁶¹ Consistent with this, experimental observations of the backscattered light showed a small net red shift (implying $M \approx 0.9$). However, other observations (on lower- Z targets) have shown a net blue shift (implying $M > 1$). It is fair to say that, at this point, flow Mach numbers are not well understood.

We can see the effect of M on SBS from Eq. (18). There are two main regimes, the weakly damped [$\nu \ll C_s(1-M)(\partial/\partial x)$] and the strongly damped [$\nu \gg C_s(1-M)(\partial/\partial x)$]. Initially ξ is small, so one expects to be in the weakly damped regime. This is not true at the sonic point, $M = 1$, which is clearly a special point for SBS, and may be where the instability originates in a realistic density profile.

The character of the instability is determined by the product of the group velocities, $-cc_s(1-M)$. For $M < 1$, this is negative, so that SBS may be absolute or convective. For $M > 1$, SBS is purely convective. Also, the boundary conditions change; for $M < 1$, density fluctuations are convected from $x = 0$ towards $x = L$, so that $n(0) = 0$. For $M > 1$, the convection changes direction, and $n(L) = 0$. It is interesting that, in the latter case, an exact analytic solution can be found for weak damping.

From Eqs. (16) and (17),

$$\frac{\partial a_0^2}{\partial x} = \frac{\partial a_s^2}{\partial x} \quad (27a)$$

Thus, $a_0^2 = a_s^2 + T$. From Eqs. (16) and (18), with $\nu = 0$,

$$c \frac{\partial a_0^2}{\partial x} = c_s(M-1) \frac{\partial n^2}{\partial x} \quad (27b)$$

so that

$$c_s(M-1)n^2 = c(a_0^2 - T) \quad (27c)$$

Therefore,

$$\begin{aligned} c \frac{\partial a_0}{\partial x} &= -\gamma_0 \sqrt{a_0^2 - T} \left[\frac{c}{c_s(M-1)} \right]^{1/2} \sqrt{a_0^2 - T} \\ &= -\gamma_0 \sqrt{\frac{c}{c_s(M-1)}} (a_0^2 - T) \end{aligned} \quad (27d)$$

The solution is

$$\frac{(\sqrt{T+\epsilon} - \sqrt{T})(1 + \sqrt{T})}{2\sqrt{T}(1 - \sqrt{T})} = e^{-\frac{2\sqrt{T}\gamma_0 L}{\sqrt{cc_s(m-1)}}} \quad (27e)$$

For $\epsilon \ll T$,

$$\frac{4T(1 - \sqrt{T})}{1 + \sqrt{T}} = \epsilon e^{\frac{2\sqrt{T}\gamma_0 L}{\sqrt{cc_s(m-1)}}} \quad (28)$$

A similar analysis for the case $M < 1$ shows a finite length threshold, given by $L = \pi/2 L_g$, where L_g is the growth length, $\sqrt{cc_s(1-M)/\gamma_0}$. Equation (18) shows no threshold.

Mach number effects also appear in the ion heating equation. Here, the main effect is that as ions are convected away faster and their temperature is less, it leads to reduced damping and larger reflectivity.

We have solved Eqs. (16-18) and (27) numerically, using linear and nonlinear Landau damping but not wave trapping. This regime occurs if the instability goes over to the strongly damped regime before trapping sets in.⁶⁰ A schematic representation of the results is shown in Fig. 3-37. We can distinguish four regimes. In the first, $\xi \ll 1$ and $n \ll 1$, so we are in the weak damping regime. As V_0^2/V_e^2 increases, $\tilde{n}$ increases and so does nonlinear Landau damping, so that in the second regime, we go over to heavy damping. In the third regime, $\xi \approx 0.1$, and linear Landau damping comes in exponentially. Thus, further increases in V_0^2/V_e^2 actually lead to a decrease in reflectivity. A decrease of R with increasing V_0^2 has been observed experimentally.⁶² In the fourth regime, $\xi \lesssim 0.3$, and linear Landau damping has saturated at about ω_s .

Fig. 3-37. Schematic representation of reflectivity vs V_0^2/V_e^2 . Numbers are representative for $k_0 L = 200$, $n/n_c = 2$.

Fig. 3-39. Ion temperature profile for gold disk target with strong thermal flux inhibition.

From here, reflectivity again increases with V_0^2/V_e^2 . Comparing the supersonic case (R_{sup}) with the subsonic case (R_{sub}), we see that at powers below the subsonic threshold, $R_{sup} > R_{sub}$. After the subsonic threshold, $R_{sub} > R_{sup}$ until linear Landau damping comes in. Because $\xi_{sup} < \xi_{sub}$, $\nu_{sup} < \nu_{sub}$ and therefore $R_{sup} > R_{sub}$. Finally, both cases approach the same value as linear Landau damping becomes saturated.

Figures 3-38 and 3-39 contain results from the hydrodynamic code AURUS. A 200-ps laser pulse

of intensity $3 \times 10^{15} \text{ W/cm}^2$ is incident on a gold slab. The heat flux is inhibited to 0.03 of the classical value. The electron density profile shows the steep drop through critical characteristic of inhibited heat transport. SBS is occurring on a shelf of density 0.3 critical and a length of about $40 \mu\text{m}$. The Mach number in this shelf is about 0.9. The shelf is uniform because momentum is being deposited in the underdense plasma as a result of SBS. Figure 3-39 shows the ion temperature as a function of distance. The heating region extends over the SBS unstable region. The final temperature ratio is $T_i/ZT_e = 0.3$, leading to significant Landau damping in this region. The Landau damping in the SBS active region is significantly lower, however, because of the lower ion temperature here.

The picture that emerges from this AURUS calculation is remarkably similar to our simple model: a box of uniform plasma with a uniform expansion velocity. However, the interaction length L is determined self-consistently by the SBS momentum deposition and ion heating.

Figure 3-40 shows an electron density profile from an AURUS run similar to those shown in Figs. 3-38 and 3-39 but without nonclassical thermal flux inhibition. The SBS active region is now from critical to about 0.8 critical. The Mach number at critical is about 2.4, decreasing to about 1.1 at 0.8 critical, as a result of SBS momentum deposition. The ion temperature rises to about 1.3 ZT_e . Here the zero-order density profile is closer to an isothermal expansion profile than to a uniform density shelf. However, the fluid velocity is approximately constant in this region. These two AURUS runs differed only in the magnitude of the thermal

Fig. 3-38. Electron density profile in (n/n_e) for gold disk target with strong thermal flux inhibition.

Fig. 3-48. Electron density profile (n/n_0) for gold disk target with constant electron temperature.

flux limiter, yet we see that the flow profile and the characteristics of the SBS-active region are drastically different. Further, we have seen that the momentum deposition due to SBS has significantly altered the flow pattern, leading to localized density steepening, slowing of the plasma flow, and localized ion heating. The length of the SBS-active region, and thus the total reflectivity, depends on the self-consistent interaction between plasma flow and reflection. We are presently using the code AURUS to study this in more detail.

It should be noted that this discussion was directed towards SBS in high-Z targets, where inverse bremsstrahlung is the predominant absorption mechanism. For low-Z targets, collective effects will predominate, leading to different flow profiles and thus different values of SBS reflectivity. This subject is also being studied.

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3.5.8 Comparative Study of Stimulated Brillouin Scattering and Filamentation in Homogeneous Plasmas

Stimulated Brillouin scattering and filamentation are both processes involving the interaction of incident light with ion modes in a plasma. To a large extent they may be expected to coexist in typical laser fusion situations, as they occur in similar regimes of laser intensity and plasma density. This work is a comparative study of Brillouin scattering and filamentation, and yields new results on their linear space-time behavior in the two limits where the ion mode is undamped and strongly damped. A more complete description is found in Ref. 63.

Weak Damping Regime: $ZT_e \gg T_i$. Much is known about Brillouin scattering and filamentation when the ion modes are weakly damped ($ZT_e \gg T_i$). References 64 through 66 contain extensive reviews of the subject. We present here new results on space-time behavior.

We have performed an absolute-instability analysis of stimulated Brillouin scattering using methods described in Ref. 67. We find that only backscatter is absolutely unstable. Sidescatter and forward scatter are convective. We can then study the spatial and temporal evolution of Brillouin scattering following a delta-function excitation, both analytically and numerically.

Analytically, the asymptotic Green's function describing density perturbation for Brillouin backscattering well above the threshold for absolute instability is

$$G(x, t) \propto \exp[i2k_0(1 - c_s/v_g)(x_{\parallel} - c_s t)]$$

$$\exp[2\gamma_0(c_s/c)^{1/2} t] \times (\sigma_{\perp} \sigma_{\parallel})^{-1}$$

$$\exp[ik_0 x^2/c_s t - \gamma_0 x_{\parallel}/(c_s c)^{1/2}]$$

$$\exp[-x_{\perp}^2/2\sigma_{\perp}^2 - x_{\parallel}^2/2\sigma_{\parallel}^2], \quad (29)$$

where

$$\sigma_{\perp}^2 = (cc_s^3)^{1/2} (\tau/\gamma_0)$$

$$\text{and } \sigma_{\parallel}^2 = (cc_s^3)^{1/2} (\tau/\gamma_0) [2 - (v_0^2/c^2)$$

$$\times (\omega_{pi}^2/16k_0^2c_s^2)] .$$

Green's function for the backscattered transverse wave is proportional to $\exp(i\vec{k}_0 \cdot \vec{x} - i\omega_0 t)$ $G^*(x, t)$. Here k_0 , ω_0 , and V_g^x are the wave vector, frequency, and group velocity of the incident light wave, $x_{\parallel}$ and $x_{\perp}$ are, respectively, distances parallel and perpendicular to k_0 ; $c_s = (ZkT_e/M_i)^{1/2}$ is the sound speed, $\gamma_0^2 = k_0^2 v_0^2 \omega_{pi}^2 / (8k_0 c_s \omega_0)$, $v_0 = eE_0 / m_e \omega_0$, $\omega_{pi}^2 = 4\pi n_0 Z e^2 / M_i$, and n_0 is the unperturbed electron number density.

Green's function exponentiates in time with rate $2\gamma_0(c_s/c)^{1/2}$ and has a diffusing spatial envelope with widths $\sigma_{\perp}$, $\sigma_{\parallel} \propto \sigma_{\perp}^{1/2}$. The envelope is spatially asymmetric; half-widths $(\alpha \sigma_{\perp, \parallel})$ scale similarly but differ by a numerical factor.

Validity requirements for the Taylor expansions used in calculating the Brillouin pinch point are

$$\frac{\text{Im} \omega_*}{\text{Re} \omega_*} = \frac{\gamma_0}{2k_0 c_s} \left(\frac{c_s}{v_g} \right)^{1/2} \ll 1$$

well above threshold. Here ω_* and k_* are the frequency and wave number characterizing absolute instability. The growth rate for absolute instability is thus reduced by the factor $(c_s/v_g)^{1/2} \ll 1$ below the convective growth rate for Brillouin weak coupling: $\text{Im} \omega \approx \gamma_0$.

For strong pump waves, if one simply solves for the frequency of the density perturbation as a function of its real k , one finds a well-known regime called "strong-coupling" Brillouin, where the imaginary part of ω is comparable to its real part. For $k^2 - 2kk_0 \cos \theta = 0$,

$$\omega = (1/2) (1 + i\sqrt{3}) (\cos \theta)^{2/3} (\omega_{pi}^2 k_0^2 v_0^2 / 2\omega_0)^{1/3} . \quad (30)$$

Here θ is the angle between $\vec{k}_0$ and $\vec{k}$. However, we find that for all practical purposes, this distinction

between weak and strong coupling Brillouin disappears when one considers absolute instability.

This can be seen from Eq. (29), but is perhaps shown more vividly in Figs. 3-41 through 3-43. These figures present direct numerical solutions for the Brillouin pinch-point frequencies and wave numbers, describing absolute instability. They show that the absolute instability growth rate and its real frequency remain very close to those describing weak-coupling Brillouin, even in the regime $k^2 v_0^2 \omega_{pi}^2 / (8\omega_0) \gg k^3 c_s^3$, where the simple dispersion relation indicates that the strong-coupling limit should apply. Figures 3-41 through 3-43 show instead that the frequencies and wave numbers for absolute instability deviate from the weak-coupling form only for pumps so strong that the forward-scattered light wave must be included in the analysis. Estabrook⁶⁸ confirms that particle-in-cell computer simulations tend to show weak-coupling characteristics even in the regime where simple stability analyses predict strong coupling.

One can also analyze the linear instability behavior of filamentation for $ZT_e \gg T_i$. For very weak pump-wave intensities and $\omega_{pe} < \omega_0$, Brillouin and filamentation are well separated in wave number space. Brillouin weak coupling is localized to wave numbers for which $|k - 2k_0 \cos \theta| \ll |k + 2k_0 \cos \theta|$, and it has a maximum

growth rate for backscatter. Filamentation generally has lower growth rates and thresholds and

is characterized by long-wavelength ($k \ll k_0$) density perturbations with orientation nearly perpendicular to $\vec{k}_0$. Numerical solutions for weak pumps demonstrate that filaments with finite $\cos\theta$, and hence finite $k_{\parallel}$, have a wave number k corresponding to maximum growth that is shifted relative to the wave number when $k_{\parallel} = 0$, a narrower range of unstable wave numbers, and generally reduced growth rates.

On the other hand, for pump waves of sufficient intensity to induce Brillouin strong coupling, the growth rates of Brillouin and filamentation merge smoothly into one another (see Fig. 3-44). The dashed line marked 90° in Fig. 3-44 corresponds to the growth rate for filamentation, which has $\text{Re } \omega = 0$. For each $\theta \neq 90^\circ$, the growth rate peaks at a value of k given by $k = 2k_0 \cos\theta$, corresponding to strong coupling Brillouin scattering. However, to the right of every peak, $\text{Re } \omega \rightarrow 0$ and $\text{Im } \omega$ approaches the (purely growing) growth rate for filamentation. Analytically, one can show that purely growing Brillouin strong coupling has slightly higher growth rates than filamentation, but that its scaling is essentially the same: $\text{Im } \omega \sim \omega_{pi} (v_0/c)$.

To construct the space-time pulse response for filamentation, one first ascertains that there is no absolute instability for this example of a traveling-wave pump in a uniform plasma. The absence of absolute instability is shown by the fact that the pinch-point solutions in the complex $k_{\perp}$ and $k_{\parallel}$ planes do not properly retreat to opposite sides of the integration contours⁶⁷ as $\omega \rightarrow i\infty$. The approximate Green's function for density perturbations having maximum convective growth (with $k_{\parallel} = 0$) is

$$G(x_1, t) \propto \frac{\exp(ik_{1s} x_1) \exp[(\text{Im } \omega_s) t] \exp[-(\text{Im } \omega_s) x_1^2 / (c_s^2 t)]}{[c_s^2 t / (\text{Im } \omega_s)]^{1/2}} \quad (31)$$

where

$$\text{Im } \omega_s \approx \omega_{pi} v_0 / \sqrt{2} c, \quad k_{1s}^2 = (\omega_{pe}^2 / c^2) (v_0^2 / 2 v_e^2) \times (1 + T_i / Z T_e)^{-1}$$

We observe that in the pulse responses for convectively unstable filamentation and absolutely unstable stimulated Brillouin backscattering, the envelopes spread diffusively in a similar manner. The characteristic step size for the diffusion is given roughly by the product of the sound speed and the characteristic time step, which is the inverse of the appropriate growth rate.

Strong Damping Regime: $ZT_e \sim T_i$. When ZT_e is comparable with T_i , the ion wave in stimulated Brillouin scattering is strongly damped, because its phase velocity $(\omega/k) \cong c_s$ is comparable with the ion thermal speed. Thus, Brillouin thresholds are raised and growth rates are correspondingly lowered, relative to their weak-damping limits. Filamentation on the other hand is unaffected by this damp-

ing, since its ion disturbances were not propagating normal modes in the first place. For this reason, Langdon and Lasinski and others have set $T_i \sim ZT_e$ to isolate filamentation in some of their particle-in-cell computer simulations.⁶⁹

In the strong-damping regime, absolute instability thresholds are high, and the most relevant stimulated scattering behavior is the convective growth of induced scattering. For the strong damping limit well above threshold, the spatial growth rate of induced scattering is

$$L^{-1} = \left(\frac{\omega_{pe}^2}{8 k_0 c^2} \right) \left(\frac{v_0}{v_e} \right)^2 \left[\frac{\tau}{\tau^2 + (4 k_0^2 \lambda_e^2 \cos \theta + 1)^2} \right], \quad (32)$$

where

$$\lambda_c^2 \equiv k_B T_e / 4\pi n_0 e^2, \\ \tau \equiv (\pi/2)^{1/2} (Z T_e T_i) (\Omega/2k_0 v_i \cos \theta) \\ \times \exp(-\Omega^2/8k_0^2 v_i^2 \cos^2 \theta) = O(Z T_e / T_i).$$

By comparison, the maximum spatial growth rate for filamentation is

$$(\text{Im} k_y)_g = (\omega_p^2/8\omega_0) (v_0/v_e)^2 (1 + T_i/Z T_e)^{-1} + \gamma_t/2. \quad (33)$$

where γ_t is the damping rate of the light waves caused by inverse bremsstrahlung. We see that when $Z T_e \sim T_i$ and $2k_0 \cos \theta \lambda_c < 1$, induced scattering and filamentation spatial growth rates are comparable if γ_t is small.

Implications for Real Laser Fusion Experiments.

Our calculations thus far have been idealized, in that they assume linear behavior in a homogeneous plasma and ignore possible interactions between stimulated scattering and filamentation. In this subsection, we consider qualitatively how the conclusions change when realistic effects such as non-uniform laser beams and plasma density gradients are taken into account. Although we emphasize the laser-fusion application here, many of our comments will apply to other situations as well.

Realistic high-power laser beams are far from uniform. In fact, they frequently contain large-amplitude intensity variations at just the transverse scale sizes that filamentation can preferentially amplify. For example, Fig. 3-45 shows typical beam profiles of the Argus Nd-glass laser system at LLL.⁷⁰ The three scans, which were taken in 1977, represent power levels of 0.9, 1.9, and 2.8×10^{12} W. All the scans show large intensity fluctuations, with peak-to-valley variations between 2:1 and 4:1, and scale sizes between 10 and $20 \mu\text{m}$ full width. This scale size corresponds closely with that giving the fastest growth of filamentation. For example, if $I = 10^{15} \text{ W/cm}^2$, $n = 1/3n_c$, $T_i = Z T_e/2$, and $T_e = 1 \text{ keV}$, the scale size for fastest spatial growth of filamentation is $8 \mu\text{m}$.

Thus, we see that large-amplitude initial perturbations will probably be present on the laser beam itself to strongly drive filamentation. There is experimental evidence that such a process occurs in CO_2 laser-plasma irradiations.^{71,72}

Next, we must ask ourselves which mechanisms might tend to suppress filamentation. The fact that Brillouin or induced scattering can be occurring simultaneously with filamentation need not necessarily stop the growth of a filament. This is because stimulated scattering excites mainly short-wavelength density perturbations ($\lambda \approx \lambda_0/2$), whereas filaments are structures having much larger scale sizes, and they are not particularly sensitive to the presence of the small-scale density inhomogeneities produced by Brillouin scattering.

Rather than being affected by the ion perturbations caused by Brillouin scattering itself, a filament is more likely to be suppressed by the effects of scattering on the laser light and plasma density profile. The crudest example of this kind is that filamentation will obviously not proceed if Brillouin has already sidescattered or backscattered all of the laser light.

It has been useful in the past to envisage two distinct regimes for the nonlinear evolution of Brillouin scattering. The first corresponds to short laser pulses at high intensities, where Brillouin scattering is thought to be limited by the momentum and energy deposited in the underdense plasma as a result of reflection of the light. In this case, Ref. 73 shows that the resulting reflection front steepens the density gradient length in the underdense plasma to a value of 10 to $15 \mu\text{m}$ for parameters similar to those quoted in the second paragraph of this subsection. This gradient should be steep enough to suppress the spatial amplification of a filament entirely, because a typical spatial growth length (for the parameters in the second paragraph) is about $13 \mu\text{m}$, comparable to the density-gradient scale length. Thus, for high-intensity, short-pulse experiments, one expects that filaments will not amplify much beyond the initial noise level imposed by the laser beam itself.

The second, contrasting regime for nonlinear evolution of Brillouin scattering applies for long laser pulses and lower intensities.⁷⁴ For these conditions, there is a large, nearly uniform region of underdense plasma, and it is ion heating that limits Brillouin scattering. In this regime filamentation can be quite strong.

Table 3-3 illustrates this point. The first three columns of the table are from a self-consistent theory for steady state reflectivity caused by Brillouin scattering,⁷⁴ in the regime where $T_i \approx Z T_e$. The parameters for the table are $n = n_c/2$

Fig. 3-45. Spatial profile of the 1977 Argus laser beam at three different powers, from Ref. 70.

($n_c = m_e \omega_0^2 / 4\pi e^2$), and $(v_0^2 / 4v_e^2) = 0.1$. The first column gives the length of the underdense plasma, the second is the consequent reflectivity caused by Brillouin scattering, and the third is the self-consistent ion-to-electron temperature ratio. One sees that as the length of the underdense plasma increases from 20 to 80 vacuum wavelengths, the reflectivity rises from about 15 to 40%.

The last three columns of Table 3-3 describe the growth of a filament under these same conditions. Only the very simplest model for filamentation has been used; we neglect the spatial variation of the pump wave caused by Brillouin reflection, and we ignore the possibility that filamentation might be made absolutely unstable as a result of feedback provided by the Brillouin-reflected light. These effects should, of course, be included in a more complete treatment. Column 4 of Table 3-3 gives the fastest spatial growth length for a filament, which is considerably shorter than the available

Table 3-3. Brillouin scattering reflectivity and filamentation growth lengths in the $T_i \sim ZT_e$ regime. Plasma parameters are $n = n_c/2$ and $v_0^2 / 4v_e^2 = 0.1$. Columns 1 to 3 are from Ref. 74 and give (1) the plasma length L , normalized to a vacuum wavelength λ_0 , (2) the percentage reflectivity R produced by Brillouin scattering, and (3) the self-consistent ion-to-electron temperature ratio T_i / ZT_e . Column 4 gives the fastest growth length L_f for filamentation, normalized to a vacuum wavelength. Column 5 is the amplification factor for filament, $\exp(L/L_f)$. Column 6 is the preferred transverse spatial scale for a filament.

(1) L/λ_0	(2) $R(\%)$	(3) T_i/ZT_e	(4) L_f/λ_0	(5) $\exp(L/L_f)$	(6) λ_1/λ_0
80	42	0.7	10.8	1.6×10^3	12.0
60	35	0.6	10.2	3.6×10^2	11.3
40	25	0.45	9.2	77	10.2
20	15	0.3	8.3	11	9.2

plasma length. Column 5 gives the resulting spatial amplification factors, which range from a factor of 1600 for the 80- μ m-length plasma to a factor of 11 for the 20- μ m plasma. The spatial amplification factors greatly exceed unity for all the plasma lengths shown. Column 6 shows that the preferred transverse spatial scales for such filaments are about 10 vacuum wavelengths. Experiments on the Cyclops laser facility at LLL may have shown evidence for filamentation in this long-pulse regime.⁷⁵

We conclude that in the regime of long laser pulses and large focal spots where ion heating limits Brillouin scattering, filaments would be expected to amplify many times beyond the initially imprinted intensity variation as a result of the laser beam itself. In contrast, for the short-pulse, high-intensity regime, filamentation is probably a weak effect compared with Brillouin scattering and its accompanying strong reflection front.

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3.5.9 Raman Backscatter in High-Temperature, Inhomogeneous Plasmas

Introduction. Recently, there has been a strong surge of interest in stimulated scattering of intense laser light by plasmas.^{76,77} As the pulse length of the laser light is increased, larger regions of underdense plasma are created. This should produce more stimulated Brillouin scattering, which has been confirmed in a number of recent experiments.⁷⁸ In these experiments, a significant fraction of the incident laser light was found to be scattered by the Brillouin instability, corresponding to the decay of the incident light wave into a scattered light wave plus an ion wave. Much experimental and theoretical attention is currently being devoted to better understanding the level and the scaling of Brillouin scattering.

In contrast, very little experimental attention has been recently given to Raman scatter, which corresponds to the decay of the incident light wave into a scattered light wave plus an electron plasma wave. A signature of this process in cold plasma theory is that the scattered light wave has a frequency $\geq \omega_0/2$, where ω_0 is the frequency of the laser light. Early attempts to observe scattered light with frequency near $\omega_0/2$ indicated that stimulated Raman scatter was either very weak⁷⁹ or not present.⁸⁰ However, we have reexamined this process in recent, longer pulse experiments that are presumably characterized by much larger regions of underdense plasma.

Here, we examine in simulations and theory Raman backscatter of intense light for underdense plasma conditions and sizes thought to be characteristic of longer-pulse-length experiments. Our simulations show significant levels of reflected light with a frequency near $\omega_0/2$, a frequency not commonly monitored in experiments. We also find that the plasma temperature can lead to a sizeable shift of the frequency of part of this reflected light below $\omega_0/2$. Such a shift could be important to take into account when attempting to experimentally observe the signal, and could provide a rough monitor of the plasma temperature near one-fourth the critical density.

Theoretical Considerations. Theory can help us understand many features of Raman scatter. First, let us describe the underdense plasma conditions that we will consider. The typical density gradient length L of the underdense plasma that forms when a target is irradiated can be estimated as either the sound speed times the pulse length, or the focal spot radius, whichever is smaller. In typical experiments with 1-ns pulses of 1.06- μm light, L is commonly $\lesssim 100 \mu\text{m}$ (or $\lesssim 100$ free space wavelengths for 1.06- μm light). At the lower plasma density ($\gtrsim 1/4 n_{cr}$) where Raman scatter operates, the plasma temperature can be quite high. This is the case either when the lower density plasma is flooded with hot electrons from the critical density region, or when high-Z plasmas exhibiting poor thermal transport are heated by inverse bremsstrahlung. For example, if 30% of 1.06- μm light with intensity $3 \times 10^{15} \text{ W/cm}^2$ is absorbed at the critical density into hot electrons with a 10-keV temperature, the hot electron density is nearly one-fourth the critical density, even if the transport is its maximum value. Hence, plasma temperatures in the lower density regions ($\gtrsim 1/4 n_{cr}$) can readily range from about 10 to 40 keV for intensities from 10^{15} to 10^{16} W/cm^2 (1.06- μm light).

In such hot plasmas, Landau damping of the plasma wave significantly restricts the region over which Raman backscatter operates. For example, if $\theta_e = 10 \text{ keV}$ and $n_p/n_{cr} = 0.1$, the plasma wave is very heavily damped ($k_p \lambda_{De} \approx 0.9$, where k_p is the wave number and λ_{De} the Debye length). However, the damping becomes much weaker near $0.25 n_{cr}$, where $k_p \lambda_{De} \approx 0.28$. Hence, the scattering will tend to occur preferentially at the higher densities. Other physical effects also cause the Raman scatter to prefer its maximum density. In particular, the inhomogeneous intensity threshold is smallest near $1/4 n_{cr}$, where the backscatter becomes absolute.⁸¹

The effects of high plasma temperature can be explored more quantitatively by a full kinetic treatment that includes both Raman scatter and stimulated Compton scattering on the electrons. The dispersion relation⁸² specialized to one dimension is then

$$1 + \chi_e(k, \omega) = \frac{\chi_e(k, \omega) k^2 v_0^2 / 4}{c^2 k^2 - 2k k_0 c^2 + 2\omega \omega_0 - \omega^2}, \quad (34)$$

where V_0 is the oscillation velocity of electrons in the electric field of the incident light (which has wave number k_0 and frequency ω_0), and χ_e is the usual electron susceptibility. We solved this dispersion relation numerically for a variety of conditions. Figure 3-46 shows (a) the maximum backscatter growth rate and (b) the corresponding frequency of the reflected light wave as a function of ω_{pe}/ω_0 for $\theta_e = 10 \text{ keV}$ and $V_0/c = 0.1$ (about 10^{16} W/cm^2 , 1.06- μm light). Note that the growth rate is strongly peaked at the higher densities (i.e., for $1/6 \gtrsim n_p/n_{cr} \gtrsim 1/4$), although there is an extended region of small growth rate caused by stimulated Compton scattering. Note also that the frequency of the scattered light wave is below $\omega_0/2$ throughout the region in which the growth is peaked.

Fig. 3-46. Plot of (a) the maximum backscatter growth rate and (b) the frequency of the backscattered light as a function of ω_{pe}/ω_0 . The plasma temperature is 10 keV, and the incident light is 1.06- μm light with an intensity of about 10^{16} W/cm^2 .

This interesting result, first noticed in the 1.5-dimensional computer simulations, is easy to understand when one considers the thermal modifications of the electron plasma wave. To see this, let us calculate the frequency of the Raman-backscattered light, corresponding to the process occurring at its maximum allowable density. This frequency (ω_*) is given by the frequency-matching conditions supplemented with the condition that the scattered wave is at its cutoff density. Hence,

$$\omega_* + \sqrt{\omega_*^2 + 3k_0^2 v_e^2} = \omega_0,$$

where v_e is the electron thermal velocity. It is already apparent that $\omega_* < \omega_0/2$ (the cold plasma result) because of thermal corrections. Defining $\Delta\omega = \omega_0/2 - \omega$ and assuming that $\Delta\omega \ll \omega^*$, we obtain

$$\frac{\Delta\omega}{\omega_0} = \frac{9}{8} \frac{v_e^2}{c^2},$$

or

$$\frac{\Delta\omega}{\omega_0} = \frac{\Theta_e(\text{keV})}{454}. \quad (35)$$

We note that if the temperature is high ($\Theta_e \lesssim 10$ keV), this frequency shift is much larger than the expected Doppler shifts as a result of plasma motion.

In principle, relativistic corrections to the frequencies should be included as we are considering terms of order v_e^2/c^2 . However, for our problem, this correction is less than the thermal dispersion correction by a factor of more than 3. In particular, the magnitude of the relativistic correction to the frequency of the plasma wave is about $5/4 \omega_{pe} v_e^2/c^2$. The minimum thermal dispersion correction is about $9/2 \omega_{pe} v_e^2/c^2$, which is 3.5 times larger. In addition, we obtain a similar relativistic correction for the scattered light wave, and so the relativistic corrections tend to cancel.

Simulation Results. To investigate the frequency spectrum of Raman-scattered light in large, underdense hot plasmas, we have conducted several computer simulations using a 1.5-dimensional parti-

cle simulation code. These calculations include both density gradients and ion motion (and hence Brillouin backscatter). The principal restriction of this one-dimensional treatment is that it omits both the $2\omega_{pe}$ instability⁸³ and the Raman sidescatter. Hence, we have included some two-dimensional simulations to indicate how the 1.5-dimensional simulations results should be qualified. As will be discussed later, the two-dimensional simulations show similar frequency spectra near $\omega_0/2$, but they also show significantly smaller reflected signals.

Let us first discuss a typical 1.5-dimensional simulation. In this simulation, 1.06- μm light with an intensity of $3 \times 10^{15} \text{ W/cm}^2$ is propagated through a plasma with initial density rising from zero to $0.4 n_{cr}$ in a distance of $105\lambda_0$, where λ_0 is the laser light wavelength. The initial electron temperature is 10 keV, the electron-ion temperature ratio is 5, and the ion-electron mass ratio is 100. Particles expand into vacuum at the low density boundary and are reemitted with their initial temperature from the higher density boundary, modeling the loss of heated electrons into the target.

Figure 3-47 shows the frequency spectrum of the reflected (and incident) light, which is observed after the reflectivity has reached a quasi-steady state. Note the distinct signals both near $\omega_0/2$ (Raman scatter) as well as near ω_0 (Brillouin scatter). The large signal exactly at $\omega_0/2$ is simply the incident light. The Raman reflected signal is entirely shifted below $\omega_0/2$. In this example, approximately 15% of the incident light is scattered into frequencies near $\omega_0/2$. This amount is nearly as large as the Brillouin scatter, which is about 22% in this simulation with an initial electron to ion temperature ratio of only 5. The Raman scatter signal early in time consists of a peak at approximately $0.48 \omega_0$ as expected from Eq. (35) but later develops a secondary peak at even lower frequency, as shown in the figure. We attribute this small secondary peak to the presence of ion waves (either scattering of Brillouin-scattered light off plasma waves or scattering of incident light by plasma waves down-shifted in frequency). This was confirmed by rerunning the simulation with fixed ions. The secondary peak disappeared.

The electron plasma wave associated with the Raman scatter damps into the electrons, producing the heated distribution shown in Fig. 3-48. A high-energy tail with an effective temperature of 40 keV (about four times hotter than the background

plasma temperature) is generated. Recent experiments have also indicated a higher-temperature electron distribution.⁸⁴

A similar run simulation at 10^{16} W/cm^2 again shows the Raman-scattered signal to be peaked at approximately $0.48 \omega_0$, but the signal now extends to higher frequencies ($0.54 \omega_0$) before it strongly drops off. The heated electron temperature caused by Raman scattering is then approximately 60 keV. We also conducted other simulations with higher background temperatures (25 and 40 keV). In all these cases, the Raman signal extended below $\omega_0/2$ and by an amount corresponding to that expected from Eq. (35) within a factor of less than or equal to 2.

Two-dimensional simulations confirm that the frequency spectra of the reflected light near $\omega_0/2$ extend below $\omega_0/2$. The most striking result of these simulations is that the level of this reflected signal is strongly reduced. For example, consider a two-dimensional simulation in which the density initially rises from $0.15 n_{cr}$ to $0.35 n_{cr}$ in $5\lambda_0$, giving an effective density gradient from zero to the critical density of $k_0 L = 160$. The 1.06- μm -light intensity is 10^{16} W/cm^2 , the initial electron temperature is 10 keV, the electron-ion temperature ratio is 4, and the ion-electron mass ratio is 100. Approximately 1% of the incident light is reflected into frequencies near $\omega_0/2$, but this mainly comes out at an angle of 31° . The signal reflected straight back is only about

0.1%. All these levels, although significant, are much less than the approximately 10% reflection near $\omega_0/2$ observed in the 1.5-dimensional simulations. In the two-dimensional simulations, the $2 \omega_{pe}$ instability is dominant⁸³ and enhances the profile steepening near $1/4 n_{cr}$, strongly reducing the Raman scatter in this preferred region.

Conclusions. We have presented calculations of Raman scatter for plasma conditions thought to be relevant to recent long-pulse-length experiments. These calculations show that a significant reflected signal near $\omega_0/2$ is expected. In addition, the frequency spectrum can extend below $\omega_0/2$ as a result of thermal corrections in the hot plasma, a novel feature that can be used to estimate the temperature in the underdense plasma. These results emphasize that it is worthwhile to look for reflected light near $\omega_0/2$, a frequency not commonly monitored in experiments.

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W. L. Krue

3.5.10 Qualitative Aspects of Underdense Magnetic Fields in Laser-Fusion Plasmas

An important absorption process for high-intensity laser light is resonant absorption,⁸⁵ which accelerates electrons in the general direction down the density gradient. Consequently, the electrons are heated with an anisotropic velocity distribution. As was shown by Weibel,⁸⁶ a sufficiently anisotropic velocity distribution will cause the plasma to break into filaments and surrounding magnetic fields, which grow exponentially because the magnetic fields compress the filaments, which in turn increase the magnetic field. The minimum wavelength $\lambda_{\min}$, the fastest-growing wavelength λ_f = 1.7 $\lambda_{\min}$, and the growth rate of that mode γ_f are given by Krall and Trivelpiece,⁸⁷ from whom we obtain

$$\lambda_{\min}/\lambda_0 = [(n/n_c)(T_x/T_y - 1)]^{-1/2}, \quad (36)$$

$$\frac{\gamma_f}{\omega_{pe}} = 0.31 \left(\frac{T_y}{m_e c^2} \right)^{1/2} \left(\frac{T_y}{T_x} \right) \left(\frac{T_x}{T_y} - 1 \right)^{3/2}, \quad (37)$$

in the limit of the growth rate, which is much less than the wave vector times the electron thermal speed. T_x is the average temperature in the heated direction and T_y is the average temperature in the cold direction. λ_0 is the vacuum wavelength of the light, ω_{pe} is the electron plasma frequency at the density (n) where the Weibel instability occurs, n_c is the critical density, m_e is the electron mass, and c is the speed of light. The filaments occur in the direction of the hotter particles and the consequent wave number is in the direction perpendicular to the hot particles. The saturation magnetic field B_{sat} may be obtained from

$$\frac{\omega_{c \text{ sat}}}{\omega_0} \sim 4 \left(\frac{\gamma}{\omega_{pe}} \right)^2 \frac{n}{n_c} \frac{\lambda}{\lambda_0} \frac{c}{v_{ex}}, \quad (38)$$

where $\omega_{c \text{ sat}} = eB_{\text{sat}}/m_e c$, e is the electron charge, γ is the growth rate of the Weibel-unstable wavelength λ , and $v_{ex}^2 = T_x/m_e$, as given by Davidson et al.⁸⁸ and correlated with their one-dimensional simulations. In one-dimensional, initial-value periodic simulations, the magnetic field stayed near the saturated value for the length of the simulations. However, two-dimensional, doubly periodic simulations by Morse and Nielson⁸⁹ demonstrated that for an initial-value problem the magnetic field peaks and then rapidly drops, because wave numbers of the magnetic field turn in the direction of the hot particles. These particles, with the normal magnetic modes, rotate and cause the electrons to become isotropic. The consequence for laser fusion is that the Weibel instability is another source for magnetic fields that can inhibit energy transport.⁹⁰

The present problem differs from those studied in Refs. 86-89, in that the electron distribution function is not a one-temperature Maxwellian in one direction and a one-temperature Maxwellian in the other directions. Rather, the heated-electron distribution⁸⁵ in the direction along the density gradient has a heated fraction ($n_{\text{hot}}/n_{\text{cold}}$) with a hot temperature, while the remainder is cold and has the same temperature as the plasma in the other directions. Krall and Trivelpiece⁸⁷ describe their solution of this problem theoretically as simply using the average temperature in their equations for the fastest-growing modes [Eqs. (1, 2), Ref. 87]. We ran a series of one-dimensional, electromagnetic, relativistic simulations with a T_{cold} in both directions

and a fraction of the density having a T_{hot} in the nonperiodic direction. We found that the average temperature model did indeed predict the fastest-growing mode, its growth rate, and its saturation.

The growth and saturation of magnetic fields caused by the Weibel instability have been examined in two-dimensional, relativistic, electromagnetic, kinetic simulations,⁹¹ in the same runs used to generate the data for Ref. 85 and other runs. For laser intensities of 10^{16} W/cm² and cold temperatures of 4 keV, it was found that typically megagauss fields were generated, that the resulting heating was affected by the magnetic field with large variations in $E_x J_x$ at the critical surface in phase with critical surface ripples, and that the accelerated electrons are filamented.

Figures 3-49 through 3-51 present a simulation example in which the laser intensity is 2×10^{16} W/cm² and T_{cold} is 2.2 keV, producing $T_{\text{hot}} = 40$ keV and $n_{\text{hot}}/n_{\text{cold}} \approx 0.2$ in the underdense region. The density profile is shown in Fig. 3-49(a). The laser is incident from the lower left at an angle of 10 deg to the critical surface. A plot of $p_x - p_y$ [where $p_{x,y} = (\nu_{x,y}/c) [1 - (\nu_x/c)^2 - (\nu_y/c)^2]^{-1/2}$], averaged over the underdense region, shows the velocity-space anisotropy at early times. At later times, the anisotropy is much less. See Fig. 3-49(b).

Figure 3-50(a) shows the time-averaged magnetic field B_z with direction out of the plane of the simulation. The time average cancels out the in-

cident pump field. Three different sources for the magnetic fields are shown here: At the critical density, a B_z field is produced directly by resonant absorption⁹²; the large diagonal field is characteristic of the Weibel instability, but may be more (as will be discussed); the field at the very low-density region is caused by the electrons being rotated around the ambipolar electric field. See Fig. 3-49(a). The latter field is not obvious in Fig. 3-50(a) as the amplitude is much less than that caused by the Weibel instability. However, this field is clear from plots of B_z averaged over y because it does not change sign. Because the electrons are resonantly driven at a nonzero angle with the density gradient, away from the laser light, the Weibel instability occurs at a nonzero angle. Similarly, the electrons rotating around the ambipolar field have a preferred direction, driving a positive B_z field there.

As both the time-averaged two-dimensional plots of $E_x J_x$ in Fig. 50(b) and the vectors of the current density in Fig. 51 show, the magnetic field significantly affects the heating and hot-electron transport. Note that $E_x J_x$ is greatest where J is greatest and where the magnetic field is nearest zero (this is generally true, although not always so). The critical-density surface of the ions and electrons shows small-amplitude surface ripples⁹³ with the kink of the ripple in phase with the maximum $E_x J_x$. The patterns of B_z , $E_x J_x$, and J do move together on the critical surface but at a speed much less than the

function as is found on the two-dimensional runs. The two-dimensional situation is complicated by the finite length of the underdense plateau. One may estimate a spatial growth length by dividing the average velocity in the density-gradient direction by the growth rate, which is in reasonable agreement with the simulations. If the underdense plasma has

Fig. 3-51: Arrows of current density (with positive current convention so that the arrows go in the opposite direction of the clearance). Note that horizontal and vertical scales are different. The arrows generally follow the lines of minimum magnetic field [Fig. 3-50(c)] and maximum $E_{x,z}$ [Fig. 3-50(b)].

enough length to allow the magnetic instability ample space to grow, and if the swelled, average oscillatory energy has been subtracted from T_y used in Eqs. (36-38), then the saturated magnetic field is in reasonable agreement with Eq. (38), with the theory somewhat low and the one-dimensional simulations in agreement with the theory. The fact that we see critical surface ripples in phase with the edge of the magnetic field J and $E_x J_x$ indicates the possibility of a more encompassing feedback mechanism of which the Weibel instability is only a subset.

The above simulations include runs in which the light was incident at an angle not perpendicular to the critical surface. A run was made in which the light was incident perpendicular to the critical surface and the ripples were small enough so that resonant absorption did not dominate. In this case, ion acoustic decay and oscillating two-stream instabilities heated electrons mainly along the critical-density surface, which drove a Weibel-instability magnetic field with wave vector along the density gradient. The magnetic field reduced the T_{hot} of the slowly heated electrons by deflecting them out of the heating electric fields after a short time. We inferred this effect when we noticed that, after the time averaged, Weibel-instability-induced field B had grown to megagauss amplitude, T_{hot} dropped a factor of two, although other characteristics (such as the density profile) of the plasma were unchanged.

Some limitations of the present model should be noted. It is not clear what n_{hot}/n_{cold} should be to match the experiment, and probably n_{hot}/n_{cold} and the total underdense shell density will depend on the time history of the laser pulse and the materials of the target. The maximum wavelength of the simulated Weibel instability seen in Eq. (36) is artificially limited by the width of the periodic system (the vertical direction in Fig. 3-50). Consequently, the experimental magnetic field pattern and saturated amplitude would be different from those presented in this simulation. In particular, in the lower-density regions shown in Figs. 3-49(a) and 3-50(a), an experiment might have larger-amplitude magnetic fields with wavelengths longer than the system width of the simulation with similar density and T_x/T_y . The possible three-dimensional effects are not clear, particularly in view of the larger ripples expected in the direction perpendicular to the polarization.⁹³ Because the sign of the magnetic field varies rapidly on a spatial scale of a few

wavelengths, it is not clear how quantitatively one could observe this magnetic field with a Faraday-rotation experiment. One suggestion is to look for broad-band synchrotron radiation or perhaps try to focus the synchrotron light [at a frequency of $\omega_c/\omega_0 = B(\text{MG})/100$ of the incident light at $1.06 \mu\text{m}$] onto a detector array. One could use a prism and streak camera to get a frequency spectrum vs time. However, for the synchrotron radiation to occur, the cyclotron frequency must be greater than the local plasma frequency.

In conclusion, we have simulated magnetic fields in the underdense region of laser-produced plasmas on one- and two-dimensional self-consistent codes and have found them to have megagauss amplitudes for laser intensities of 10^{16} W/cm^2 . These amplitudes would inhibit heat transport and help cause the electron distribution to become isotropic.

Valuable conversations with W. L. Kruer, A. B. Langdon, B. F. Lasinski, and C. E. Max are acknowledged.

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3.5.11 Parametric Instability-Producing B Fields

Time-averaged electron velocity distribution in the presence of intense laser light is anisotropic. It is natural to speculate that a Weibel-like instability⁹⁴ may result, producing a magnetic field. We show here that this anisotropy does not feed a Weibel instability but that a parametric process produces dc magnetic fields.

A kinetic analysis includes both the Weibel and parametric processes and clarifies their separate nature. We specialize to a uniform plasma with uniform laser wave field $E_0 = (mv_0/c\omega_0) \cos\omega_0 t$. We derive a dispersion relation,

$$1 + \frac{\omega_p^2}{c^2 k^2} \int \frac{d\mathbf{v}}{\omega - k\mathbf{v}_x} \omega f_0 = \frac{(v_{ty}^2 - v_{tx}^2)}{c^2} \frac{\omega_p^2}{k} \int \frac{d\mathbf{v}}{\omega - k\mathbf{v}_x} \frac{\partial f_0}{\partial v_x} + \left(\frac{v_0}{2c}\right)^2 \times \left[\frac{1}{1 + \chi^{-1}(k, \omega - \omega_0)} + \frac{1}{1 + \chi^{-1}(k, \omega + \omega_0)} \right],$$

where $\omega < \omega_0$, the zero-order electron distribution function is $f_0 \exp(-v_x^2/2v_{tx}^2 - v_y^2/2v_{ty}^2)$, and χ is the electron susceptibility. The first term on the right, as a result of the true, nonoscillatory anisotropy, is the source term for the Weibel instability. The left side describes the diffusion of the B field, controlled by nonlocal conductivity⁹⁵ rather than by resistive diffusion for wave lengths shorter than the mean free path.

The second term on the right is the result of the parametric instability, whose coupling mechanism we now explain. Given a magnetic field $B(k, \omega)$, the $v_0 \times B$ force drives plasma waves at frequencies $\omega_0 \pm \omega$. The resulting density perturbations, proportional to $\epsilon^{-1}(k, \omega_0 \pm \omega)$, beat with v_0 to create a low-frequency transverse current, which produces the B field.

This dispersion relation shows that Weibel instability is independent of and unaffected by the oscillatory motion. From numerical solutions, we find that a small anisotropy has more effect than a large $v_0 \sim v_t$. In the warm isotropic case, there is a connection to the instability examined in Ref. 96, at lower densities. A complete analysis should include relativistic corrections.⁹⁷ We have not conducted any ZOHAR simulations specifically to test this theory, but it may account for unexpected plasma oscillations seen near critical density in simulations of relativistic self-modulation,^{97,98} and it explains why oscillation "anisotropy" must not be included in calculating Weibel growth rates for comparison with simulations.⁹⁹

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3.5.12 Hot Electron Transport and Anomalous dc Resistivity

We have used a computational/theoretical model to study laser-heated-electron heat flux inhibition caused by anomalous dc resistivity driven by ion acoustic waves. The model assumes that (1) the laser-heated (hot) electrons are collisionless, (2) the hot electrons are emitted from a finite area source with the hot electrons spreading after leaving the critical surface ($\omega_0 \approx \omega_p$), (3) the thermal electrons have a Maxwellian velocity distribution, and (4) the thermal electrons are heated by anomalous dc resistivity. The spreading of the hot electrons is a two-dimensional effect. We can model this effect by inverting the geometry. Rather than depositing energy on the outside of a spherical target, the model deposits energy on the inside of a hollow sphere. Then the hot electrons spread as a result of geometry. To describe the hot electron transport, we have constructed a steady-state BGK solution for the dc potential, self-consistent with the thermal electrons in spherical geometry.¹⁰⁰ The plasma is composed of hot electrons obeying the steady-state Vlasov equation and thermal electrons satisfying the steady-state fluid continuity, momentum, and

energy equations. The momentum equations are closed by assumptions on the thermal pressure $P_e = n_e T_e$ and heat flux $Q_e = \int 1/2 m_e (v - u_e)^3 f_e d\mathbf{v} = \beta P_e U_e$, where β is assumed constant. The momenta of the trapped hot electrons are coupled to the cold electrons through the quasi-neutrality condition $Zn_i = n_h + n_e$. Within this model, the ions are stationary with a specified linear density profile and constant temperature $T_i \ll T_e$. An effective resistivity is given by the Sagdeev resistivity formula¹⁰¹ for ion turbulence $\nu/\omega_{pe} \approx 0.01(T_e/T_i)(U_e/V_e)$, where $V_e = \sqrt{T_e/m_e}$. To compare with PROMETHEUS experimental data,¹⁰² we computed the results for an argon plasma with $m_i/m_e = 7.3 \times 10^4$, $n_i/n_e = 1$ lev in the overdense region, $n_e = 1.8 \times 10^{19} \text{ cm}^{-3}$, and $T_i = 1 \text{ eV}$. Preliminary results indicate that, for low power ($v_{os}/v_{eo} < 0.6$, where $v_{os} = eE_0/\omega$, in which E_0 is the peak electric field of the incident microwaves, and frequency $\omega/2\pi = 1.2 \times 10^9 \text{ GHz}$, and the initial thermal velocity $v_{eo} = \sqrt{T_{eo}/m_e}$), $\Delta(\phi/T_h) \approx 0.30$ and the hot electron heat flux reduction factor $f_h = r^2 H(r)/r_c^2 H(r_c) \lesssim 0.80$, where $H(r_c)$ is the hot heat flux at the critical surface. These results compare well with PROMETHEUS experimental data with similar parameters ($n_h = 0.20 n_c$, $T_e = 0.25 T_h$) $\Delta(\phi/T_h) \approx 0.33$ with $f_{exp} \approx 0.50$. Preliminary computer calculations made with $T_h = 80 \text{ eV}$, $T_e = 0.145 T_h$, and $n_h \approx 0.1 n_c$ at the critical surface has $\Delta(\phi/T_h) \approx 0.10$, $H_h \approx 4H_i$ with $f_h \approx 0.90$. This agrees also with experiments for $0.05 \leq n_h \leq 0.10$; a measured $\Delta(\phi/T_h) \approx 0.10$ with $f_{exp} \approx 0.80$. Results indicate that anomalous dc resistivity caused by ion acoustic turbulence is not sufficient in strongly reducing the hot heat flux, even though the anomalous dc resistivity is more than 100 times the classical value.

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3.5.13 Resonant Absorption and Electron Heat Transport at Very High Power

We have used very intense microwaves ($V_{os}/V_{eo} \gtrsim 1$, $\omega_0/2\pi = 1.2 \text{ GHz}$) to experimentally study resonance absorption and the thermal transport of heated electrons.¹⁰³ We performed the experiments in the U.C. Davis PROMETHEUS device, which models oblique incidence of a P-polarized laser onto a pellet. The cylindrical vacuum chamber is divided into two parts by a thin sheet of ceramic that provides a plasma boundary. Microwaves in a TM_{01} mode (left chamber, vacuum waveguide) are incident on an inhomogeneous plasma (right chamber, plasma-filled waveguide with inhomogeneous scale length $L/\lambda_{DE} \approx 10^3$). The radial profile of the axial electric field of the incident microwaves is $E_z \propto J_0(0.18r)$, so that the heating region is localized near the center of the microwave beam. See Fig. 3-52(a). This axial component of the high-frequency electric field excites localized electrostatic waves near the critical surface (resonant absorption). These localized electrostatic waves heat electrons. The heated electron distribution is bi-Maxwellian as shown in Fig. 3-52(b). These typical data give suprathermal electron temperature $T_H \approx 40 \text{ eV}$, bulk electron temperature $\approx 5 \text{ eV}$, and suprathermal electron density $n_H/n_0 \approx 10\%$ with $P_0 = 2 \text{ kW}$. Electrons traveling down the density profile are reflected at the plasma boundary by the strong ambipolar potential, as the current must be zero at the ceramic (dielectric) sheet. Thus, most of the heated electrons are transported toward the overdense region along the axis of the vacuum chamber. The return current excites ion wave turbulence in the overdense region. A dc plasma potential is then induced, which traps some of the heated electrons and reduces the electron thermal transport.

Suprathermal electrons are produced immediately after turning on the microwave power, because resonant absorption excites the localized high-frequency plasma wave on an electron time scale, while the bulk electrons heat slowly on the ion time scale. The dc plasma potential is also created slowly on an ion time scale, and then the forward electron current increases. Figure 3-53 shows that the dc potential, the bulk electron temperature, and the forward current increase in the same slow time scale. This time scale increases as the microwave power is reduced (curve a').

(b)

(a)

Fig. 3-55. Heat flux reduction of suprathermal electrons vs microwave power or V_{0s}/V_{0s} .

Figure 3-54 shows the spatial profile of the induced plasma dc potential. The plasma potential is induced positively near the critical surface and decreases toward the overdense region (curve a). The forward electron current also increases near the critical surface, and decreases toward the overdense region with a distance of approximately $\exp(e\phi/kT_e)$, indicating that the low-energy electrons ($1/2 mv_e^2 < e\phi$) are trapped in the potential trough. For the return current, the bulk electron temperature increases toward the critical region. The measured drift velocity of the returning electrons is smaller than the thermal velocity. The directional energy of the returning electrons is apparently converted to thermal energy via ion wave resistivity. The heated bulk electron temperature is on the order of the induced dc potential. This is expected from energy conservation if one neglects the heat flow of the thermal electrons $[(\partial kT_e/\partial z) \sim (\partial e\phi/\partial z)]$. We have observed that strong ion waves are excited in the overdense region and propagate obliquely toward the critical surface, where they apparently cause anomalous resistivity.

We have estimated the heat flux reduction of suprathermal electrons by the induced dc potential, shown in Fig. 3-55. The results indicate that the heat flux reduction of the suprathermal electrons is not great by the present mechanism.

At distances from the heating region larger than the heating diameter, the suprathermal electron density and heated electron temperature

decrease with distance as a result of the geometrical spreading of the heated electrons [see Fig. 3-52(a)].

Reference

103. I. S. DeGroot, R. B. Spielman, and K. Mizuno, *Resonance Absorption and Heated Electron Thermal Conductivity*, University of California at Davis, UCD PRG R-33 (1978).

Authors

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3.5.14 Hydrodynamics Code with Wave Optics to Study Brillouin Scatter

We have developed the computer code AURUS to understand more fully the role of stimulated Brillouin scattering in current long-pulse experiments. This one-dimensional code incorporates a hydrodynamic description of the plasma and a wave optics solution for the laser electric field. Because the plasma is treated as a fluid rather than as a collection of particles, it is possible to simulate at once both the high-density ablation region and the underdense Brillouin scattering region. Then the effects of realistic density, temperature, and flow profiles on the level of Brillouin scatter and, conversely, the modification of these profiles by momentum deposition, ion heating, and reduced absorption, are included self-consistently.

The equations solved are the following:

$$\frac{\partial n}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 nv) = 0, \quad (39a)$$

$$M \left[\frac{\partial}{\partial t} (nv) + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 nv^2) \right] = - \frac{\partial}{\partial r} (nT_i + nT_e) - \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 W) - \frac{\bar{Z} n e}{2 m \omega_0^2} \frac{|E|^2}{2}, \quad (39b)$$

$$\frac{\partial}{\partial t} \left(\frac{3}{2} n T_i \right) + \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{3}{2} n v T_i \right) = \left(\frac{n T_i + W}{r^2} \right) \frac{\partial}{\partial r} (r^2 v) + C_{ei} \quad (39c)$$

$$\frac{\partial}{\partial t}(C_v n T_e) + \frac{1}{r^2} \frac{\partial}{\partial r}(r^2 v C_v n T_e + r^2 Q_e) \\ = - \frac{\bar{Z} n T_e}{r^2} \frac{\partial}{\partial r}(r^2 v) + \nu_{ei} \frac{\omega_p^2}{\omega_0^2} \frac{|E|^2}{8\pi} - C_{ei} - R, \quad (39d)$$

$$\frac{\partial E}{\partial t} = \frac{i\omega_0}{2} \frac{1}{k_0^2 r} \frac{\partial^2}{\partial r^2}(rE) + \left[1 - \frac{\omega_p^2}{\omega_0^2} \left(1 - i \frac{\nu_{ei}}{\omega_0} \right) \right] E \\ + \frac{E}{2} \frac{\partial}{\partial t} \left(\frac{\omega_p^2}{\omega_0^2} \right). \quad (39e)$$

Here n , v , T_i , T_e , and E are the ion density, fluid velocity, ion and electron temperatures, and laser electric field, respectively; W , C_{ei} , R , and Q_e are the viscous pressure, electron-ion coupling term, radiation loss term, and electron heat flux, respectively. Ion conduction is neglected. C_v is the electron specific heat including ionization energy, $\bar{Z}$ is the average ionic charge state, ω_0 is the laser frequency, and ν_{ei} is the electron-ion collision frequency. All other symbols have their conventional meanings. The Schrödinger-like equation for the laser electric field results from removing the high-frequency time dependence as $E = E(t)e^{-i\omega_0 t}$, and retaining terms through first order in ω_h/ω_0 , where ω_h is a typical hydrodynamic frequency. The single space dimension is the radius r in a spherical coordinate system to allow modeling of multidimensional divergence effects.

As discussed in previous annual reports,^{104,105} ion heating by Landau damping and wave breaking play a major role in limiting stimulated Brillouin scattering. While these processes are inherently kinetic (i.e., nonfluid) processes, they can be reasonably modeled through the viscosity coefficient μ , where $W = -\eta\mu\partial v/\partial r$. For example, the ratio of the ion Landau damping rate to the frequency for an ion wave is a function of the temperature ratio and wave number, k : $\omega_i/\omega_r = \omega_i/\omega_r [ZT_e/T_i, k\lambda_{De} Z(Me/Mi)]$, where λ_{De} is the electron Debye length. Because the ion wave associated with Brillouin backscatter has a fairly well-defined wave number, $k \approx 2k_0(1 - \omega_p^2/\omega_0^2)^{1/2}$, we can easily calculate a Landau damping viscosity, μ_{LD} , sufficient to give the required damping rate, given the

local density and temperatures. To model wave breaking, we compare the local density fluctuation amplitude $\delta n/n$ to the wave breaking limit, so that

$$\left(\frac{\delta n}{n} \right)_{\max} \sim \frac{1}{4} \left\{ 1 - \left[\frac{3T_i(1 + k^2\lambda_0^2)}{\bar{Z}T_e} \right]^{1/2} \right\}^2 (1 + k^2\lambda_0^2)^{-1}. \quad (40)$$

We then assign a wave breaking viscosity, $\mu_{wb} = \mu_0(\delta n/n)^2/(\delta n/n)_{\max}^2$, where μ_0 is chosen to yield a very large damping rate at the wave breaking fluctuation limit. We obtain best agreement with particle simulations when μ_0 is chosen to give $\omega_i/\omega_r = 0.7$ at $(\delta n/n) = (\delta n/n)_{\max}$. Finally, we choose the total viscosity, $\mu = \max(\mu_{LD}, \mu_{wb})$. The kinetic energy dissipated by the viscosity becomes a source term in the ion temperature equation, thus heating the ions and ensuring energy conservation.

In the numerical solution, Eqs. (39 a-e) are split. The advection terms are advanced by the Shasta Flux Corrected Transport¹⁰⁶ algorithm, while the diffusion terms are advanced by a Crank-Nicholson scheme. The finite-difference schemes employed are accurate to second order in both space and time.

As a check on the code, we have made comparisons with the theoretical result for the steady state reflectivity of an underdense slab in the heavily damped regime. We have found that

$$\frac{B}{r} = \frac{(1-r)}{cQ(1-r)-r} \quad (41a)$$

$$Q = \frac{1}{8} \frac{\omega_p^2}{\omega_0^2} \left(\frac{V_0}{V_e} \right)^2 k_0 L / \frac{\omega_i}{r} \left(1 + \frac{3T_i}{\bar{Z}T_e} \right). \quad (41b)$$

Here, B is the noise level relative to the incident power, L is the plasma length, and V_0/V_e is the electron oscillation velocity/electron thermal velocity in the swelled laser field. In Table 3-4, we show calculated steady state reflectivities for a wide variety of plasma parameters. The noise level in the calculation, $B = 10^{-3}$, is set by an opposite-directed, very-low-power laser source at the Brillouin-shifted

Table 3-4. Calculated steady reflectivity r vs Q for a variety of plasma parameters.

	$k_0 L$	$\frac{\omega_p^2}{\omega_0^2}$	V_0^2/V_0^2	ω_r/ω_r (1 + 3 Ti/ZTe)	Q	$r, \%$
A	300	0.25	0.29	0.5	5.5	14
B	300	0.25	0.29	0.25	10.9	55
C	300	0.25	0.44	0.5	8.2	35
D	300	0.25	0.58	0.5	10.9	52
E	300	0.1	0.53	0.5	4.0	4
F	300	0.33	0.61	0.5	15.1	70
G	300	0.50	0.75	0.5	28.1	81
H	200	0.33	0.61	0.5	10.1	50
I	100	0.33	0.61	0.5	5.1	12
J	260	0.25	1.15	0.5	17.7	73

frequency $\Delta\omega = -2k_0 c_s (1 - \omega_p^2/\omega_0^2)^{1/2}$. In Fig. 3-56 these results are plotted along with the theoretical result of Eq. (41), with good agreement. As a further

Fig. 3-56. Steady state reflectivity data r vs Q of Table 3-4. Dotted curve is the theoretical result of Eq. 41.

check, we have made comparisons with a particle simulation code. Figure 3-57 shows the time histories of the transmitted power for AURUS (solid line) and a particle code (dotted line). The parameters are $k_0 L = 188$, $\omega_p^2/\omega_0^2 = 0.33$, and $(V_0/V_0)^2 = 4$. This problem provides a stringent test of the method. The very high power means that there is vigorous ion heating by wave breaking and

Fig. 3-57. Time histories of the transmissivity T of an underdense plasma slab at very high power. Solid line — AURUS; dotted line — particle code.

Landau damping. In fact, for this simulation, the fluid code tracked the ion temperature very well from 0.2 keV to more than 1.4 keV, an increase of a factor of 7. The time-averaged transmission from the particle code was 30% while AURUS gave about 34%, and, as Fig. 3-57 shows, AURUS gave a fair approximation for the placement and amplitude of most of the transmission bursts resulting from the crashing of the ion waves, a highly nonlinear effect. Several example simulations of 200-ps Gaussian laser pulses on gold slabs are given in §3.5.7.

At present, we are adding several new physics models to AURUS, including a very simple two-group (thermal and suprathermal) diffusion electron transport package, improved radiation and equation-of-state models, and distinct parallel (to r) and perpendicular ion temperatures to allow better modeling of ion heating.

References

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Author

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3.5.15 Wavelength Scaling in Laser Fusion from a Plasma-Physics Point of View

In this subsection, we discuss the scaling with laser wavelength of several plasma physics processes important for laser fusion. We emphasize the behavior of spherical targets of a scale appropriate for an eventual fusion reactor. Thus, the targets are large, with diameters ranging between about 1 nm and 1 cm. The laser intensities are correspondingly low by present-day standards (10^{13} – 10^{15} W/cm² at the target surface). Shells can be from fractions of a millimetre to several millimetres thick. We are envisioning a laser with about one megajoule of energy per pulse. However, most of our conclusions would remain valid even if eventual reactor lasers are forced closer to the 10-MJ range.

We studied wavelength scaling for the following plasma processes: (1) generation of suprathermal electrons, (2) stimulated Brillouin scattering, (3)

Fig. 3-58. Schematic plot of positions on the plasma density profile where various plasma processes occur.

transport inhibition mechanisms, and (4) the effect of transport inhibition on implosion efficiency.

These processes occur in different locations on the plasma density profile, as shown in Fig. 3-58. Stimulated Brillouin scattering, which can cause premature reflection of the incident laser via decay into an ion wave and backscattered light wave, occurs in the underdense plasma where the electron density n is less than the critical density n_c , $m_e \omega_p^2 / 4\pi e^2$. Hot electron generation occurs at the critical density surface. Transport inhibition is important in the region between the critical density surface and the ablation surface.

Hot electron generation^{107,108} has received the primary emphasis in past studies of wavelength scaling. The main point we wish to make here is that there are important plasma physics processes other than hot electron generation that show considerable sensitivity to laser wavelength. Moreover, in the cases we discuss here, short-wavelength lasers are strongly favored for wavelengths less than a few micrometres. The target conditions produced by CO₂ lasers (wavelength 10 μ m) are sufficiently unique to require scaling arguments different from those relevant to shorter laser wavelengths.

Hot Electron Generation and Preheat. Suprathermal electrons are created when laser light is absorbed by resonance absorption at the critical density surface. These electrons typically have long mean free paths, and can thus cause preheat of inner target layers or of the fuel region. Consequences of such preheat include decreased peak ρR values, or higher required laser energies to attain a given ρR .

Recent research on the effect of laser light pressure and density profile steepening at the critical surface has shown a rather weak dependence

of the hot electron temperature T_{hot} on laser intensity and the square of the wavelength, $I_L \lambda_L^2$. Estabrook and Krue¹⁰⁷ find that

$$\frac{T_{\text{hot}}}{1 \text{ keV}} \cong 8.5 \left(\frac{T_{\text{cold}}}{1 \text{ keV}} \right)^{0.25} \left(\frac{I_L}{10^{15} \text{ W/cm}^2} \right)^{0.39} \times \left(\frac{\lambda_L}{1.06 \mu\text{m}} \right)^{0.78} \quad (42)$$

Crudely, $T_{\text{hot}} \propto (I_L \lambda_L^2)^{0.4}$. Reference 108 obtains qualitatively similar results, with the hot electron temperature scaling as $T_{\text{hot}} \propto (I_L \lambda_L^2)^{0.3}$. Thus,

$$T_{\text{hot}} \propto \lambda_L^{0.6-0.8} \quad (43)$$

This applies for CO_2 lasers as well as for lasers having micrometre or submicrometre wavelengths.

However, the quantity most pertinent to preheat is the hot electron range λ_r , which scales as

$$\lambda_r \propto T_{\text{hot}}^2 \propto \lambda_L^{1.2-1.6} \quad (44)$$

Thus, the range is still rather sensitive to laser wavelength.

Consider electrons reaching a fixed high-density region of the target, for example, a shell having electron density $n_e = 3 \times 10^{22} \text{ cm}^{-3}$, from the critical surface where $T_{\text{cold}} = 1 \text{ keV}$. For a laser intensity $I_L = 10^{14} \text{ W/cm}^2$ and using the scaling from Eq. (42), we find the following values for the range of an electron with velocity $2(kT_{\text{hot}}/me)^{1/2}$:

- Laser wavelength = 10.6 μm , 1.06 μm , 0.25 μm .
- Hot electron range = 340 μm , 12 μm , 1.5 μm .

Thus, the range can become quite long, particularly for $\lambda_L = 10 \mu\text{m}$.

Nevertheless, reactor targets are so large that it is not clear how extensively the longer hot electron range typical of a 10- μm laser would seriously degrade target performance. For example, an outer shell thicker than roughly 1 mm would keep most hot electrons out of the inner fuel regions even for a CO_2 laser. The preheat issue then becomes a quantitative question of the energy price paid for adding

shielding against the most energetic suprathermals far out on the tail of the distribution.

We conclude that although the hot electron range increases strongly as laser wavelength gets longer, large reactor-sized targets with thick shells will tend to be less sensitive to this increased range.

Stimulated Brillouin Scattering. In stimulated Brillouin scattering, the incoming laser light wave decays into an ion acoustic wave plus a reflected light wave. If this process occurs before the laser light reaches the critical density and is absorbed, Brillouin scattering represents a premature reflection that can dramatically lower the absorption efficiency.

Experiments on the wavelength scaling of Brillouin scattering are not yet conclusive. Brillouin scattering has been seen in Nd laser-plasma interactions ($\lambda_L = 1.06 \mu\text{m}$), when a long density gradient was created in the underdense plasma.^{109,110}

Apparently, Brillouin scattering is not obvious in CO_2 laser irradiations ($\lambda_L = 10.6 \mu\text{m}$) of initially solid targets.¹¹¹ On the other hand, vigorous Brillouin scattering has been seen in many CO_2 laser-heated magnetically confined plasmas, where the plasma is long and entirely underdense to the CO_2 laser light.¹¹²

The theory for the amount of Brillouin reflectivity has two different regimes. If the length of underdense plasma is less than roughly $100 \lambda_L$, strong Brillouin scattering is both predicted¹¹³ and observed¹¹⁴ to be suppressed after an initial transient. This is because the small mass and heat capacity of the underdense plasma make it easy for momentum and energy deposition, caused by Brillouin scattering and ponderomotive force, to steepen and heat the underdense region. Once these processes occur, Brillouin reflectivity is sharply reduced. Under such circumstances, the Brillouin reflectivity is typically limited to at most 30 to 40%.

However, if the length of underdense plasma is considerably longer than $100 \lambda_L$, the plasma is too massive to be steepened, and its large heat capacity makes ion heating, as a result of Brillouin scattering, occur relatively slowly. Thus, when $L \lesssim 100 \lambda_L$, it is the gradual heating of the ions that determines the amount of Brillouin reflectivity.

The CO_2 irradiation experiments currently being conducted at the Los Alamos Scientific Laboratory seem to be in the first regime, where the length of underdense plasma is shorter than $100 \lambda_L \approx 1000 \mu\text{m}$ and is thus too small to Brillouin-scatter

much laser light. For example, at an expansion speed of 3×10^7 cm/s (typical of $T = 1$ keV), the plasma reaches a length of only $300 \mu\text{m} = 30 \lambda_L$ in a nanosecond. Thus, large Brillouin reflectivities would not be expected, consistent with current experimental data.

In fact, it may be true that this pleasantly small amount of Brillouin reflectivity for CO_2 lasers could persist even for reactor-sized targets. The reason is as follows: For a spherically irradiated target of radius R , spherical divergence will typically limit the density gradient scale length L roughly to a value $L \gtrsim R$, even for very long laser pulses. Thus, as long as the pellet size satisfies $R \gtrsim 1$ mm, the plasma length L will be $\gtrsim 100 \lambda_L$ for CO_2 lasers and Brillouin reflectivity may not be strong. Because reactor targets are projected to be roughly between a millimetre and a centimetre in diameter, the low-reflectivity condition $L \gtrsim 100 \lambda_L$ may be marginally satisfied for CO_2 with targets at the smaller end of this size range.

However, in a reactor situation, the low-reflectivity condition $L < 100 \lambda_L$ is clearly violated for wavelengths shorter than $10 \mu\text{m}$. Hence, ion heating is expected to set the amount of Brillouin reflectivity for all lasers except CO_2 . The reflectivity can be parameterized¹⁰⁹ by a quantity Q , the number of Brillouin spatial gain lengths in a plasma of length L . For densities small compared with n_c ,

$$Q = \frac{\pi}{2} \left(\frac{L}{\lambda_L} \right) \left(\frac{n}{n_c} \right) \left(\frac{v_0^2}{v_{te}^2} \right) \left(\frac{\nu_i}{\omega_{ia}} \right)^{-1} \left(1 + \frac{3T_i}{ZT_e} \right)^{-1}. \quad (45)$$

Numerically, Q is given by

$$Q \approx 2\pi \left(\frac{n}{n_c} \right) \left(\frac{L}{\lambda_L} \right) \left(\frac{I_L}{10^{16} \text{ W/cm}^2} \right) \left(\frac{\lambda_L}{1 \mu\text{m}} \right)^2 \left(\frac{1 \text{ keV}}{T_e} \right) \times D^{-1}, \quad (46)$$

where

$$D \equiv \left(\frac{\nu_i}{\omega_{ia}} \right) \left(1 + \frac{3T_i}{ZT_e} \right).$$

In these expressions, $v_0^2/v_{te}^2 = E_0^2/4\pi n_c T_e$ and ν_i and ω_{ia} are the ion wave damping rate and frequency, respectively. When Q is large, the reflectivity is large.

For example, $Q = 3$ and 15 correspond to reflectivities of approximately 19% and 62%, respectively.

If the laser pulse length is long enough for the ion temperature to reach $T_i \approx ZT_e$, the damping factor D in Eq. (46) will self-adjust^{109,115} to be of order unity. For a spherical target, the plasma length L will be given roughly by R . Then the wavelength-scaling of Q can be found by using T_{hot} from Eq. (42) and recalling that $v_0^2 \propto I_L \lambda_L^2$. The quantity (n/n_c) can be estimated by supposing that $n \approx n_{\text{hot}}$ in the underdense plasma, and by noting that for resonance absorption the hot electrons carry off the absorbed laser intensity I_a : $n_{\text{hot}} m_e^{-1/2} T_{\text{hot}}^{3/2} \approx I_a$. This gives an upper limit on n_{hot} , because at shorter wavelengths increasing fractions of the absorbed energy should go into the thermal electrons. The net result of these scaling arguments is that

$$Q \propto \lambda_L \quad (47)$$

in this long-pulse regime. Thus, the Brillouin reflectivity should be strongly decreased by the use of short-wavelength lasers, for $\lambda_L < 10 \mu\text{m}$.

In summary, our analysis of stimulated Brillouin scattering indicates that targets irradiated spherically with laser light having $\lambda_L < 10 \mu\text{m}$ should show significantly decreased reflectivity when short-wavelength lasers are used. CO_2 lasers may be able to stay away from the high-reflectivity regime by using targets with radii $\gtrsim 1$ mm, since these targets may not produce enough underdense plasma to cause significant Brillouin reflectivities.

Transport Inhibition Mechanisms. Efficient electron thermal conduction from the hot, critical-density surface to the cold, dense, inner regions of the target is central to the achievement of high implosion velocities and efficient implosions. Later, we will be discussing the favorable scaling of implosion properties for short laser wavelengths for a given amount of transport inhibition. In the present subsection, we emphasize that we also expect thermal electron transport to be more efficient for short-wavelength lasers than for long-wavelength lasers. Both of these effects strongly favor short-wavelength lasers.

Recent experiments^{116,117} suggest that thermal-electron heat flux is strongly inhibited below its classical value¹¹⁸ $Q_e = -K\Delta T$, for $1.06\text{-}\mu\text{m}$ lasers and laser pulses shorter than 100 ps. The

mechanism producing inhibited transport has not yet been precisely identified, but it is generally attributed to a variety of plasma physics processes that produce "effective" collisions at a rate greater than the classical¹¹⁸ collision frequency: $\nu_{\text{eff}} > \nu_{\text{ei}}$. Because electron heat flow is a diffusive process, a greater collision rate ν_{eff} produces a velocity of heat flow that is slower than classical, or inhibited velocity.

For the purposes of inward heat transport, we are interested in the values of ν_{ei} and ν_{eff} at a density several times critical. Because $\nu_{\text{ei}} \sim n_e T_e^{-3/2} \sim \lambda_L^{-2} T_e^{-3/2}$, we see that classical collisions increase rapidly with shorter laser wavelength. As the laser wavelength becomes shorter, it becomes more and more difficult for an anomalous plasma physics process to produce an effective collision frequency ν_{eff} comparable with ν_{ei} . Transport inhibition should then be less strong for short-wavelength lasers.

Consider magnetic fields as a case in point. Megagauss dc magnetic fields have been observed in laser-produced plasmas¹¹⁹, and are thought to be generated by nonparallel density and temperature gradients. By balancing the magnetic field source with loss caused by fluid convection,

$$\frac{c}{en_e} \nabla n_e \times \nabla T \cong \nabla \times (\mathbf{v} \times \mathbf{B}),$$

we find by dimensional analysis that the product of the electron cyclotron frequency Ω_{ce} and the electron-ion collision time τ_{ei} is

$$\Omega_{ce} \tau_{ei} \cong \frac{\lambda_{\text{mfp}}}{L_T} \sqrt{\frac{M_i}{m_e}}, \quad (48)$$

where λ_{mfp} is the scattering mean free path of an electron, L_T is the temperature-gradient scale length, and M_i and m_e are the ion and electron masses, respectively.

One expects significantly inhibited transport when $\Omega_{ce} \tau_{ei} \gg 1$. The temperature gradient length L_T is at least as large as the impressed gradient in the laser illumination pattern. On the other hand, the mean free path λ_{mfp} at a few times the critical density scales as $n_e^{-1} T_e^2 \sim \lambda_L^2 T_e^2$. Thus, short laser wavelengths tend to sharply decrease the value of

$\Omega_{ce} \tau_{ei}$, and consequently decrease the inhibiting effect of magnetic fields on thermal transport in the overdense regions. The strength of this effect is somewhat decreased in the special case of CO_2 lasers because, for CO_2 , extreme profile steepening raises the density just inside the critical surface to a value well above n_c . However, even for CO_2 one has $\Omega_{ce} \tau_{ei} \propto T_e^2 \propto T_{\text{hot}}^2$. Because T_{hot} can be large, $\Omega_{ce} \tau_{ei}$ can be $\gg 1$ for CO_2 as well as for shorter-wavelength lasers.

In a second class of proposed mechanisms for transport inhibition, a crucial role is played by the collisionless outward streaming of suprathermal electrons produced at the critical surface. Electric fields that form to oppose the outward flux of suprathermals can have a variety of transport-inhibiting effects via their interaction with the thermal electron population. However, short-wavelength lasers cause conditions where the suprathermal electrons are more collisional at the critical surface, because at the critical density the mean free path is

$$\lambda_{\text{mfp}}(n_c) \sim T_{\text{hot}}^2 / n_c \sim \lambda_L^{3.6}, \quad (49)$$

using Eq. (42). This is a very strong scaling with wavelength. It suggests that lasers having wavelengths in the 1/2 to 1/4- μm range might be able to eliminate entirely this class of transport inhibition mechanisms; suprathermal electrons born at the critical surface would be thermalized right in the critical surface region, rather than free-streaming into the underdense plasma and creating large electric fields there.

We conclude that many classes of mechanisms that inhibit the inward heat flux of thermal electrons are expected to become weaker for shorter laser wavelengths.

Implosion Efficiencies. If one knows the degree of inhibition of inward electron heat flow for a given set of laser parameters, one can then ask how this inhibition affects implosion efficiency. By implosion efficiency we mean the inward kinetic energy of the imploding target, relative to the incident laser energy. Previous authors¹²⁰ have investigated implosion efficiencies for uninhibited heat transport. If inward heat flow is rapid, the newly heated material at the surface of the cold dense target will expand outward rapidly. Then by

conservation of momentum, the cold remainder of the target gets a bigger push inward as a result of the rocket effect. Figure 3-59 illustrates this process. Conversely, inhibited inward heat flux leads to slower outward expansion of the blow-off, and a less vigorous implosion of the inner parts of the target.

In general, the critical density surface is farther from the ablation surface for long laser wavelengths than for short ones, for lasers having $\lambda_L < 10 \mu\text{m}$, so that profile steepening is not extreme. As a consequence, transport inhibition has a relatively larger impact on implosion properties for long-wavelength lasers, since the inward-diffusing electrons have to transport their energy over a longer distance.

These phenomena can be quantified using a model for ablative implosions developed recently at LLL¹²¹. In this model, the conductive electron heat flux is taken to be the minimum of the classical and flux-limited values,

$$q_e = \min \begin{cases} -\kappa \nabla T \text{ ergs/cm}^2 \text{ s} \\ -f(n_e k T_e) v_{te} (\nabla T / |\nabla T|) \text{ ergs/cm}^2 \text{ s} \end{cases} \quad (50)$$

Here $v_{te} = (kT_e/m_e)^{1/2}$ and f is the flux limit, which is assumed for simplicity to be constant in space. The equations for conservation of mass, momentum, and energy are solved for a quasi-steady state in spherical geometry. The model does not apply to CO_2 lasers, where suprathermal electrons dominate the heat flux. For lasers with wavelengths $< 10 \mu\text{m}$, a generalized rocket equation describes the mean implosion velocity resulting from given initial values of the pressure at the ablation surface, p_0 , and the initial mass-loss rate $\dot{m}_0$:

$$\bar{v} = \left(\frac{4\pi R_0^2 p_0}{\dot{m}_0} \right) \ln \left(\frac{m}{m_0} \right) \quad (51)$$

Here m and m_0 are the remaining and initial target masses, respectively.

The implosion efficiency is then

$$\epsilon = \left(\frac{2\pi R_0^2 p_0^2}{I_0 \dot{m}_0} \right) \times \left[\frac{(m_f/m_0) \ln^2(m_f/m_0)}{t_p \dot{m}_0/m_0} \right], \quad (52)$$

where m_f is the final mass remaining in the pellet. The two factors in this expression have distinct physical interpretations. The second factor (in square brackets) represents the matching between the laser pulse and the target, and is order unity if the pulse length t_p is roughly equal to the natural mass-loss time of the target, $m_0/\dot{m}_0$. On the other hand, the first factor in Eq. (52) represents the effects of transport inhibition and laser wavelength on implosion efficiency, and can be evaluated using the expressions for p_0 and $\dot{m}_0$ derived in Ref. 121. If we isolate this transport-dependent factor ϵ_t , we can investigate its scaling with laser wavelength:

$$\epsilon_t \equiv \frac{2\pi R_0^2 p_0^2}{I_0 \dot{m}_0} \propto \lambda_L^{-p} \quad (53)$$

Figure 3-60 plots the exponent "p" in $\epsilon_t \propto \lambda_L^{-p}$ as a function of the flux limit f , for a DT target. In all cases, short laser wavelengths produce more efficient implosions. We see that for good thermal conduction ($f \sim 0.5$), the implosion efficiency scales as $\epsilon_t \propto \lambda_L^{-0.5}$. But for the small values of the flux limit typical of transport inhibition, we find much stronger wavelength scaling, with efficiency varying faster than $\lambda_L^{-1.2}$ for $f \leq 0.05$.

We conclude for $\lambda_L < 10 \mu\text{m}$ that if transport is strongly inhibited, short-wavelength lasers produce much more efficient implosions than do long-wavelength lasers. If thermal transport is good, short wavelengths are still favored, but not so strongly. The moral is that an improved knowledge of conduction inhibition is very important for the choice of optimum wavelength for a fusion-reactor

Fig. 3-66. Exponent "p" as a function of the flux limit f , measuring the degree of transport inhibition. The implosion efficiency ϵ_t is proportional to $\lambda_L^{-1.2}$, where λ_L is the laser wavelength.

laser, because the wavelength-scaling of implosion efficiency is a sensitive function of the degree of transport inhibition.

Conclusions. Each of the four plasma physics processes discussed above has its own distinct scaling with laser wavelength. In the past, the issue of suprathermal electron generation has received the most attention. Yet reactor targets, because of their large sizes, may be to some extent self-shielding from hot electron preheat. Consequently, we would like to urge that more attention be paid to the wavelength scaling of Brillouin scattering, transport inhibition, and implosion efficiency. Our preliminary analysis of these processes indicates that they make short laser wavelengths look very favorable, with CO_2 being a possible special case because of the preponderance of hot electrons and the short spatial extent of underdense plasma measured in vacuum wavelengths.

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3.6 Code Development

Recently the work of the code group has been influenced by two major factors: (1) the large amount of experimental information relating to laser interaction with high-Z targets, and (2) the need to produce versions of our codes that can run efficiently on the newly acquired Cray-I computer.

Calculations of high-Z disk experiments (§5.2-5.4) have pointed out the need for several improvements. In particular, self-consistent models are needed for stimulated Brillouin scattering, non-LTE physics, and electron transport inhibition. These calculations have also shown that the models for absorption, θ_{hot} , and x-ray emission can be sensitive to zone size and should be improved.

Stimulated Brillouin scattering reduces the amount of laser light near critical density and is therefore important in predicting the amount of absorption. We have implemented a model of this process (§3.6.1) which is consistent in that it depends on local plasma quantities, accounts naturally for geometry and scale length factors, and produces self-consistent ion heating. The model, however, assumes that scattered light is simply lost, ignoring any further interaction with the plasma. Overall agreement with absorption measurements has improved.

The non-LTE treatment of emission and absorption processes is in fairly good shape, both physically and numerically, and has been found important in predicting x-ray emission spectra. The non-LTE pressure and energy, however, are not thermodynamically consistent. This results in a poor hydrodynamic treatment of the non-LTE regions. To establish this consistency, we must use Fermi statistics in the ionization equations and include pressure ionization terms in the thermodynamic quantities. This work is nearly completed.

We are a long way from being able to consistently model electron transport inhibition, primarily because we do not yet know what is causing the inhibition. Currently, we have models for inhibition by the electron-ion two-stream instability and by self-generated magnetic fields, but both of these models need improvement. The two-stream model must be modified to account for the fact that the instability is not infinitely strong as well as to do consistent ion heating. The magnetic field physics lacks corrections of the finite gyro radius of the electrons and has only a crude description of turbulent fields. The field equations are also sensitive to zone size. Improvement of these aspects are long-term projects.

It is also possible that the need for electron transport inhibition is merely an artifact that corrects for some other physical or numerical problem in the code. Suprathermal electron

transport has been particularly suspect in this regard, because the possibility existed that electrons were numerically "leaking" through physical potential barriers. We have completely reworked the numerical methods for suprathermal transport (§3.6.2) and now have a scheme that produces an exactly consistent electric field, at least for one-dimensional problems. We have not yet obtained enough experience with this new method to say whether or not it affects the need for transport inhibition.

The use of inhibited transport produces very steep temperature and density profiles in the plasma. This is necessary to obtain agreement with the experiment, but it also places very severe limitations on zone size if one is to adequately resolve the gradients. We have been trying to formulate difference equations that account for large gradients so that accurate calculations need not be prohibitively expensive. For example, we have redone the spatial integration of inverse bremsstrahlung absorption and the determination of θ_{hot} so that they are exact for linear density and temperature profiles. This has somewhat reduced the zoning dependence of these quantities, but the fact that the profiles are only approximately linear means that reasonably fine zones are still required. We are currently considering methods of improving this integration.

The Cray-I computer will be available for our use in Spring 1979. Because our codes use a great deal of 7600 time, it is important for the codes to be running on the Cray as early and as efficiently as possible. In the process of rewriting for the Cray we are also restructuring the codes so that the codes will be easier to understand, modify, and maintain. At the same time, several old inconsistencies and redundancies in the coding will be eliminated.

We have made several basic decisions about how to handle our codes: (1) we will maintain one version of each code (at the source level) that must function for all mainframes; (2) the coding will make near-optimal use of machine-dependent hardware features; (3) all input, output, and user interfaces will be identical and all files will be portable between machines. These decisions have not, in practice, been limitations. Rather, they have led us to a philosophy of code and data structure where modularity, simplicity, and symbolic manipulation of data have resulted in increased reliability and flexibility. Implementation of this philosophy is discussed in §3.6.3.

3.6.1 A Simple Brillouin Backscatter Model for Fluid Codes

Stimulated Brillouin scattering (SBS) is a three wave interaction involving two transverse light waves and an ion acoustic wave. It is described by the resonance condition,

$$\omega_0 = \omega_s + \omega_{ia}$$

where ω_0 , ω_s , and ω_{ia} are the laser, scattered transverse light wave, and ion acoustic wave frequencies, respectively. The maximum growth rate occurs when the two light waves are oppositely directed, i.e., backscatter. In the case of a laser-target interaction, the incident laser light is scattered back toward the source by SBS, preventing this light from being absorbed by the target.

In early laser target experiments, SBS was not found to be important.^{122,123} However, as more energetic lasers become available, experiments with longer pulse lengths and larger spot sizes are possible while keeping the laser intensity times the square of its wavelength in the regime of interest for fusion, that is, around $10^{15} \text{ W}\mu\text{m}^2/\text{cm}^2$. For the latter situation, the underdense plasma, in which the Brillouin interaction occurs, is much larger and SBS may be very important.

Experimental evidence for Brillouin backscatter is strong. Light absorption is seen to decrease as pulse lengths increase.^{124,125} The backscattered light shows a clear redshift and its polarization is primarily out of the plane of incidence implying SBS.^{124,125}

Using the results of the one-dimensional, kinetic, relativistic, electromagnetic simulation code OREMP,¹²⁶ we have made a semi-empirical fit to an adaptation of the Brillouin scaling described by Krue, ¹²⁵ which is made independent of zoning. At each time step for each zone from vacuum to critical, starting with the edge that the laser first strikes, light is reflected according to that description. The ions are then heated according to the Manley-Rowe relations, and the intensity in the next zone away from the light is decreased by the fraction of light reflected by the previous zone.¹²⁷ The ion heating increases the ion Landau damping, which in turn decreases the reflection on the next time step.¹²⁷ Momentum is also deposited to model profile modification. The results show reasonable

agreement with one-dimensional spherically symmetric experiments at 200-ps pulse lengths. At intensity $10^{15} \text{ W}/\text{cm}^2$, we find about half the Brillouin reflection for laser wavelength $0.25 \mu\text{m}$ as compared to $1.06 \mu\text{m}$.

A simple physical description¹²⁸ of stimulated Brillouin backscatter is: The incident laser light oscillates the electrons in a direction perpendicular to the direction of the beam propagation and in the direction of its transverse electric field. In an imaginary plasma of uniform density, the light reradiated by the current density would cancel out. In a real plasma, there is always some noise that produces density nonuniformities and, consequently, the current density produced by the incident laser light is nonuniform. In the case of the Brillouin instability, a feedback mechanism occurs such that a density fluctuation forms from noise with wavelength half the swelled wavelength of the light in the plasma. Now the current density is nonuniform and the light is reradiated coherently backward and interferes with the input light, such that the resultant ponderomotive pressure enhances the density fluctuation. The electron density is coupled to the ion density by the longitudinal electric field and the density fluctuation exponentiates until saturated by pressure balance, ion Landau damping, or wave breaking, in the case of strongly driven waves. The linear theory for this was derived in the context of laser fusion plasmas in Ref. 126. A nonlinear theory that describes the Brillouin reflection as a function of the laser light intensity, plasma electron and ion temperatures, density, and charge state was recently presented.¹²⁴

To fit this theory into a fluid code it had to be made independent of zoning and its noise parameter needed to be calibrated to some independent test. A zone-independent form is shown in Fig. 3-61; Eqs. (3-54) and (3-55) describe it reasonably well:

$$\text{Reflection} = 1 - \exp$$

$$- \frac{A[(v_{osc}/v_{the})^2(n/n_c)^y(\ell/\lambda_0)]}{(\omega_i/\omega_r)[1 + (3T_i/ZT_e)](1 - n/n_c)^{1/2}} = 1 - e^{-q} \quad (54)$$

$$\Delta T_i/\Delta t = \text{reflection} (\omega_r/\omega_0) (1/\ell n_i) \quad (55)$$

where ω_r/ω_0 = ion acoustic frequency/laser frequency = $2kc_s/\omega_0$, where c_s = sound speed = $\{(ZT_e + 3T_i)/[m_i(1 + k^2\lambda_D^2)]\}^{1/2}$, and k is the ion acoustic

Fig. 3-41. Zone-independent Brillouin reflection.

wave number $= 2(\omega_0/c)(1 - n/n_c)^{1/2}$. The ion acoustic wave Landau damping is ω_i , and ℓ is the ray path length in the zone. Y and A have best fits of 2-3 and 0.1 $v_{osc} = eE/m_e\omega =$ peak oscillatory velocity $= 8.55 \times 10^{-10} \lambda_0^{1/2}$ of an electron in the electric field (E) of the laser light of angular frequency ω , e/m_e is the electron charge to mass ratio, λ_0 is the laser vacuum wavelength in micrometres, I is the laser vacuum intensity in W/cm^2 , $v_{the} = T_e/m_e$, n/n_c is the electron density/critical density, λ_D is the electron Debye length, m_i is the ion mass, $T_e =$ electron temperature, and $T_i =$ ion temperature. This form is reasonably good only for $v_{osc}/v_{the} \gtrsim 1$, and consequently the code has a nonlinear statement such that the time-averaged amplitude of the ion fluctuation, $1/8(v_{osc}/v_{the})^2 / [(\omega_i/\omega_r)(1 + 3T_i/(ZT_e)(1 - n/n_c)^{1/2})]$, maximizes at 0.125. For numerical reasons, the swelling factor was dropped as a first pass. Krueer's more complete form¹²⁸ showed a region of exponential increase with q for low q and a region of pump depletion limit at high q , and it was consequently zoning-dependent if fitted to each zone. Equation (54) assumes that the Brillouin backscatter is always in a pump depletion limit, which is not always strictly correct, but has the advantage that it is independent of zoning and is suited to density and temperature gradients.

This equation is fitted to a large number of simulations with the relativistic, electromagnetic, kinetic, one-dimensional computer code OREMP,¹²⁶ which self-consistently studied Brillouin backscatter as a function of the parameters of Eq. (54) between limits $0.3 < v_{osc}/v_{the} < 2$, $10 < L/\lambda_0 < 127$, $0.05 < n/n_c < 0.7$, $1 < \text{initial } T_e/T_i < 30$. The effect of noise was studied by

varying the number of particles and by studying the effect of the reflecting boundary condition for the light that had propagated through the underdense plasma and was reflected by the critical density surface. A spot check showed that the reflection was somewhat sensitive to the right electromagnetic boundary condition and to noise. One can see from the theory^{123,128} that for small reflection, the reflection is proportional to the noise, whereas for large reflection, it is proportional to the logarithm of the noise. The effect of a partially reflecting boundary condition to model a critical surface¹²⁸ was also examined and found to initially cause higher reflection, but the multiple reflection and consequent higher ion heating reduced the Brillouin reflection to about the same as with a transmitting boundary condition after about 6 ion acoustic periods. A best fit for Eq. (54) to the simulation data was for y between 2 and 3 and for A about 0.1. We understand two reasons why y is greater than one. First, Brillouin reflection is a convective instability and for q small, the reflection grows exponentially¹²⁴ rather than the pump depletion limit $1 - e^{-q}$. A low-density run with 127 wavelengths is much more consistent with $y = 2.5$ than with $y = 1$, and it is also more consistent with the other data, even though there is ample room for the instability to grow many e-foldings and saturate. A closer examination of runs with density less than $0.25 n_c$ reveals that the Compton instability (another word for Raman below the resonant density) heats in a surprisingly vigorous fashion and thus lowers q by increasing v_{the} . If one includes the Compton heating, and if the swelling is included, OREMP runs are consistent with the theory¹²⁴ with $y = 1$; however, to make a numerical approximation independent of zoning it was necessary to make $y = 2$ to 3.

A second reason may be that the noise is a function of the density. Consequently, this is a subject for further work. The reflection of the simple model is not as sensitive to y and A as one might first guess, because the approximation is to some extent self-stabilizing. That is, the model will reflect a fair amount of light for most situations until the ions heat up to limit the reflection.

The theory of ion Landau damping was first worked out in detail by Fried and Gould,¹²⁹ Because it requires the solution of a complex integral equation that would require too much time for each point and time step of a fluid code, we worked out the integral equation for a large region

of parameter space (Figs. 3-62 and 3-63). We then fitted these equations by a four-piece fit to simple analytic formulas. It is interesting that the saturated reflection is proportional to the exponential of ZT_e/T_i in the sensitive region of parameter space where Brillouin backscatter reflects a large amount of light and where the ions heat by ion Landau damping. We wrote a simple, fixed-density one-dimensional simulation code to test Eqs. (54) and (55) and we then compared the time-dependent reflection and ion heating to the kinetic code runs. It was through this simple model that we made the fit for A and y.

The implementation of our semi-empirical Brillouin-backscatter model works in the following manner. At each time step, the incident laser light is tracked through the target material from vacuum into its turning point and back out. Starting with the zone that the laser strikes first, a fraction r of the light is backscattered according to Eq. (54). The ions in this zone are heated by an amount governed by the Manley-Rowe relations. The remainder of the backscattered energy is assumed to propagate back out of the target. In practice, this energy is lost. The laser energy used in the next zone is decreased by the amount of energy backscattered and absorbed by inverse bremsstrahlung or collective processes, and thus we self-consistently include

Fig. 3-62. Ion Landau damping vs $T_e/T_i \approx ZT_e/T_i$.

the competition between the two. Inverse bremsstrahlung is also modeled by an exponential in space and so the Brillouin backscatter and inverse bremsstrahlung are numerically evaluated simultaneously by a sum of the arguments. The proper momentum is deposited in the zone. This process is repeated in each zone encountered by the laser.

Fig. 3-63. Ion Landau damping vs $k\lambda_D$.

Thus, our new Brillouin backscatter model affects the amount of laser energy available for absorption as well as the energy of the ions. Ion heating increases the damping of the ion acoustic wave which, in turn, decreases the Brillouin backscatter for the next time step.

The Brillouin model shows reasonable agreement with one-dimensional, spherically symmetric glass microsphere experiments. We find for long pulse lengths (~ 200 ps) that SBS reduces the absorption by 70% or more. For shorter pulse lengths (~ 40 ps) the absorption suffers a reduction of only about 25%.

Finally, the limitations of our implementation of SBS should be clearly stated. The backscattered light is not tracked. It is assumed to have left the problem without further interaction. Therefore, the light intensity in the underdense slab is not entirely correct as the backscattered light is not present. Also, the backscattered light, reflected as the laser light propagating back out of the target after it has reached its turning point, should interact with the target. Instead, this energy is lost. Generally, we have found this to be only about 10% of the light reflected by SBS on the laser beam's trip in. However, for the shorter pulses, there is quite a bit more scattering as the ray is traced back out of the target.

Also, one must be careful when using this model in one-dimensional planar configurations. These calculations correspond to an infinite spot size, and they give a much larger underdense plasma than would actually occur if the spot diameter were less than the product of the sound speed and the laser pulse length. In our one-dimensional test calculations on gold disks, the underdense plasma was three to four times too large. This unrealistically large underdense plasma coupled with our SBS model will backscatter more light than is actually observed. Brillouin sidescatter is only indirectly modeled and is important for spot sizes larger than 100 light wavelengths.

The new Brillouin backscatter model, when used with care, will allow one to model laser target interactions with more confidence. Previously when no SBS was calculated, a target designer had to just throw away a fraction of the incident light before beginning the target calculation. The ion heating resulting from SBS is of interest. It will affect the ion-electron two-stream transport inhibition through ZT_e/T_i . The reduced laser intensity at the

critical surface, where resonance absorption occurs, will affect the hot electron temperature. These phenomena may now be studied.

Limitations of the Model. Brillouin backscatter heats up the ions^{124,127} on each reflection and there can be multiple reflections.¹³⁰ Multiple reflections by Brillouin backscatter in an underdense plasma have been observed before in simulations.¹²⁶ However, the effect is clearly much greater when the critical surface is included, since the light reflected from critical forms a partial standing wave that drives higher-amplitude ion waves. The OREMP simulations, upon which the model was based, had transmitting boundary conditions for the light.

Most of the heated ions are accelerated up to higher densities so that they are in position and velocity space to do the most damping. Because the ion-ion equilibration time is generally not small, this effect is significant.¹²⁸ Our target simulation model does not specifically include this effect, although there is a parameter to artificially mock-up the effect by a multiplier on T_i .

The ion acoustic instability^{131,132} transfers energy from the electron drift to the ion kinetic energy. We are considering using Manheimer's model¹³¹ for ion heating.

Ion-ion streaming instabilities between ion species of different Zm_e/m_i may produce ion heating.^{132,133} Thomson and Randall¹³⁴ have recently found that Brillouin backscatter increases greatly in the region where the relative velocity between critical and that region is $\text{Mach}(1 - n/n_c)^{1/2}$.

One very interesting effect learned from runs of $n/n_c = 0.1$ and $127\lambda_D$ long is that stimulated Compton scattering significantly heats electrons for the long density gradients associated with long pulse lengths. Because Compton scattering occurs below the region of traditional absorption by inverse bremsstrahlung, resonant absorption, and instabilities, and also below the region of Brillouin backscatter at higher densities, then it and quarter-critical instabilities (see below) might become the dominant absorption mechanisms. For example, for $T_e = 1$ keV and $I = 2.5 \times 10^{15}$ W/cm², Compton scattering reflected 12% of the light and about 4% was absorbed into electrons of Maxwellian T_{hot} of 12 keV. Peak reflection and absorption were much higher. For long density gradients, other plasma effects that also become important are the $2\omega_p$ and Raman back- and side-scatter,¹³⁵ which can heat electrons to suprathermal temperatures, and

filamentation, which can concentrate the light so that when it reaches critical (as well as quarter-critical), the high intensity can heat electrons to higher temperatures than would otherwise occur. For filamentation to dominate Brillouin back- and side-scatter, $ZT_e/T_i \sim 1$.

Experimental evidence shows that the density profile undergoes relaxation oscillations that occur on both fast¹³¹ and slow¹³² time scales. Some of these may result from the flow through critical becoming sub- and super-sonic¹⁴, laser hot spots, surface instabilities, magnetic fields, or other unknown effects. Even in the short time and space scales of the kinetic simulations, very large oscillations occur in the Poynting vector of the reflected and transmitted light. At times, much more light is reflected than is transmitted, because light undergoes multiple reflections even in an entirely underdense plasma. The data in Fig. 3-61 are averaged over the oscillations, but there is still inherent variation.

Density gradient thresholds¹³⁶ are not included, but are being seriously considered. We did consider velocity gradient thresholds, and we did do some OREMP simulations. We found that unrealistically large velocity gradients were necessary to significantly reduce reflection.

One may estimate the scaling of Brillouin backscatter with time by considering that the length of the underdense plasma $L \sim c_s t = \text{sound speed times time}$. For long pulses, geometry has to be taken into account. For example, if the geometry is Cartesian, then the spot size determines the density scale length if that is smaller than $c_s t$. Also, in spherical geometry, if L is longer than the pellet radius, then spherical effects are clearly important. In addition, if the light is obliquely incident, then L is obviously greater than the density gradient normal to the critical surface and is the ray trace path. Equation (54) assumes a flat density. When fitting to a density gradient, that integral must be made. The time for the ions to heat up to ZT_e for effective damping is $(n/n_0)(v_{the}/c) L[m_i/(Zm_e)]^{1/2}/[(v_{osc}/c)^2 cr]$, where L and c are in cgs units.

So What Can be Done About Brillouin Backscatter? Laser intensity can be reduced, which also has the effect of reducing T_{hot} , thus offsetting somewhat the effect of reducing the intensity. Increasing the laser frequency reduces v_{osc} for a fixed-light intensity and also has the effect of simultaneously reducing the electron temperature.

However, the inverse bremsstrahlung increase that occurs at the higher density associated with a higher frequency laser results in increased absorption and higher relative T_e . Figure 3-64 shows results¹³⁷ of reflection vs wavelength for $\lambda_0 = 0.265, 0.53$, and $1.06 \mu\text{m}$, respectively.

A multiline^{126,138} laser can be used, where the frequency width between the line is greater than the growth rate of the instability. If the difference between the frequencies is more than the Brillouin growth rate, then the Brillouin instability for each line is reasonably independent of the other. One can estimate the relative reduction in reflection by analyzing each line in Fig. 3-64 independently. Kinetic simulations (OREMP) have verified this method for lines 2 and 7. The Brillouin growth rate is given by the following two limits,^{128,139}

$$\gamma/\omega_0 = (v_{osc}/c)[(Zm_e/m_i)(n/n_e)/(8c_s/c)]^{1/2} \gamma \ll kc_s \quad (56)$$

$$\gamma/\omega_0 = 0.87[0.5(v_{osc}/c)^2(Zm_e/m_i)(n/n_e)]^{1/3} \gamma \gg kc_s \quad (57)$$

Laser bandwidth can be increased. Experimental evidence from Yamanaka's group¹⁴⁰ and KMS,¹⁴¹ as well as theoretical work from Thomson¹³⁸ and LLL¹⁴¹ shows that bandwidth reduces the reflection caused by Brillouin backscatter. Figure 3-65 presents OREMP simulation data and shows reflection vs bandwidth for a variety of cases. For $\Delta\omega/\gamma$ greater than about 10 when v_{osc}/v_{the} is less than one, reflection is considerably reduced ($\Delta\omega$ is the laser bandwidth). The scaling parameter $\Delta\omega/\gamma$ is simplified; the reader is referred to Thomson¹³⁸ for a more complete theoretical description. Two-dimensional kinetic simulations of resonant absorption with large bandwidth show that the absorption and T_{hot} are about the same.

Another way to somewhat reduce Brillouin backscatter was suggested some years ago by Langdon and more recently by Perkins. They stated that putting a light species such as hydrogen into the target would increase the Landau damping on the ion acoustic waves from the heavier species, because the thermal speed of the light species is nearer to the phase velocity of the heavy species.¹⁴² Langdon found from simulations that this was not a very important effect, but that it did help.

Fig. 3-64. Results of reflection vs wavelength for $\lambda_0 = 0.266, 0.53$, and $1.06 \mu\text{m}$, respectively.

$$\gamma/\omega_0 = \frac{\sqrt{3}}{2} \left(\frac{v_0^2}{2c^2} \frac{Zm_e}{m_i} \frac{n}{n_c} \right)^{1/3}$$

$$v_0/c = 8.65 \times 10^{-10} \quad \lambda_0(\mu) \sqrt{I_L \text{ W/cm}^2}$$

$$n/n_c = \frac{\text{Average density}}{\text{Critical density}}$$

Fig. 3-65. GEMEP simulation data showing reflection vs bandwidth.

One can reduce Brillouin sidescatter about a factor of two (and also T_{hot}) by circular or cross polarization. In measuring Brillouin scatter, it is important to consider (as pointed out by Biskamp and Welter¹⁴³) that the light may not come directly back toward the lens. Using two-dimensional simulations, Ref. 142 showed that light entering at 24 deg came out at 11 and 37 deg with p polarization (no sidescatter) and at 53 deg with s polarization (where sidescatter is allowed). An example from a fluid code¹⁴⁴ with perpendicular incidence shows the reflected light patterns¹⁴⁵ in which about as much light is sidescattered as backscattered, and that it is scattered and refracted to about a 45-deg angle to the normal for $v_{\text{osc}}/v_{\text{the}} = 0.5$. Light sidescattered at high density is then refracted to an angle nearer to that of the incident light in vacuum. For sidescatter to be effective, the spot size must be hundreds of wavelengths wide because many growth lengths in the sideways direction are needed.

Parenthetically, it is worth noting here that the mean free path (λ_{mfp}) of an electron heated by resonant absorption at the local critical density goes as the laser vacuum light wavelength (λ_0) to the 3.6 power: $\lambda_{\text{mfp}} \sim T_{\text{hot}}^2/n_c^2 \sim [(1/0.4)^2/(1/\lambda_0)^2] \sim \lambda^{3.6}$. For example, if $Z = 50$, $\lambda_0 = 0.25$, irradiance $= 10^{15}$ W/cm², the mean free path from electron-ion collisions is ~ 0.6 μm at critical. By comparison for similar conditions at $\lambda_0 = 1$ μm , the mean free path is 100 μm . Most of the $\lambda_0 = 0.25$ μm heated electrons thermalize before leaving the heating region. The significance for laser fusion is that there is less preheat, and if transport inhibition is caused by electrostatic fields from the fast electrons,¹⁴⁶ then at least the electrostatic part of transport inhibition should be much reduced. Experimental evidence from Ecole Polytechnique¹⁴⁷ supports this reduction. If the transport inhibition is caused by magnetic fields, then the wavelength scaling is not so clear.

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3.6.2 Suprathermal Electron Subroutine

In laser plasmas, energetic electrons that do not have a thermal energy distribution are generated at the critical density, and these "suprathermal electrons" must be followed as a function of energy to

model real experiments. A new subroutine to model suprathermal electron physics has been written that overcomes the difficulties that have plagued past attempts. Our treatment is fully relativistic.

The basic equation describing the fast electron transport¹⁴⁸ is

$$\left(\frac{\partial n}{\partial t}\right)_L = - \left(\vec{\nabla} \cdot e \vec{E} \frac{\partial}{\partial \epsilon} \right) \vec{F} + \frac{\partial}{\partial \epsilon} (\alpha n) , \quad (58)$$

where

$$\left(\frac{\partial n}{\partial t}\right)_L = \frac{\partial n}{\partial t} + \vec{\nabla} \cdot (v n)$$

is the Lagrangian time derivative; v is the matter velocity; n is the number of electrons/cm³ keV, so that $\int n d\epsilon d^3x$ = number of electrons; E is the electric field = $-\vec{\nabla}\phi$; ϵ is kinetic energy; and $\sigma(\epsilon)$ is the thermal loss coefficient or the rate at which fast electrons lose energy to the background thermals through Coulomb collisions. The flux

$$\vec{F} = -\beta \left(\vec{\nabla} \cdot e \vec{E} \frac{\partial}{\partial \epsilon} \right) \left(\frac{n}{p m \gamma} \right) , \quad (59)$$

where $\gamma = 1 + \epsilon/(mc^2)$ and $(n/pm\gamma)$ is the phase space density.

In addition, the model includes fast electron pressure terms

$$\left(\frac{\partial n}{\partial t}\right)_L = \frac{(\nabla \cdot \vec{v})}{3} \frac{\partial}{\partial \epsilon} (p n) , \quad (60)$$

where $u = p/(m + \epsilon/c^2)$, and the fast electron pressure is $P_{ST} = \int d\epsilon (pu/3)n$.

Finally, the effects of bremsstrahlung are included in the form

$$\frac{\partial n}{\partial t} = n_i \left[\int_0^\infty dk n(\epsilon + k) u_k \frac{d\sigma}{dk} - n(\epsilon) u \int_0^\epsilon dk \frac{d\sigma}{dk} \right] , \quad (61)$$

where n_i is the ion density, k is the photon energy,

$$u_k = c \sqrt{(\epsilon + k)^2 - (mc^2)^2} ,$$

and $d\sigma/dk$ is the bremsstrahlung cross section.

The fast electron pressure term in Eq. (60) and the bremsstrahlung in Eq. (61) are split off and calculated separately from transport and thermal loss [Eqs. (58) and (59)]. To better understand Eqs. (58) and (59), we change our energy variable from kinetic to total energy:

$$\epsilon_T = \epsilon + c\phi(z, t)$$

$$\vec{E} = -\vec{\nabla}\phi .$$

If we now take our density as a function of total energy, Eqs. (58) and (59) become

$$\left(\frac{\partial n}{\partial t}\right)_L = -\nabla \cdot \vec{F} + \frac{\partial \alpha n}{\partial \epsilon_T} , \quad (58a)$$

$$\vec{F} = -\beta \vec{\nabla} (n/pm\gamma) . \quad (59a)$$

This says that electrons move along surfaces of constant total energy. Thus, in total energy space the transport equations are much simpler because $\vec{E} \cdot \vec{v}$ longer appears.

In addition to the suprathermal electrons, we have a thermal electron group satisfying

$$\left(\frac{\partial n_{TH}}{\partial t}\right)_L = -\vec{\nabla} \cdot \vec{F}_{TH} + S_{TH} ,$$

where

$$F_{TH} = -\beta_{TH} \left(\vec{\nabla} p_{TH} + e \vec{E} n_{TH} \right) ,$$

and S_{TH} is a source of all the suprathermals that have lost so much energy they have become thermals.

The electric field $\vec{E}$ is chosen so that quasi-neutrality will be maintained, i.e.,

$$\int d\epsilon \vec{F}(\epsilon) + \vec{F}_{TH} = 0. \quad (62)$$

Equation (62) is used to calculate the electric field.

Fully implicit finite difference equations are used throughout, because this allows one to use time steps much larger than the transient times, and because transient times for the fast electrons are often too short for a practical time step.

Thermal electron transport is calculated each cycle. In every cycle, the fast electrons are mapped from a kinetic-energy space-bin structure, to a total-energy space-bin structure and then the transport and thermal losses are calculated with Eqs. (58a) and (59a), thus eliminating the electric field coupling between the bins. After the transport and thermal losses are calculated, the electrons are mapped back into kinetic energy bins.

The electric field is determined by calculating

$$\int d\epsilon \vec{F}(\epsilon) + \vec{F}_{TH} = \vec{F}_{ERR},$$

after the thermal and fast electron transports have been calculated. This will be not quite zero because the electric field is not exactly right and these $\vec{F}_{ERR}$ values are used to relax the electric field $\vec{E}$ towards a value that will make $\vec{F}_{ERR} \rightarrow 0$.

Finally, charge neutrality is enforced every cycle, so n_e will not slowly drift away from $\bar{Z}n_i$. The P·dV work and bremsstrahlung are then calculated. Virtues of this scheme are:

- Algebraic energy and electron number conservation.

- Electron densities can never go negative.

- Suprathermal electrons can move up or down in kinetic energy, thus making partial simulation of runaway phenomena possible. (Thermal electrons can only increase their temperature as they slide down a potential hill; they cannot become suprathermals.)

- The E·j coupling between the thermal electrons and fast electrons is now well behaved and there are no more problems with anomalous heating

or freezing of the thermals that plagued previous attempts.

- In steady state, the electric field will relax to exactly the right value to make the numerically calculated total current exactly zero.

The new subroutine is being used to perform better design simulations than were possible with the old suprathermal subroutines.

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3.6.3 Conversion to the Cray-1

We are in the process of modifying the laser program codes to make them available on the Cray-1 computer. The prime objective is effective utilization of the Cray-1 hardware features. The scope of this effort involves more than simple code conversion. We are redesigning the internal structure and organization of the codes. We intend to create new codes that are machine-independent on the source level. We intend this code to be easily optimized for the Cray, easily tested, easily modified, and easily maintained.

We have had to solve many technical problems in the creation of these new codes. A partial list of problems includes:

- Word size. The Cray-1 has a 64-bit word length, whereas the CDC-7600 has a 60-bit word length. The coding we generate or the data we manipulate must be insensitive to this hardware characteristic.

- Character sets. The Cray-1 uses the standard 8-bit ASCII character set, whereas the CDC-7600 uses a 6-bit ASCII character set. Coding and data must be insensitive to character size or value.

- Data format. The format of numbers on the Cray-1 is very different from the number format on the CDC-7600. We must design data structures that are easily and automatically translatable from machine to machine.

- Memory management. The Cray-1 has a single level memory, whereas the CDC-7600 has a split memory hierarchy. Arrays must be allocated in

such a manner that the hardware memory organization is hidden. Yet we must be able to make optimal use of the limited memory space available.

- **Operating system.** The Cray-1 will be using an operating system that is functionally similar to the time-sharing system on the CDC-7600. But because the system requests are formatted differently, we must generate coding that hides the details.

- **Language features.** We have become accustomed to compiler features that may not exist on the Cray-1. There are new features in Cray-1 compilers that we must utilize to make efficient use of the Cray-1. We must be careful how we make use of machine-dependent language features.

- **Vectorization.** The Cray-1 hardware includes a set of vector registers. We must make use of this hardware to greatly increase performance on the Cray-1. But we must do this in a manner that allows us to run on the CDC-7600 as well.

- **Interactivity.** We are intending to use the Cray-1 as an interactive design tool, and therefore we must structure the codes to allow this to happen in an efficient manner. We must be concerned about the human engineering aspects of the codes, so that we can readily integrate new user features into them.

We have addressed these problems and are solving them by directing our efforts to three distinct areas:

- Structured design.
- Machine portable data structures.
- Machine-independent I/O.

We are extending the relatively new ideas of structured software design, and have been spending considerable time and effort in the design of the major portions of our codes. We are creating program modules with simple, functionally cohesive interfaces. The result of this will be easily maintained and modified codes. The time spent in debugging and testing should be considerably reduced. Our efforts to optimize the codes by making use of the Cray-1 vector registers will be greatly simplified.

We are modularizing the data structures as well. By using macros we have been able to create our own language constructs for data declaration. The interfaces to these macros are machine independent, data independent, and code independent. The internal coding of these macros generates the desired machine-dependent statements at compile time. By making trivial changes, we are able to af-

fect the declaration and assignment of all variables throughout the code systems.

We are striving for simplicity as well. The macro constructs we have implemented are easily understood and are few enough in number to be totally comprehended. We are using macros throughout as primary building blocks for code modules and data definitions. This centralizes the machine-dependent code to a very small area that is easily changed for new machines. We have designed the macros to be general enough for use in a variety of situations and to make the code systems easier to manage. In many instances, we have implemented a macro syntax that is as readable and understandable as an English sentence.

To enhance the machine-to-machine portability of data, we have been intimately involved in the creation of an A-Division Community File (ACF) data structure. Each record in an ACF has the following elements:

- A header, containing machine, code, and data information.
- A symbol table, giving names and addresses to all the data items.
- An attribute table that describes the characteristics of each variable.
- An optional table, giving additional information on how to access individual data items.
- The actual data.

Several of these records may appear in an ACF. This allows the data to be split into logical sections. The development of the ACF will have several positive effects. These include:

- Simple and automatic translation of data between the Cray-1 and the CDC-7600. The ACF tables contain sufficient information to accomplish this.

- Reliable data transport between machines. All records, tables, and data items may be checksummed in an ACF. The translation routines verify and recompute the checksums.

- Shared software between several code systems. Our users will be able to use utility programs written by other code systems.

- Other code systems will be able to use programs written by us. Besides the translator, other software tools include an ACF subroutine library, an interactive ACF editor, and an interactive plotting routine. User frustrations will be reduced as a result of a consistent set of input commands to these programs.

- Symbolic access to data. This enhances the interactive capabilities of the codes. Our users will be able to interactively plot and edit data items by name as well as symbolic algebraic expressions. This also allows us to add new variables, delete old variables, change the data format of variables, or change the physical ordering of the data without seriously affecting codes in the system. Our ability to maintain many codes is greatly enhanced.

To enable the codes to efficiently perform input and output operations in a multimachine environment, we have developed a set of macros that interface with the operating system. These macros allow us to do I/O in a completely machine-independent manner. This set of macros forms a high level language that allows us to interface directly with a very primitive set of system functions. The result is a small, fast means of doing I/O. The functions performed by these macros include:

- Formatted output to many devices.
- Interpretation of input messages.

- Disk file management.
- Requests to the system for information.
- Requests to the system to perform certain tasks.
- Word, bit, and character string manipulation.
- Definition of machine word size, character size, and other machine-dependent parameters.

By using this set of macros throughout, we will be able to maintain many more codes on several different mainframes. We will cease to depend on operating systems remaining the same. Our requirement that I/O libraries be available and identical on all machines is significantly reduced. Any I/O optimization we do will have global effects.

We are proceeding with the conversion to machine-independent versions with the goal of having a basic code capability ready to debug when the Cray-I arrives. We will have tested many areas of the code on the CDC-7600 prior to Cray-I's arrival.

Section 4

**Target
Fabrication**

SECTION 4

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TARGET FABRICATION

4.1 Introduction

The past year's work in target fabrication involved research and development in several areas, including glass sphere production, hard and soft coatings, target characterization, cryogenics, and material analysis. Work in these areas arises from the need for targets for current laser fusion experiments, the need for research and development to produce targets for the near future, and the eventual requirement for rapid, low-cost production of power reactor targets.

The production of experimental targets, which may differ from day to day, uses much of our resources. We report here on the development of new techniques in the areas of characterization, glass sphere production, cryogenics, and coatings and layers.

It has been common practice in many fields to deposit layers and coatings of numerous materials by sputtering evaporative coating, by chemical processes, by electrodeposition, etc. However, high-quality coatings (100-Å peak-to-valley surface finish) on small glass, metal, or polymeric spheres are not readily available. Thus, part of our effort is devoted to research and development in the area of coatings and layer deposition. Our aim is to be able to produce multiple layers of materials that meet rigorous target-quality specifications.

Currently, one of the containers for the DT fuel in laser fusion targets is a glass shell. The shell must be very smooth and appropriately thin, have uniform walls, and be the correct size for the experiment. The glass composition is important, though not critical, and must be known with good accuracy.

Glass shells are usable as fusion targets only if they are filled with appropriate gases, liquids, or solids. Experimental target designs include targets with a wide variety of fills in which the density of the DT fuel can vary from 2 to 210 mg/cm³. At the highest densities, the target must be cooled to avoid disruption resulting from high internal pressures. Gaseous fuel densities up to 20 mg/cm³ at room temperatures are required in our current experi-

ments. We expect liquid densities to be necessary in the near future.

In addition to fuel gases such as DT, we also occasionally need spheres containing gases such as argon, krypton, or nitrogen. We have developed techniques that allow us to fill glass spheres with gases to which glass is normally impermeable.

Current experimental efforts do not include the irradiation of cryogenic targets. However, in preparation for designs that may soon be needed, we have developed techniques for producing and maintaining frozen DT layers in glass shells. The apparatus used for inserting the cryogenic targets into the Shiva target chamber has been designed and is largely complete.

Accurate characterization of the targets is extremely important. Only if all aspects, including the dimensions, of the glass spheres and their coatings are known can experimental data be analyzed meaningfully. To determine all the parameters of a target, we use several techniques, including optical interferometry, radiography, electron microscopy, and others. The need for increasingly accurate measurements requires continual improvement of existing techniques and development of new methods of characterization. To keep pace with the need for larger numbers of increasingly complex targets, we have developed automated techniques for examining and measuring the surface and wall characteristics of the shells. A complete "4 π " characterization is performed on every sphere used as a target. We cannot rely on statistics, examining only a portion of each shell and hoping the remainder will be of similar quality.

In addition to dimensional characteristics of our targets, we are concerned with their chemical composition. Using both modern and traditional methods of analysis, we have been able to gather highly accurate data on material composition, contamination, gas fill, etc. Such determinations depend on wet chemical analysis, x-ray fluorescence, Auger techniques, secondary-ion mass spectroscopy, infrared spectroscopy, thermogravimetric analysis, and other techniques. The analytical methods must evaluate samples containing elements

from almost the entire periodic table, including many of the gaseous elements.

Overall, a broad spectrum of methods, techniques, and skills are required to develop and produce laser fusion targets. While we have already developed and used many approaches, new requirements necessitate continual improvement and innovation in target fabrication.

Fortunately, we are able to utilize the capabilities of other groups, both within and outside LLL. On a contractual basis, we are assisted by both industrial and university groups and by many of the other research teams at LLL. In particular, several groups directed by W. L. Rooker and W. L. Ramer at the Rocky Flats plant, operated by Rockwell International, have provided excellent support in many areas of our work. At the University of Arizona, a group directed by Professor M. B. Denton of the Chemistry Department has been instrumental in developing some very versatile ion-beam systems. Professor K. Kim and his group in the Department of Electrical Engineering at the University of Illinois are continuing to assist us in the cryogenics area. In this same field, excellent support is provided by a group at the National Bureau of Standards, Boulder. An exhaustive list of other laboratories and industrial suppliers, whose assistance has made our work much easier, would extend to many pages. To those not mentioned by name, we extend our appreciation for jobs well done and our hope for continuing fruitful collaborations.

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4.2 Glass Technology

During the past year, we met the ever-increasing needs of the Laser Fusion Program for quality glass microspheres. Current experiments require a variety of hollow glass microspheres filled with 10 to 100 atm of equimolar deuterium and tritium (DT). Depending on the fusion experiment, the microspheres range from 50 to 500 μm in diameter, with wall thicknesses from 1 to 20 μm .

For exploding pusher targets, the quality of the glass shell is not extremely critical. Variations in wall thickness, surface irregularities, and some bubbles or voids in the wall can be tolerated. Although spheres for early exploding pusher experiments

could be obtained by tediously sorting through large amounts of commercial stock, the larger sizes required by the Shiva laser system cannot be found in commercial sources.

For experiments designed to achieve high-density implosions, the criteria for the target microspheres are very stringent. Sphericity and wall uniformity should be better than 1%, and the surface finish must be better than 2000 $\text{\AA}$, peak to valley. An even more demanding requirement is the need for batches of these microspheres that are suitable for coating with additional pusher and ablator layers. A sufficient yield of acceptable coated spheres requires initial batches containing a high percentage of quality microspheres. Furthermore, the wall thicknesses of the microspheres must fall within a narrow range. Such individual microspheres, let alone high-quality batches, are simply unavailable commercially.

We use two techniques to produce the desired quantities of high-quality hollow glass microspheres.¹ With both, we are able to control the size and composition of the microspheres. The liquid-droplet method is particularly successful in producing quality batches for coating. The dried-gel method gives us added flexibility in available sizes and composition. Spheres made by both processes have similar compositions and are subjected to the same surface treatment to obtain the necessary smooth surfaces.

4.2.1 Liquid-Droplet Process

During 1978 we refined our understanding of the liquid-droplet process² and markedly improved and expanded our batch production of microspheres. Briefly, the liquid-droplet method of making microspheres starts with an aqueous solution of water-soluble glass-forming compounds, such as sodium silicate. Subjecting drops of this solution to elevated temperatures traps water vapor within the drops as a gel membrane forms on the surface. The encapsulated water vapor acts as an internal blowing agent, and with the appropriate temperature-time profiles, we can make hollow glass microspheres that are exceptionally spherical and symmetric. Most importantly, by using acoustic disintegration of a liquid jet to produce uniform drops of the solution,³ we can produce microspheres with specified diameters and wall thicknesses.

Our study of the dynamics of microsphere formation has shown that, when producing spheres

with either extremely thin walls ($\sim 1 \mu\text{m}$) or thick walls ($> 15 \mu\text{m}$), it is important to form thin gel microspheres during the drying process. Stress analysis shows that the forces from surface tension and pressure difference on the glass-liquid interface of a forming glass microsphere are centripetal and quite large compared with the force of gravity. Suitable furnace temperatures and appropriate glass composition are also essential to produce concentric glass microspheres.⁴

Figure 4-1 is a representative interference micrograph of an excellent batch of spheres. Most of the spheres in this batch satisfy stringent concentricity requirements. This batch was sieved for spheres with diameters between 145 and 160 μm . More than 80% of the spheres have thicknesses within 10% of the average—a reflection of the uniform mass of the initial liquid droplets. The narrow thickness distribution and the consistent symmetry make this an ideal batch for coating. Batches with similar quality are produced routinely over the wide range of sizes shown in Fig. 4-2.

We now have multiple-droplet furnaces (see Fig. 4-3) that allow us to produce several sphere sizes simultaneously.

Fig. 4-4. Comparison of available sphere sizes.

4.2.2 Special Gas Fills

An important parameter in the laser fusion experiments is the peak DT fuel density attained during implosion. In some cases, this density can be measured by including a diagnostic gas, such as argon, with the DT fuel in the glass microsphere targets.

We routinely fill the glass microspheres with DT fuel by simple permeation at 400°C for a day or so. Unfortunately, normal glasses are about a million times less permeable to argon than to hydrogen, under similar conditions. To introduce argon into the glass microspheres by permeation, we would first maximize the permeability of the glass spheres by increasing their silicon content. Even then, however, it would be necessary to subject the spheres to high temperatures and pressures for prolonged periods. Often, these processes damage the spheres by devitrifying the glass, by roughening the surface because of alkali precipitation, and by distorting the symmetry because of the high stress and high temperatures.

Therefore, we use another approach. In our liquid-droplet process, large, thin gel microspheres (1-mm i.d., 0.1- μm -thick walls) are formed before the glass-forming chemicals fuse into glass. These gel microspheres are readily filled with argon (or with other inert gases, such as krypton, xenon, or neon) by flooding the droplet system with the desired gas. When the gel transforms into glass, the argon (for example) is trapped within the sphere, forming argon-filled, target-quality glass microspheres. On the average, we obtain partial

Fig. 4-3. Liquid-droplet microsphere generator.

pressures of 0.2 atm (at room temperature) by this process.

4.2.3 Dried-Gel Process

The liquid-droplet technique has two constraints. First, the glass-forming compounds must be in solution or in a free-flowing slurry. Second, the maximum mass of the glass microsphere is limited by the length of the drying section and by the maximum usable viscosity in the droplet generator. Thus, to expand our range of compositions and available sizes, we also use a dried-gel process to make hollow glass microspheres. In Fig. 4-2, the sphere sizes we have produced using both methods are compared with those available commercially (in this case, from 3M).

In the dried-gel process, a solution containing glass-forming oxides is dried and ground into fine particles. The powder, after sieve-cutting for granules of appropriate size, is dropped through a furnace. The water of hydration in the gel is encapsulated, and the oxide particles blow and fuse into hollow glass shells.

The tower for the dried-gel process consists of a particle injector mounted on a vertical furnace. The injector (Fig. 4-4) is a fluidized bed with a small hole through which particles occasionally fall. For some applications, we can use a furnace similar to that shown in Fig. 4-3. Usually, however, there is no drying section, because the dried gel contains only water of hydration. Thus, we can have a long refining section where we can make relatively thick microspheres of high quality. In general, we find that the longer and hotter the furnace, the better the sphericity and concentricity of the microspheres.

Typical gel particles and resultant microspheres are shown in Fig. 4-5. Wide varieties of sphere sizes and wall thicknesses are produced from the irregular gel particles. Sieve-cutting the spheres yields a narrow range of diameters, but unlike the spheres produced by the droplet system, the thicknesses still vary. We are trying to make spherical gel particles so that a more uniform powder can be injected into the furnace. For our initial experiments, we used a glass composition similar to that employed in the liquid-droplet system.

The main advantage of the dried-gel process is that we can produce more massive spheres, such as those needed for initial multishell target experiments (with a 140- μm i.d. and a thickness of 20 μm). By adding urea, which acts as an additional blow-

ing agent, we produce large-diameter, thin-walled spheres (see Fig. 4-6).

4.2.4 Surface Preparation

Glass-surface stabilizing agents, such as Al_2O_3 , are omitted from the liquid-droplet and dried-gel chemical solutions, because these agents generally increase the viscosity of the molten glass. This, in turn, reduces the concentricity of the resulting microspheres. Therefore, to ensure high surface quality, we add a stabilizing agent to the surfaces of

Fig. 4-5. Dried-gel particles and resultant microspheres.

the glass microspheres through a chemical vapor-exchange process in the furnaces. AlCl_3 vapor is injected into the furnaces just above the high-temperature transition region. As the gel microspheres fuse into glass, the aluminum in the AlCl_3 vapor exchanges with the sodium on the glass surfaces to form Al_2O_3 . The vapor-exchange process, plus the acid wash procedures described in the 1977 annual report,² produce a stable glass surface.

4.2.5 High-Z Glass Spheres

Near the end of the year, we began using high-Z glass compositions to make microspheres for advanced multishell targets. In our attempts with the dried-gel process, we produced spheres with up to 70 wt% lead oxide, depending on the initial solution composition. We also demonstrated the possibility of fabricating lead-glass microspheres with good surface quality and concentricity. From permeation experiments, we learned that silica glasses containing up to 50 wt% lead oxide are reasonably permeable to DT.

In the future, to narrow the thickness distribution of the sphere batches, we will adapt the lead-glass solutions to the liquid-droplet furnace. More data on the permeability of the lead glass to DT must also be obtained to determine optimum DT fill procedures.

4.2.6 Advanced Sphere Fabrication Techniques

Although the dried-gel method is not subject to some of the constraints of the liquid-droplet technique, it has an important disadvantage. We have little control over the mass distribution in a batch of microspheres because of the irregular sizing of the dried-gel granules. To compensate for this shortcoming, we are developing a technique that combines the merits of the two methods.

First, raisin-like dried-gel pellets, such as those shown in Fig. 4-7, are made in the liquid-droplet furnace with a gradually increasing temperature profile in the drying section and with no high-temperature zone. These pellets are dried further in

Fig. 4-6. Microspheres made by the dried-gel process with urea as an additional blowing agent. These spheres range in diameter from 340 to 400 μm , with wall thicknesses between 1 and 1.5 μm . Inner and outer surfaces are concentric to within 3 to 5%.

Fig. 4-7. Raisin-like dried-gel pellets made in the liquid-droplet furnace.

the open air, then passed through a high-temperature furnace, as in the dried-gel process. Because these pellets have more consistent sizes and masses than do ground and sieved gel, the resulting glass microspheres have a narrower thickness distribution than batches produced by the dried-gel process.

We are also experimenting with another two-step process. Dried-gel particles are passed through a low-temperature furnace, which produces hollow, thin gel microspheres. These spheres are then sieve-cut and dropped through a high-temperature furnace to form glass spheres. Like the raisin technique, this process shows promise in reducing the thickness distribution of the microspheres in a batch.

To avoid being limited by the need for a stable solution of the glass-forming oxides, we are developing a double-nozzle droplet generator. With this droplet generator, two different liquids can be mixed, even if the combination of the two liquids is chemically unstable.

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4.3 Polymer Coatings

In the last two years, we have refined techniques to coat glass shells with pure or well-defined composite materials. Plasma polymerization provided the first useful target coating—a polymerized fluorocarbon (CF)—and offered the possibility of producing coatings from other materials.

The problem of coating shells has two aspects. First, a coating environment must be provided that results in materials and surface qualities of practical interest. Second, the shells to be coated must be in random motion in the coating environment. We have approached these two parts of the problem separately. To develop and produce coatings of practical use, we have set the following goals:

- To develop techniques for the reliable production of fluorocarbon-coated targets.
- To extend the fluorocarbon-coating technology by developing (1) plasma-activated hydrocarbon (CH) polymer coatings, and (2) plasma-activated metal coatings, for example, WF₆.

To improve our ability to manipulate the shells being coated, we have sought to develop two techniques:

- Molecular beam levitation.
- Electrostatic levitation.

4.3.1 Production of Current Targets

Fluorocarbon Coatings. Helical resonator A provided the coated targets this year. As shown in Fig. 4-8, the plasma polymerization process activates a monomer gas as it passes through an electrical discharge. The activated molecules then condense uniformly on the DT-filled glass microspheres. The thickness of the coating varies from less than 1 μm to 30 μm , and can be controlled by changing the plasma process parameters and the coating time. To ensure a uniform coating, the microspheres are kept in random motion by a combination of ultrasonic vibration of the thin, stainless-steel dish containing the microspheres and

Fig. 4-8. PFB plasma polymerization coating process. Molecules activated in the helical resonator condense on the shells randomly circulated in the vibrator dish.

charge exchange with the plasma. The vibrating pan is negatively pulse-biased to draw ions from the plasma to the coating surface. The ion flux helps the shells remain in free motion and improves the surface finish, perhaps through some ion reaction.

A target-quality coated shell is shown in Fig. 4-9. The specification ranges for such shells are as follows:

- Mandrel: 140- μ m-diam, DT-filled glass shell.
- Coating: $\text{CF}_{1.3}$.
- Ambient surface: 100 to 200 $\text{\AA}$.
- Total surface variation: 0.1 to 0.2 μm .
- Concentricity: 3% to 5%.
- Coating thickness: 1 to 30 μm .

Typical yields for this process were, initially, one satisfactory target in 10^4 coated shells. Precise control of shell position relative to the active plasma, ion bombardment, improved monomer purity, and a cleaner apparatus has improved the reliability of the coating process. This improvement and the significantly better surface finish of the glass shell mandrels used as coating stock have increased the yield to one useful target in 10^3 coated shells. This 10-fold increase in yield has meant less coating and sorting effort to supply target-quality coated shells.

Prospective targets must now pass 4π inspection after the coating process. This inspection provides closer quality control than was imposed initially. Thus, our improved yield has come in spite of more stringent target specifications. Targets currently passed through 4π inspection seldom have

more than one defect as large as 0.1 μm . At the beginning of the year, targets often had three or four such defects.

Experience with helical resonator A proved that reliable surfaces and predictable coating thicknesses can be obtained by carefully controlling the process variables: discharge power, chamber pressure, and gas flow rate. Control of these parameters is complicated by dissolution and partial condensation of species generated by the electrical discharge in perfluoro-2-butene.

Manual control of the processes is impractical in providing the optimum coating rates and surface finishes needed for coatings about 10 to 12 μm thick. Therefore, an automated system, helical resonator C, was designed and built. This system is currently committed to the development of CH coatings, but it provides a backup for the CF coating effort.

Hydrocarbon Coatings. During our development of useful CF coatings, we found that experimental reproducibility was a serious problem. The plasma polymerization technique involves many interacting variables, including discharge power dissipated in the gas, pressure, gas flow rates, gas compositions, reaction chamber geometry, temperature, and ion current and voltage. We successfully developed an automated coating system that monitors and stabilizes the plasma process variables through interactive computer feedback and control.

Fig. 4-9. Target-quality $\text{CF}_{1.3}$ -coated glass shell.

Helical resonator C uses a Hewlett Packard 9825A programmable desk-top calculator to control the system. The calculator can control the flows of two different gases from an inventory of eight gases. The flow rates are maintained at 0.01 std cm^3/min using Balzer valves. The flow rates are measured by a set of mks precision molecular flow elements, and the pressure is monitored by an mks differential pressure transducer. We developed a special wide-range variable conductive valve, which controls the coating chamber pressure through a computer-driven stepping motor. This automatic system provides reliable control of plasma conditions for many days at a time, with little operator action required. This is a 50-fold improvement over the control possible with the manual helical resonator A system.

Some targets require a two-layer coating on a glass microsphere. The innermost layer is a high-density pusher. The outer layer must be a low-atomic-number, low-density ablator. An option for this ablator is a hydrocarbon polymer having a density of 1.0 g/cm^3 . These target designs have stimulated our work on production of a very thickly CH-coated glass shell. We have encountered new materials problems, new surface problems, and new problems relating to the thickness of the coating.

Other investigators have studied a host of hydrocarbon gases for plasma polymerization coatings.^{5,6} Gases that chain-polymerize are particularly troublesome, because they polymerize in

the gas phase, thus generating gas-phase particles.⁵ These polymer particles adhere to microspheres and cause serious coating defects. The best fluorocarbon coatings we have obtained have been deposited using perfluoro-2-butene, a gas that is not chain-reactive. Trans-2-butene is the hydrocarbon analog to this source gas, which successfully produced the $\text{CF}_{1.3}$ coatings. We are using it as a monomer gas to produce CH coatings.

Early CH experiments showed that maintaining a clean environment for the coating shells was complicated by flaking of the surface coating in the coating chamber. Flaking arises from adhesive failure between the coating and its substrate. It can be caused by internal stress, stress due to thermal variations, or changes in the coating after deposition. The reaction chamber walls, which also become coated as the glass shells are coated, thus become a source of flaking polymer. The flakes are caught in the dish and mixed with the shells.

Figure 4-10 shows SEM micrographs of a very thick ($55\text{-}\mu\text{m}$) CH coating. The structure of the fractured coating indicates that the material is not being deposited in an amorphous phase. As was the case in the development of CF coatings, chemical control of the growth may offer some latitude in optimizing the surface finish for target-quality CH coatings.

Figure 4-11 shows an SEM micrograph of a three-layer coating on a glass slide. In this example, $\text{CBr}_{0.4}$, CCl , and $\text{CF}_{1.3}$ were sequentially deposited

Fig. 4-10. Glass microsphere coated with $55\text{ }\mu\text{m}$ of $\text{CH}_{1.3}$. The coating was deliberately broken to measure the coating thickness and assess its concentricity.

Fig. 4-11. A fractured section of a three-layer film (bottom layer, $\text{CBr}_{0.4}$; middle layer, CCl ; top layer, $\text{CF}_{1.5}$).

in the same coating environment. This displays the feasibility of multiple-layer target coating with the plasma process.

Metallic Coatings. The energy in a plasma can be used to decompose metal fluorides, carbonyls, or alkalis. Each of these three classes of compounds presents formidable gas-handling problems. Some are corrosive, toxic, carcinogenic, or unstable, but together they offer a wide choice of metals and the option of codepositing materials. This flexibility of atom-by-atom materials deposition should allow us to use amorphous mixed phases as coatings.

We chose tungsten hexafluoride (WF_6) as the gaseous precursor to tungsten metal coatings. Three factors governed our choice:

- Availability of data on coatings made from chemical vapor deposition of WF_6 .
- The relatively moderate corrosive behavior and toxicity of WF_6 .
- Potential utility to the program.

The first coatings made from WF_6 plasma are not satisfactory for target applications (Fig. 4-12). However, surface quality can be altered by varying plasma process parameters; thus, considerable potential exists for modifying the coating to meet specifications.

4.3.2 Levitation Techniques

Molecular Beams. The molecular beam levitator offers the possibility of producing individually customized targets. An individual glass shell of specific dimensions, selected for surface finish and concentricity, can be coated free of contaminating contact with any surface. This individualized processing eliminates defects caused during coating by particulate matter that is transferred to the clean glass shells.

The molecular beam levitator can operate in the coating environment of several coating processes. As a result, sequentially layered targets can be made, even though each layer may require a different technique (i.e., sputtered, plasma-polymerized, evaporative, or plasma-activated coatings). The individual result of each process will not

Fig. 4-12. A tungsten coating deposited in a discharge from WF_6 gas. The oscilloscope trace shows the tungsten x-ray emission spectrum obtained from the coating.

be confused by the shell-to-shell variability that results from batch processing. Furthermore, this individualized processing will reduce the effort required to sort the products of low-yield coating processes and will allow us to optimize the yield and quality inherent in the process itself.

The current molecular beam levitator consists of a stainless-steel array of 50- μm -diam capillary tubes. These tubes produce individual beams of collimated atoms, provided that the pressure in the chamber into which the flow expands is less than a few hundred micrometers of Hg. These beams operate in the region of free molecular flow, supporting the levitated glass sphere by momentum transfer during individual collisions. The capillary tubes are less likely to be coated over than homogeneous porous materials, which have been used in other levitator designs.

Researchers at Los Alamos Scientific Laboratory have confined a levitated microsphere to a small area by cutting a hemispherical hole in the relatively thick capillary array. This configuration produces beams that diverge by only about 10° and that offer little change in force with vertical or lateral position. We have further developed this concept as shown in Fig. 4-13. We have chosen the dimensions of the confining region so that gas beams reflected from the capillary walls provide ad-

ditional lateral stability, as shown in Fig. 4-13(b). This stability can be further enhanced by carefully machining the back side of the array to produce a variation in gas conductance across the capillary array, again as shown in Fig. 4-13(b). This gas jet levitator has been used to produce gold evaporative coatings about 1 μm thick. We have demonstrated sufficient stability and controllability to prove this technique feasible for individualized shell handling. To prove its practicality remains a problem.

Electrostatic Fields. Electrostatic levitation uses the interaction of externally applied electric fields with the charge on the shell to produce a force that supports and controls the shell. Unlike the molecular beam levitator, which requires a coating chamber pressure of at least a few micrometers of Hg, the electrostatic levitator has functioned at pressures as low as 10^{-10} Torr. The electrostatic levitator places fewer constraints on targets or their processing environment than does any other technique we have considered. But it also requires further technical development to be practically useful.

Figure 4-14 illustrates the design of the electrostatic levitator being developed to handle shells for neutral beam coating. This design is sufficiently advanced to provide reliable handling of shells in

Fig. 4-13. Molecular beam levitator. (a) Top view of the capillary-array structure used for levitation. (b) Cross section of the levitator with a microsphere being supported by molecular beams.

Observation microscope provides
information to calculate q/m
ratios and electronic dampening

X rays, electrons, or ions alter
charge on the levitated microsphere

Coating beam must be charge
neutral and charge free

Levitated microsphere is coated through a hole
in the quadrupole electrodes; microsphere
rotates randomly producing a uniform coating

Buckbee-Mears
screen

Particle injector charges and
launches microspheres into
levitator

Without rotation, only a portion
of the sphere would be coated

Fig. 4-14. Design of an advanced quadrupole electrostatic levitator system.

initiated in 1977, notably the production of double-layer hemispheres of beryllium and SiO_2 , were brought to fruition in 1978. We deposited ultrasmooth layers of both SiO_2 and Be on metal mandrels. One target type, shown in Fig. 4-15, calls for a high-density, high-Z coated glass microsphere and a separate second shell. In 1978, we laid the groundwork for such high-quality metal coating of microspheres.

We report here the general projects for inorganic coating in 1978: high-Z metal coatings, second shell fabrication, low-Z beryllium coatings, and SiO_2 coatings on mandrels.

4.4.1 High-Density, High-Z Layers

The primary requirements for a high-Z, high-density coating are thickness uniformity, 100-nm surface finish, material uniformity, near-bulk density, and high process yield.

To achieve thickness uniformity, we relied in the past on the bouncer pan to agitate the microspheres during coating. However, the bouncer pan has several drawbacks. Agitation must be strong enough to prevent sticking, but the power must be limited to prevent all the balls from bouncing into the vacuum chamber (which is unacceptable for DT-filled balls). Also, no cooling arrangement is available with the bouncer pan, yet low ball

temperatures are required for a smooth surface finish. To solve these problems, we developed the screen bouncer cage shown in Fig. 4-16. The balls are confined between two flat screens mounted with flat washers on a water-cooled block. The cage is mounted directly on the piezoelectric crystal, which ensures strong coupling, even with relatively soft, compliant, high-transmission screens.

Using the screen cage, we have successfully coated microspheres with tantalum, beryllium, chromium, tungsten, and aluminum. The radiograph in Fig. 4-17 shows a uniform 8- μm -thick tantalum layer on the 3- μm -thick wall of a 206- μm -diam glass microsphere. The P_1 , or concentricity, defect on this ball is 11%. P_1 values vary widely in each batch. We believe that such concentricity variations are caused by the ball sticking briefly during deposition. The severity of the sticking varies for different materials and is worst for soft metals such as aluminum and gold. From the motion of the balls during coating, it appears that electrostatic forces are involved.

Depositions with beryllium, chromium, and tungsten also look promising, although we have not produced thicknesses greater than 1 μm .

Achieving 100-nm surface finishes on dense metal microsphere coatings remains a serious problem. Refractory metals have a strong tendency to flake from many surfaces, causing "cone" defects on the coated balls. The SEM photomicrograph in Fig. 4-18 shows a cross section of a tantalum-coated microsphere with typical cone defects. The 1.5- μm layer, where most cones nucleated in this run, corresponds to a burst of sputtergun shedding marked by temporary shorting. A shedded particulate, landing on the sphere, grows into a cone by geometric shadowing, collecting vapor at the expense of surrounding areas. The principal cause of shedding is the high intrinsic stress caused by defects frozen into the tantalum at our low deposition temperatures. We sputter at about room temperature (only 1/10 of the tantalum melting temperature) to avoid potential problems of breakage and DT loss from filled balls. To reduce shedding, we have used bead blasting and aluminum pre-coated shields to increase adhesion and nitrogen doping during sputtering to reduce the stress.

Another problem with our present coatings is the low density of the films. The oblique incidence of the coating material during ball coating produces a porous film much like a close-packed array of

Fig. 4-24. Sputtering and water-cooled anode-biasing cage for polycrystalline coating.

round columns with small triangular voids between the columns. From SEM pictures, we estimate about a 20% reduction below bulk Ta density. In contrast, planar films sputtered onto glass slides have $100 \pm 3\%$ of the bulk density and a very smooth, shiny surface.

4.4.2 Uniform Second Shell Layers

One approach to the fabrication of a second shell is to combine two identical hemispheres into a

shell around a central ball. In the 1977 annual report,⁷ we described a method for making a composite beryllium-on-SiO₂ shell. We use the same approach to make 200-nm gold hemispheres as second shells. To provide support for the fragile gold shell, a 1- μ m precoat of Parylene on the diamond-turned copper mandrels is required. The final product is a two-layer hemisphere of gold on Parylene.

To meet the strict thickness uniformity requirements, we experimented with two methods of

Fig. 4-17. X-ray microradiograph of an 8- μm -thick tantalum coating on a 206- μm -o.d. microsphere. The coating has an 11% P_1 defect.

depositing the gold layer on the mandrels. The first method is sputtering with the cylindrical sputtergun source illustrated in Fig. 4-19. Based on the gas-phase scattering of sputtered atoms during coating,

we predicted nonuniformities of 5 to 10%. Unfortunately, the best we found, even using xenon sputtering gas to increase scattering, was about 14% nonuniformity. Thickness variations from pole to equator arose because the scattering was insufficient to overcome the line-of-sight effect. Variations around the equator were caused by the off-axis position of the mandrel, which was designed to accommodate multiple mandrels during coating.

The second method for hemisphere coating is to evaporate gold onto mandrels rotating about their axes on a carousel that revolves around the evaporation source. This method allows us to adjust the relative coating rate from pole to equator. We have achieved a 6% uniformity with this method; however, a porous area in the coatings always occurs at the tip, where the mandrel stays tangent to the incident vapor. Oblique incidence of the vapor and the same geometrical shadowing process responsible for cone development promote this open growth. Varying the mandrel tilt angle and adding negative mandrel bias during coating do not eliminate the porous area. Even with a uniform mass per unit area, the porous region is a collection of columnar grains with little lateral continuity and of doubtful strength for the application of a second shell.

Fig. 4-18. SEM photomicrograph of cone defects nucleated 1.5 μm above the glass-tantalum interface on a coated microsphere. The defects were caused by sputtergun shedding during deposition.

Fig. 4-19. Schematic of cylindrical sputtering and mandrel block.

We began work on a design for a combination sputtering and mandrel-rotating system retaining the best features of each approach. We expect to achieve better concentricities with this combination.

4.4.3 Beryllium Coatings

We made significant progress in 1978 toward our goal of coating very smooth, thick beryllium layers on both microspheres and hemispherical mandrels for second-shell applications. We demonstrated most of the necessary steps, including:

- Coating amorphous Be films on copper mandrels.

- Producing surface finishes better than 100 nm for 10- μ m-thick films on water-cooled copper mandrels.

- Producing thick, cone-free deposits.
- Producing adherent Be coatings on microspheres, using the screen bouncer cage. The remaining problems include temperature control during ball-coating to suppress grain growth and mandrel thickness uniformity.

Our 1977 results⁷ indicated problems in surface finish and sputtered film structure. The debris from arcing, flaking, and sputtergun spitting caused cone defects; and the high deposition temperature produced excessive grain growth. Thermal stress

and weak, porous columnar structure contributed to film cracking. To improve the surface finish and film density, we experimented in 1978 with dc and rf substrate biasing.

Rf sputtering eliminates sputtergun arcing and spitting as sources of cone defects. Moreover, the increased adhesion of beryllium to bead-blasted copper shields prevents flaking during deposition, which in turn eliminates virtually all cone defects from Be coatings on clean, polished mandrels. An rf bias, applied to the substrate during deposition in conjunction with rf sputtering, effectively increases the film density and eliminates all porous growth; yet it does not cause the arcing instabilities that accompany dc biasing. The dense cross section and smooth surface structure of Be deposited on a water-cooled, polished copper mandrel with rf bias sputtering is shown in the SEM photomicrograph in Fig. 4-20.

The rough surface structure of earlier Be films is typical of crystalline film growth at high deposition temperatures. By maintaining the substrate temperature below 100°C during sputtering, we can deposit amorphous or extremely fine-grained beryllium showing no x-ray diffraction lines. Films deposited above 200°C on glass slides appear rough and crystalline and show characteristic Be x-ray diffraction lines. The effect on surface finish of deposition temperature is shown in the SEM photomicrographs of Fig. 4-21. The rough surfaces that appear at high temperatures result entirely from increased crystallization and grain growth.

We extended our rf-sputtering method to microsphere-coating in a vibrating screen cage. The surface quality of a 300-μm-diam, uncooled microsphere coated with 1 μm of Be is shown in Fig. 4-22. The film structure on balls is similar to that of films deposited on glass slides under

Fig. 4-22. SEM photomicrograph of 1- μ m-thick beryllium microsphere coating.

equivalent conditions. The microsphere temperature during coating has a critical effect on the Be surface quality. We expect the water cooling to be used in later screen cage designs to reduce the temperature buildup during coating, further improving the Be surface finish on microspheres.

4.4.4 SiO₂ Mandrel Coatings

Previous techniques for coating metallic free-standing films on mandrels were uncomplicated because of the relative softness and ductility of most metals. In contrast, the small thermal expansion

coefficient of SiO₂ and its nonconductive and brittle nature create severe problems defying conventional remedies. However, we have successfully developed a new process for making strong, smooth, thick SiO₂ films on nonplanar Kovar mandrels of various shapes and sizes. The SEM photomicrograph in Fig. 4-23 shows a smooth surface on a 250- μ m-diam, hemispherical Kovar mandrel coated with 13 μ m of SiO₂. Possible applications include disk targets, hemispheres for multishell targets, and designs requiring a strong, hard transparent layer.

Our initial efforts at rf sputtering thick SiO₂ films revealed problems of adhesion and cracking and produced poor surface finishes with cone defects. Our solution involved carefully cleaned, diamond-turned Kovar mandrels, which ensured good adhesion and had an expansion coefficient similar to SiO₂; strict deposition temperature and pressure control; and specially designed Vicor deposition shields.

Careful SEM inspection of a Kovar mandrel after a sequence of solvent cleaning steps reveals that small metal particles and carbonized droplets remain on the surface. These particulates were one of the causes of cone defects in earlier SiO₂ coatings. We now use oxygen plasma stripping to remove the carbonized droplets, followed by mechanical "collodion stripping" to remove all but the most firmly attached particles larger than 0.1 μ m.

Comparison by SEM of mandrel surfaces before and after coating also indicates a second

Fig. 4-23. SEM photomicrograph of a 13- μ m-thick SiO₂ coating on a Kovar mandrel. The worst surface defect is less than 300 nm deep.

origin of cone defects. Cone growth can nucleate at SiO_2 debris that arises from shedding during coating. We overcame this problem by using a Vicor anode-cathode-shield for our sputtergun source, which is shown in Fig. 4-19. The combination of plasma and collodion cleaning and the Vicor shield virtually eliminates cone defects in our SiO_2 coatings.

Unfortunately, the shield greatly increases the mandrel temperature by confining the plasma during deposition. This, in turn, increases diffusion between the mandrel and the glass, degrading the inside surface finish of the glass shell. Mandrel expansion from this interdiffusion produces high stresses that often pop the glass shell off the mandrel. Maintaining the mandrel holder block at 500 to 600°C prevents interdiffusion and shell failure.

The SiO_2 films deposited at temperatures below 500°C form a rough, domed columnar surface, as shown in Fig. 4-24, whereas a smoother, dimpled surface prevails above 500°C. Both films in Fig. 4-24 were deposited without shields and have numerous cone defects. X-ray diffraction work indicates that both materials are crystalline, but the data were insufficient to allow identification of the phases present. The α - to β -quartz phase transformation at 573°C may be involved in the apparent change in our glass. The light dimpling of our best SiO_2 surfaces is apparently caused by ions resputtering glass from the growing coating. Increasing the argon pressure during coating reduces the average ion energy, which in turn reduces the etching. A pressure of 4 Pa produces the surfaces shown in Figs. 4-23 and 4-24, but this is not necessarily the

Fig. 4-24. Comparison of surface finishes for SiO_2 coatings at different temperatures. (a) Rough, domed columnar surface typical at deposition temperatures below 500°C. (b) Smoother, dimpled surface typical above 500°C.

optimum pressure for a balance between etching and residual defect growth.

The uniformity of the surfaces we can currently produce is equivalent to a P_2 defect of nearly 20%, relative to the average thickness. (Two hemispheres with identical P_1 defects form a sphere with a P_2 defect.) This P_2 defect is not an inherent property of our sputtering process; instead it arises from the Vicor shield we introduced. The shield may cause inhomogeneous rf coupling or local heating, or it may contain material variations, all leading to gross variations in the sputtering rate around the sputter gun target. We expect that improvements in the bonding of the sputter gun target to the backing plate will reduce the coupling and heating contributions to the nonuniformity.

Our current process is limited to coating thicknesses less than $10\text{ }\mu\text{m}$ for diameters of 2 mm, and to thicknesses of 15 to $20\text{ }\mu\text{m}$ for diameters less than $500\text{ }\mu\text{m}$. The reason for these limitations is the accumulated stress in the film, which increases in proportion to the product of the thickness, the diameter, and the thermal expansion coefficient mismatch between the glass and Kovar. Breakage during machining or deposition thus limits the sizes of pure SiO_2 films. Extending our deposition process to borosilicate glass, with an expansion coefficient matching that of Kovar, should allow thicker coatings.

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4.5 Characterization

The characterization group of the laser fusion program is responsible for measuring the dimensions of fusion targets to ensure that they meet stringent design requirements. Because of the high accuracy demanded, our newly developed measurement techniques have advanced the state of the art. Our primary advances during 1978 were in automated characterization, extended radiographic capabilities, novel optical measurement techniques,

and the measurement of noble gas doping in the fuel fill.

4.5.1 TOPO II—An Automated Interferometric Mapping System

During 1978, we developed an automated interferometric mapping system (Fig. 4-25) that automatically scans the entire surface of a target sphere, records the wall thickness variations as a function of position, stores the data on flexible computer disks, and allows display of the data in several convenient forms. This system provides many important improvements over other sphere-thickness characterization methods^{8,9}:

- Improved accuracy: 10-nm thickness resolution and $2\text{-}\mu\text{m}$ spatial resolution.
- Improved speed: the total time to map a $150\text{-}\mu\text{m}$ -diam ball is less than 1 min. A $600\text{-}\mu\text{m}$ -diam sphere can be mapped in about 10 min.
- Computer data acquisition, eliminating human measurement errors and biases.
- Minimized ball handling: only one data-acquisition scan is needed to map a sphere fully.
- Interactive software to allow the operator to tailor the measurement to specific requirements.
- Availability of real-time contour plots and pseudo-3-D data plots to improve visualization of the data, plus permanent hard copy of any desired displays.
- Data written on flexible computer disk for permanent, detailed, transportable storage.
- Capability of entering the scan data into the LLL timesharing system for more extensive analysis and display.

These improvements have been realized through a combination of innovative optical, mechanical, and electronic techniques, and the use of a controlling microcomputer.

Optical System. The optical subsystem diagrammed in Fig. 4-26 converts an optical phase shift to an electronic one. The optical phase-shift generator uses a rotating diffraction grating and birefringent crystals to provide a beam whose relative phase between the horizontal and vertical polarizations is changing at a rate of 10 kHz.¹⁰ The beam is split, and one part passes through a polarizer and onto a photodiode. The output of this photodiode provides a reference phase signal.

The second part of the beam passes through a lens and birefringent crystal assembly, which splits

(a)

(b)

Fig. 4-25. (a) Block diagram of the TOPO II automated interferometric sphere mapping system. The system can map a $150\text{-}\mu\text{m}$ -diam sphere in about 45 s with $2\text{-}\mu\text{m}$ spatial resolution and 10-nm thickness resolution. (b) TOPO II map of a portion of a target microsphere.

Fig. 4-26. Optical subsystem of the TOPO II sphere mapping system. Changes in the optical path through the sample microsphere are converted to phase changes in a 10-kHz electronic signal.

the beam into its two polarization components and focuses each to a point. One of these beams is focused on the microsphere; the other passes to the side of the sample. Another birefringent crystal and lens assembly recombines and collimates the beam. The recombined beam is detected by a second polarizer and photodiode. In the recombined beam, a phase shift from the additional optical path through the sample has been added to the reference phase shift. We cannot measure the absolute value of this phase shift, but as the ball is rotated, and the beam passes over each point on its surface, we can measure the change in the relative phases of the reference and signal beams, and relate that change to variations in the thickness of the microsphere wall.

A fast, accurate phase measurement device (Fig. 4-27) was developed to convert the 10-kHz electronic signals from the reference and signal photodiodes to digital signals that can be rapidly sampled by the controlling computer. The phase measurement is made in one cycle of the 10-kHz signal, thus providing the high speed needed to map a large sphere. Basically, the digital signals represent the time interval between the positive-going zero-crossing of the 10-kHz reference signal and the positive-going zero-crossing of the 10-kHz measurement signal.

If the 10-kHz frequency were truly stable, a time interval measurement alone would suffice to measure the phase. However, to attain 1° phase resolution, we must eliminate the effect of small variations in the 10-kHz frequency. This is done by measuring the time interval between successive positive-going zero-crossings of the reference signal and using this period to normalize the time interval from the phase measurement.

The phase detector is sampled simultaneously with the measurement of the position of the microsphere manipulator. In this way, velocity variations in the manipulator stages do not introduce mapping errors. The motion of the stages is totally controlled by the microcomputer, allowing great flexibility in sphere scan patterns and scanning rates. The system can be operated in a slow, visual scanning mode for operator setup or in a fast data-acquisition mode.

During measurement, the data can be real-time displayed, real-time stored, or both. This allows the operator to do a "pretest" of the sphere to aid in the determination of sphere quality. Once the data have been stored on flexible disk, they can be examined in detail. The data can be accessed at random from the disk for full map plots, partial mappings, or single pole-to-pole scans for cross-sectional examinations.

Fig. 4-27. TOPO II phase-measuring electronics. The phase shift between the reference and signal arms is converted to a digital signal and fed to the controlling microcomputer. The phase shift is measured to better than $\lambda/100$ in one cycle of the 10-kHz signal.

- They are capable of undergoing rapid accelerations ($15 \mu\text{m/s}^2$) without sliding.
- They are linear within $1 \mu\text{m}$ over a total travel of 3 mm.
- Their positions are repeatable to within $0.2 \mu\text{m}$.
- Reversal lag is less than $0.05 \mu\text{m}$.

These specifications were achieved by means of two innovative ideas. First, the loading between the coupling spheres and the plates is done with magnets. This avoids mechanical contact between the stages (except through the coupling spheres) and generates the necessary loading without using a massive top plate. Second, the bearing for each coupling sphere is made up of two half sockets, which contact the sphere only along thin, segmented edges. The backlash in these bearings is completely eliminated by elastically loading the half sockets against the sphere with a spring and differential screw.

This design has proved very satisfactory. The plates track all motions of the dc servodriven stages

without slipping, and reversal lag has been unmeasurable.

4.5.2 Microradiography

Optical techniques are inadequate for measuring wall thicknesses of opaque laser fusion targets. Consequently, we use x-ray microradiography to characterize opaque coated targets. We also find it useful to make x-ray images of multilayer targets to distinguish the coating layers. In microradiography, x rays are used to cast a shadow image of a laser target onto a high-resolution photographic emulsion. The images are recorded on the film with no magnification. We then enlarge the images through a high-power microscope for target characterization.

The x rays are partially absorbed by the target during exposure. The extent of absorption depends on the target's diameter, wall thickness, and elemental composition, and on the x-ray energy. Thus, by suitable interpretation of the x-ray images, we can make measurements of the laser target itself. We

have produced x-ray images of targets coated with beryllium, tungsten, chromium, gold, tantalum, and perfluorobutene. An example of these images is shown in Fig. 4-29. (The technique for making x-ray images was described in detail in the 1977 annual report.)¹³

There are two stages of measurement that we use to characterize laser targets. First, we make a radiograph of a large batch of microspheres and make coarse measurements to select potentially useful targets. Second, we make new radiographs of these candidate microspheres, which are then computer-analyzed. The computer analysis yields very accurate measurements of these spheres, allowing a final selection of useful laser fusion targets.

In the first step, we make x-ray images of about 200 microspheres on a single film plate. To hold the microspheres in place during transport and exposure, we use a simple holder. A thin plastic film is stretched across a circular metal ring that has a clear area of about 5 cm². A thin layer of mineral oil on the plastic film prevents the spheres from rolling. (The mineral oil and plastic film absorb few x rays, because they consist of low-atomic-weight elements.) To make the radiograph, we place the ring so that the plastic is in direct contact with the photographic plate. After the plate is exposed and developed, we examine the images for suitably uniform spheres.

Fig. 4-29. X-ray micrograph of a CF₂-coated glass microsphere fusion target.

The structural features of a target can be measured by examining its image with a Vicker's image-splitting microscope.¹⁴ For rapid measurement, we enlarge the images through a Leitz microscope and display them on a television monitor. The video image is processed through an Interpretation Systems, Inc., image analyzer (shown in Fig. 4-30), which we use to color-code and extract cross-sectional slices of the x-ray image. Using these techniques, we can make rapid measurements of the diameter and wall thicknesses of an opaque laser target. The accuracy of the measurements is better than 1.0 μ m.

During examination of the radiographs, the spheres themselves remain in the holder so that we can correlate images with spheres. We then retrieve the targets that satisfy specifications. Residual oil is removed in an alcohol bath.

For the second, more careful examination, we place the candidate target spheres in a special microradiographic manipulator, which enables us to rotate the microspheres to any orientation between x-ray exposures. This device and the procedure for careful microradiographic examination are described in detail elsewhere.^{13,15} Briefly, we make two x-ray images of each candidate target, with a 90° rotation between exposures. The size of these x-ray images is 0.5 μ m square. The images are enlarged 200 times on 70-mm photographic film. The enlarged images are then digitized with a Photometric Data Systems flatbed scanning microdensitometer. We use a CDC 7600 computer to process the digitized images.

Three orthogonal cross-sectional scans are extracted from the two x-ray images of each candidate target, as shown in Fig. 4-31. These scans yield measurements of the microsphere diameter, wall thickness, and concentricity. A mathematical model that is a function of these parameters is then fit to each of the three scans. Finally, we compute the average of the best-fit diameters and wall thicknesses, and the quadrature sum of the nonconcentricities. The computer fits for the x-ray images in Fig. 4-31 are shown in Fig. 4-32. These are images of a glass microsphere coated with tantalum, made with x rays having a mean energy of 40 keV. At this energy, the glass is essentially transparent to the x rays, and the coating is the only layer we measure.

Because we use a large number of correlated points in each scan, we can make very accurate measurements of opaque laser targets with this

Fig. 4-30. Video image analyzer used for rapid sorting of x-ray images.

Fig. 4-31. X-ray images of a tantalum-coated glass microsphere. The microsphere has been rotated 90° in the second exposure.

technique. For calibration, we made x-ray measurements of seven glass microspheres, which were also measured by interferometry. A comparison of the measurements of outside diameter, average wall thickness, and nonconcentricity is given in Table 4-1. Using the interferometric measurements as a standard, the root-mean-square errors in the radiographic measurements are $1.3 \mu\text{m}$ for outside diameter, $0.3 \mu\text{m}$ for wall thickness, and $0.1 \mu\text{m}$ for nonconcentricity.

Microradiography is applicable to all uncoated laser targets and to targets with a high-atomic-weight coating on a low-atomic-weight mandrel. This includes many of the current laser target designs. We can also apply digital image-enhancement algorithms to the digitized images, to see small structural defects in coating layers and to enhance the distinction between coating layers of elements of similar atomic weight. Such algorithms include pseudocolor enhancement, which facilitates

Table 4-1. Comparison of microradiographic and interferometric measurements, in μm , of seven glass microspheres. The parameters measured were outside diameter (o.d.), wall thickness (T), and concentricity defect (P_1).

Ball No.	Interferometry			Microradiography			Difference		
	o.d.	T	P_1	o.d.	T	P_1	o.d.	T	P_1
2374	179.0	9.9	0.25	177.5	10.0	0.24	-1.5	0.1	-0.01
2375	167.0	7.1	0.47	169.3	7.1	0.38	2.3	0	-0.09
2376	178.0	8.6	0.33	178.8	8.5	0.28	0.8	-0.1	-0.05
2378	139.5	5.1	0.54	139.5	4.9	0.58	0	-0.2	0.02
2385	129.3	4.0	0.48	129.6	4.5	0.50	0.3	0.5	0.04
2389	135.5	6.2	1.13	135.4	6.6	1.25	-0.1	0.4	0.12
2390	155.7	4.3	0.30	153.9	3.8	0.40	-1.8	-0.5	0.10
Absolute average							1.0	0.3	0.06
Absolute maximum							2.3	0.5	0.12
Root-mean-square error							1.3	0.3	0.07

interpretation of certain defects, and contrast enhancement, which is illustrated in Fig. 4-33. These algorithms provide dramatic qualitative improvement in the images, but much work remains to be done before we solve the problem of characterizing small-scale (100- to 2000- $\text{\AA}$) surface defects and internal irregularities.

4.5.3 Optical Measurement Techniques

We have developed several novel optical measurement techniques that aid in the characterization of laser targets. These include reflection interferometry, for characterizing multilayer coatings; spherical reflection interferometry, for target

Fig. 4-33. Example of contrast enhancement used to emphasize the distinction between layers for a beryllium coating on a glass layer. (a) Original x-ray image. (b) Image after contrast enhancement.

surface inspection; and several methods involving "symmetry interferometers," which allow us to rapidly detect asymmetries in microspheres.

Reflection Interferometry of Layered Spheres.

One of the problems in producing target spheres with a layer of CF_2 on a glass shell is the measurement of the thickness of each layer. We have developed a method of making this measurement using reflection interferometry, which is fast and accurate, and requires little sphere handling.

The new procedure is diagrammed in Fig. 4-34. Although the microspheres are transparent, about 3% of the incident light is reflected from the outer and inner surfaces of the sphere, and an even smaller amount (about 0.07%) is reflected from the interface between the glass and the CF_2 . Even with this small amount of light, it is possible to obtain a white-light interference pattern from the three reflecting surfaces.

We place the microsphere on a nonreflective background to eliminate stray reflections, then carefully match the reflectivity (about 1%) of the reference mirror to the reflectance from the inter-

faces. By using a calibrated optical path adjustment in the reference arm, we can locate the three interference patterns without refocusing the optics. This allows us to accurately measure the absolute optical path differences between the patterns. These path differences are direct measures of layer thicknesses.

Accuracy with this technique is excellent. Even with the small amount of reflected light, the center of each white-light interference pattern can easily be located within one or two fringes, corresponding to an error in thickness of 0.2 to 0.3 μm . However, this procedure does have limitations. First, if a layer is too thin (less than about 1.5 μm), the interference patterns from its two surfaces overlap and cannot be distinguished. Second, if the layer thickness greatly exceeds the field depth of the optics, we cannot obtain both interference patterns without refocusing the optics, thereby losing the accuracy of the optical path measurement. With our current optical system, we can measure coatings up to 15 to 20 μm thick.

The major advantages of this new method are greatly increased measurement speed and reduced

sphere handling. Also, by combining the information from the measurement of the layer thicknesses with a transmission interference measurement of the total wall thickness, we can independently verify the refractive index of the CF_2 coating on each sphere. This is an added check on the consistency of the coating procedure. Another benefit is that we can verify the accuracy of the radiographic procedures on multilayered targets. This verification gives us more confidence in radiographic measurements of opaque targets such as those we use for alignment, for which we have no independent checks.

Spherical Interferometry. The spherical reflection interferometer is used to determine the surface quality of nontransparent, reflecting targets. The basic scheme, illustrated in Fig. 4-35, is a Twyman-Green interferometer, where the coherent light reflected from the target is made to interfere with the light reflected from a flat mirror. The sphere is illuminated through a suitable lens, which transforms the flat wave front into a spherical wave front converging on the center of the target. By properly selecting the lens and target positions, a flat reflected wave front is obtained for a perfect sphere; imperfect targets introduce distortions in the wave fronts, which in turn produce distorted interference patterns when recombined with the reference beam. A second lens projects the image of the target surface onto a screen.

The area of the target that can be analyzed depends on the aperture of the focusing lens. We have coupled this interferometer with a microsphere

manipulator^{9,11} to permit systematic inspection of the entire surface of a target.

Symmetry Interferometry. The symmetry interferometer is designed to identify high-quality microspheres by the absence of fringes on a projected image. A laser beam is split, then each secondary beam is propagated through, or reflected from, the microsphere in different directions. A perfect microsphere affects both beams the same way, and their recombination produces no fringes. An imperfect microsphere affects the two beams differently, producing interference fringes in the recombined beam.

The advantage of the symmetry interferometer over the standard Twyman-Green interferometer for selecting microspheres is obvious. The symmetry interferometer provides a uniform field instead of a multifringe pattern whose distortions must be analyzed to identify asymmetries.

Of the several symmetry interferometers possible, three designs are particularly appealing: the 90° interferometer, the flip-image interferometer, and the reflection symmetry interferometer. The first two are applicable to transparent microspheres, the third to reflecting microspheres.

- A schematic of the 90° interferometer is shown in Fig. 4-36. This instrument compares the optical characteristics of a transparent microsphere along two different axes (which need not be 90° apart). Microspheres with an axis of symmetry perpendicular to the plane of the two beams appear "perfect," producing a fringe-free pattern on the screen. Spherical symmetry is assured by further analyses during a complete rotation of the microsphere around an axis coincident with one of the beams.

- A schematic of the flip-image interferometer appears in Fig. 4-37. A laser beam passes through the microsphere and the projection lens, and is then split. One beam is reflected from a flat mirror, while the other beam undergoes two reflections in a roof prism. The two beams, when recombined in the beam splitter, are inverted with respect to each other. Each ray going through the microsphere interferes with a second ray going through a point symmetrically opposite with respect to a plane perpendicular to the figure and bisecting the microsphere. The laser beam must be polarized along this plane of symmetry. Figure 4-38 shows two examples of the interference patterns obtained with the flip-image interferometer. A uniform

Fig. 4-35. Schematic of the spherical reflection interferometer. A lens focuses the main laser beam toward the center of the sphere. A perfect sphere, together with the lens, produces a reflection with a plane wave front matching the reflection of the reference beam from the flat mirror.

microsphere produces no interference pattern, whereas a nonuniform microsphere produces visible fringes.

● The reflection symmetry interferometer is illustrated schematically in Fig. 4-39. A laser beam illuminates the target, and the reflected light is separated into two beams. As in the flip-image interferometer, one beam is reflected from a flat mirror while the other is inverted in a roof prism. The interference pattern from the recombined beams is superimposed on the image of the target surface and projected onto a screen. Any lack of symmetry is shown by the fringe pattern. A perfect reflecting target shows a uniform, fringe-free image.

4.5.4 Noble Gas Fill Measurements

Several of the methods for diagnosing the density achieved in implosion experiments rely on an argon fill in the target. We have developed a simple, nondestructive method, illustrated in Fig. 4-40, for measuring the total amount of argon in the target.

As tritium decays, it gives off electrons with energies from 0 to 18 keV. When these low-energy electrons strike the wall of the microsphere, they penetrate a few micrometers into the wall, exciting characteristic x-ray lines and producing a broad spectrum of bremsstrahlung x rays. This x-ray emission characterizes the DT fill.¹⁴

When the balls contain argon, the tritium-decay electrons also excite the argon K_{α} line at 2.96 keV. The number of argon x rays generated is proportional to the amount of argon in the target. The argon fill has virtually no effect on the generation of x rays from electrons striking the wall; hence, this background spectrum provides a convenient calibration reference. Therefore, instead of measuring the absolute number of argon x rays, we measure the ratio of these to the bremsstrahlung x rays of the same energy. Because all the x rays are generated either inside the ball or in the first few micrometers of the wall, and because the argon line and the background of the same energy are absorbed in exactly the same way by the rest of the

Fig. 4-38. Comparison of a microsphere having good symmetry with one having poor symmetry, as seen in the flip-image interferometer. (a) Two images (one of which is flipped) of a symmetric microsphere. (b) The uniform phase pattern that results when the images in (a) are overlapped by adjusting the position of the microsphere. (c) and (d) The analogous images for an asymmetric sphere.

Fig. 4-39. Reflection symmetry interferometer. This design combines the principles of the spherical reflection interferometer and the flip-image symmetry interferometer.

wall, this measurement technique is not affected by subsequent layers of material on the target. It is also independent of the size of the target sphere, the amount of DT fill, and the efficiency of the x-ray counting procedure. The only requirement is that we accumulate enough x rays to clearly resolve the argon peak. For a target with $5\text{ }\mu\text{m}$ of glass, coated with $20\text{ }\mu\text{m}$ of CF_2 , about an hour of counting time is required.

Our measurement was calibrated for targets with a glass inner layer by measuring the argon-to-background ratio for several balls, then crushing each individually in a mass spectrometer to determine the absolute amount of argon present (see §4.6.3).

Number of x rays

Energy, keV

Fig. 4-39. Argon fill measurement. Beta decay of the tritium fill excites the argon K_{α} x-ray line. The ratio of the argon K_{α} radiation to the 3-keV background in the x-ray spectrum provides a convenient method of measuring the amount of argon in the sphere.

Our newly developed technique can be used to measure many different elements in the fill or the inner layer of the wall. As long as the element has a characteristic line between about 1.5 and 15 keV, the characteristic x rays will be excited by the tritium beta decay and will have sufficient energy to escape the sphere.

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4.6 Surface and Materials Analysis

This year, the surface and materials analysis group devoted its efforts to providing electron microscopy and chemical analysis services to the laser target fabrication group and to the laser program. New developments included

- Advances in automated 4π SEM characterization.
- Smaller-volume quantitative glass analysis techniques.
- Argon content measurements in individual glass spheres.
- Evaluations of the surface cleanliness of target materials.

These advances were made against the backdrop of a wide variety of general analytical services provided to the target program.

4.6.1 Computer-Controlled 4π SEM Examination

In addition to interferometric 4π characterization, it is necessary to examine target spheres with

the scanning electron microscope (SEM). The SEM can easily detect submicrometer defects, thus ensuring that a sample fully meets surface finish requirements. The manual 4π SEM system described last year¹⁶ has been improved by fabricating a stepper-motor-controlled stage and placing the entire system under computer control (Fig. 4-41). Currently, we can examine a sphere under completely automatic control, record up to 300 sequential images, and store them permanently on video tape.

An LSI-11 computer, coupled to both the stage and the video disk, controls the operation. This computer is also shared by an x-ray spectrometer system, whose display device is used as the control terminal. A carbon-coated sample is mounted in the stage (Fig. 4-42) between silicone-faced capillary tips and inserted in the SEM chamber for analysis. In addition to manual drives for centering and tip compression, the stage is controlled by four stepper motor drives that give $1\text{-}\mu\text{m}$ resolution. Software permits either continuous rotation of a sphere or a "step-and-photograph" sequence using the video disk.

Fig. 4-41. Computerized 4π SEM system.

Fig. 4-42. SEM manipulator stage. Four stepper motors provide 1- μ m resolution and allow complex manipulation of the microsphere.

Fig. 4-43. Comparison of SEM's of a sphere, taken at different sweep rates of the raster-scanning video disk. (a) Image obtained at TV sweep time of 1/30 s. (b) Image obtained at sweep time of 250 s.

Fig. 4-44. Cambridge S-180 SEM used in 4π examination.

to need no readjustment during this time. This requires careful adjustment of the SEM electronics, attention to contamination control in the column, and a stable electron emitter. Normal tungsten filaments have a 40-h life and change their emission properties greatly during this period. Therefore, we use a Broers-style, electron-bombardment-heated lanthanum hexaboride (LaB_6) emitter.¹⁷ When properly adjusted, this emitter is bright and stable for over 100 h. Experience to date has indicated no problems with SEM stability during even the longest scans.

Initially, we made 4π scans normal to the surface of the sphere. These scans allowed photo-mosaics to be made, but they were difficult to use for height measurements. By looking over the horizon of a sphere, we found it easier to detect significant surface features. In such scans, an image can always be found that is appropriate for a height measurement of any significant artifact. Figure 4-45 is a portion of an automated scan of a $140\text{-}\mu\text{m}$ glass sphere with a carbon coating about $100\text{ \AA}$ thick. The sphere was rotated 24° between images. The larger defects in these pictures would be detected by an interferometer, but many defects smaller than interferometer resolution can also be seen.

Note in Fig. 4-45 how much better the surface looks in the first view than in the later ones. This variation in surface quality from view to view is

common in 4π examinations and is a compelling reason to perform such analyses. An evaluation of a sphere from a single view is impossible; it seems that the best side is often seen first.

4.6.2 Glass Composition Analysis

Glass microspheres that vary greatly in diameter, wall thickness, and composition require a variety of glass formulations. To ensure consistent quality, these formulations, as well as the glass produced, require quantitative chemical analysis. Because only limited material is available, analysis techniques must minimize sample requirements.

Silicon, boron, sodium, potassium, lithium, calcium, and aluminum are the elements most often of interest in glass analysis. A typical analysis is conducted as follows:

- A 25-mg sample of glass is dissolved using an alkali fusion technique, and the silicon is then analyzed gravimetrically.¹⁸

- Boron is analyzed in the solution using a boro-manitol titration.¹⁹ Interfering ions can be complexed before titration,²⁰ or the boron can be titrated to a predetermined pH in the presence of known amounts of interfering substances.²¹ Many reagents contain traces of boron, so a reagent blank must be carried through the analytical procedure as a control.

Fig. 4-45. Six images from a 3000-times, computerized SEM scan. Between images, the sphere was rotated 24° .

● Sodium, potassium, lithium, calcium, and aluminum as well as barium, zinc, and iron are determined by atomic absorption spectrometry of the solution.

Table 4-2 summarizes the results of four glass analyses using these methods.

4.6.3 Mass Spectrometric Argon FIM Analysis

Accurate knowledge of the argon content of individual spheres is necessary to evaluate the results of some laser fusion experiments. Standard mass spectrometers require 10^5 spheres for a measurement, which wastes material and fails to give any information about individual spheres.

DT fills in individual spheres have been measured by techniques that rely on calibrating a pumped quadrupole mass spectrometer for the flow of gas from a crushed sphere.^{22,23} Clarke²⁴ has used a closed-chamber technique to measure ^3He : ^4He ratios in seawater. In conjunction with L. Bergquist of the Martin Marietta Corporation, we have developed a similar technique, which uses a closed-volume mass spectrometer. In the spectrometer, the argon partial pressure reaches a steady state for the measurement, and active gases are pumped by a zirconium-aluminum getter. This technique permits greater accuracy and easier calibration than earlier techniques.

Analysis System. The experimental system shown in Fig. 4-46 uses a UTI Model 100, open-source quadrupole residual-gas analyzer. It has an argon sensitivity of greater than 10^{-15} Pa and an emission stability better than 1%. The analyzer and three different pumps—an ion pump, a cold-trapped diffusion pump, and a chemical getter pump—are connected with bellows valves to the 3-I, all-metal system. The ion pump is used during standby to keep the system evacuated and to minimize hydrocarbon background. With the ion pump closed off, the diffusion pump is used to evacuate the chamber before and after argon measurements to reduce argon instabilities introduced by the ion pump. During calibration and sample measurement, both pumps are closed off.

A valved ion gauge, sampling fixture, and argon calibrated leak are connected to the chamber. This system can detect leaks of about 10^{-15} Pa·m³/s; hence, it is important that all fittings and valves be metal-sealed and checked. Pumping of the ion gauge could induce a significant error, so it must be closed off during measurements.

Normally, in an unpumped vacuum system, the hydrogen, water, carbon dioxide, and residual hydrocarbons rapidly raise the pressure above the tolerance of a mass spectrometer. To prevent this in our system, we use a heated 100-l/s zirconium-aluminum chemical getter pump.²⁵ This

Table 4-2. Results of analyses of glass target materials. Unless otherwise noted, figures indicate wt%.

Element	LLL microspheres (December, 1977)	LLL microspheres (October 25, 1978)	Microscope cover glass	Target mounting stalk
Si	33.0	40.5	29.3	— ^a
Na	14.5	10.21	5.07	—
K	3.14	4.37	5.64	—
B	1.35	1.6	3.8	—
Al	0.49	1.25	2.09	<1 ppm
Ti	—	—	1.67	<1 ppm
Zn	—	—	3.62	<1 ppm
Cu	—	—	— ^b	<1 ppm
Ca	0.13	0.25	—	9.00
Ba	—	—	—	6.00
Fe	—	—	—	0.2
Li	0.01	0.01	—	—

^aBalance of mounting stalk was SiO₂.

^bNot measured.

pump removes active gases by combining them with the getter elements. Noble gases are not pumped by the Zr-Al system; thus, the argon partial pressure is allowed to stabilize.²⁶ The getter is activated by heating it to 800°C for 15 min, which releases the hydrogen in solution and reactivates the surface. During analysis, the temperature is maintained at about 250°C, which is the lowest temperature that causes no discernible reduction in argon sensitivity.

Measurement Procedure. We use a Hastings-Raydist 4.59×10^{-8} std cm³/s calibrated capillary leak for calibration. The measured stability is 2%, but the absolute pressure calibration is no better than 10%. The quantity of argon in a sphere is calculated as

$$Q = \frac{\Delta I \cdot L}{dI/dT}$$

where Q is the argon content in Torr·l, ΔI is the quadrupole current rise (in A) from a broken sam-

ple, L is the calibration leak rate in Torr·l/s, and dI/dT is the current rise rate (in A/s) during calibration. As long as the system volume is held constant, the actual volume need not be determined, nor must we consider any transient flow phenomena. In practice, a small argon background must be subtracted.

The sphere to be measured is mounted using 0.1% collodion on a stainless-steel disk, which is then inserted in the valve seat of an all-metal valve. A sorption pump evacuates this microsphere breaking fixture (see Fig. 4-46) to a pressure of a few micrometers. The diffusion pump then reduces the pressure to near 10^{-8} Torr. One hour is usually sufficient, but longer pumping times can produce a 10-fold reduction in background.

With the activated getter pump open, the other pumps and the ion gauge are closed off, and the argon leak valve is opened. The resulting rate of quadrupole output current rise at the argon mass of 40 is used as an initial calibration. It is important that this first calibration be performed, not only to

check the instrument, but also to condition the system components and to reduce pumping by the clean chamber walls. With the argon leak closed, we again evacuate the system with the diffusion pump. When the partial pressure of the argon background is less than 10^{-10} Torr, the diffusion pump is closed off. The argon pressure then noted is used as the background. If this background is acceptable, the sphere is crushed, and the resulting output current step is measured. The current is monitored for at least a minute to ensure that the system is stable. After a few seconds, the argon pressure stabilizes, and any current increase is due strictly to background. Any decrease would indicate argon pumping, which we do not observe in normal operation.

To complete the analysis, the argon is again pumped out, and a second calibration is performed. We use the average of the two calibrations, which compensates for sensitivity drift, to calculate the argon fill. We can analyze about one sample each hour with a sensitivity better than 10^2 Pa (10^{-3} atm) in a $140\text{-}\mu\text{m}$ -i.d. sphere.

Results. Table 4-3 shows the results of argon analyses of eight spheres from one batch, performed over a period of three days. Individual measurements can be made to within 1%; however, the non-uniform sensitivity drift, which appears to be caused by electron multiplier aging, introduces a 5% error. Furthermore, the calibrated leak allows absolute accuracy of no better than 10%. An accurate leak calibration and pulse-counting electronics should permit measurement precision of at least 5%. The

background is less than 1% of most readings and is subtracted during the calculations.

Other Gases. The argon analysis system works with other noble gases; however, calibrated leaks are difficult to obtain. Nonetheless, even in the absence of a specific calibration, we can roughly measure unpumped, inactive gases by adjusting the argon sensitivity, using published sensitivity factors for the spectrometer.

4.6.4 Surface Cleanliness

Target surfaces must be as clean as possible, and the composition and thickness of any contaminants must be known. A firm requirement is that the thickness of contamination layers be kept below $200\text{ \AA}$. For the many materials commonly used in target fabrication and in fabrication research and development, high-resolution Auger electron spectroscopy is one of very few applicable nondestructive analysis techniques with the necessary spatial and depth resolution. Initial evaluations by both Auger electron and ion microprobe analysis suggested undesirable levels of contamination that were not being detected by SEM and other monitoring techniques. A program was started both to examine representative samples and to develop cleaning techniques that ensure clean metal surfaces.

Some uranium samples exhibit thick layers of calcium, sodium, and aluminum (Fig. 4-47), and iron (Fig. 4-48), even in apparently clean areas. In some cases, the aluminum and oxygen layer was

Table 4-3. Results of mass spectrometer argon analysis of $140\text{-}\mu\text{m}$ spheres. The standard leak was 4.59×10^{-8} std cm^3/s .

Sample No.	Sensitivity, 10^{-8} A/s	Background, 10^{-10} A	Current increase after break, 10^{-7} A	Calculated argon fill, 10^{-7} cm^3	Volume-corrected argon fill, std atm	Argon fill, μg
500	10.3	13.0	9.88	4.18	0.21	0.745
501	8.45	9.0	1.90	1.04	0.10	0.185
502	7.12	3.0	1.89	1.90	0.17	0.339
503	6.46	3.52	3.84	2.79	0.25	0.498
504	4.64	3.50	0.99	0.949	0.08	0.169
505	3.66	2.3	0.810	1.10	0.12	0.196
506	3.08	0.75	1.60	2.39	0.21	0.426
507	2.94	0.60	0.799	1.25	0.11	0.223

Fig. 4-47. Scanning Auger analysis of a contaminated uranium sample. (a) SEM image. (b) Aluminum Auger image; heavy areas are ~ 2000 Å thick. (c) Sodium Auger image; depths range to ~ 500 Å. (d) Calcium Auger image.

Fig. 4-49. Sputtered Auger depth profile of a uranium sample after cleaning. The thin carbon layer indicates a very clean surface.

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hollow glass microspheres.^{27,28} We are now adapting these cryogenic target fabrication techniques to the Shiva laser facility.

4.7.1 Laser System Constraints

Depending on the type of target and the inspection requirements, we need two target fabrication options. One option is to freeze the DT in the laboratory, then transport the target, with the DT layer intact, to the target chamber. The other option is to form the uniform DT layer after the cryogenic pylon is located in the target chamber. The Shiva facility imposes several constraints on the cryogenic equipment we have designed to satisfy both of these options.

Cryogenic transport of the target requires the freezing cell to be surrounded by a removable room-temperature vacuum shroud. It also requires the pylon to be inserted into the target chamber while cold. A mechanism for loading and positioning a noncryogenic target pylon already exists, and it would be convenient if the cryogenic system were compatible. However, this limits the diameter of the cryogenic pylon.

In addition to the difficulties of preparing and loading the target into the target chamber, exposing the target for irradiation by the laser also presents some problems. For a 100- μm -diam sphere with a 1- μm -thick DT layer, the absorption of room-

temperature radiation from the target chamber wall will partially melt the DT layer and destroy its symmetry within a few tens of milliseconds. Even the more massive targets for Shiva and Shiva Nova will deteriorate within a fraction of a second. Cooling the chamber walls with liquid nitrogen could reduce the radiation by only a factor of three, because one third of the area surrounding the target is covered by beam optics and diagnostics that cannot be easily cooled. Thus, all protective shields surrounding the target must be removed and the laser must be fired quickly before the cryogenic layer melts.

The shield removal problem is compounded by the need for the target to be within 5 μm of its aligned position when the laser fires. This suggests that the shields should be as loosely attached to the target support as possible. However, there must be enough contact to cool the cryogenic shield and to prevent too much helium exchange gas from escaping into the target chamber.

4.7.2 Cryogenic Target Pylon

With the target fabrication requirements and laser system constraints in mind, we have designed a cryogenic target pylon. The 2-m-long pylon is currently being constructed with the aid of the National Bureau of Standards, Boulder.²⁹ The tip of the pylon, which supports and maintains the target, is shown in Fig. 4-51. Flowing liquid helium

Fig. 4-51. Cryogenic target pylon.

Fig. 4-52. Laser alignment and cell removal sequence.

target pylon and retractor. This ensures that the target will not change position when the inner shield is removed. Just before the laser is fired, the inner shield magnet is again released. A short, high-current pulse, applied to a coil at the base of the outer shield, magnetically repels the movable disk near the retractor end of the inner shield. The disk, in turn, moves the inner shield from the target in a few milliseconds, as shown in Step 4.

The cryogenic pylon has been built, the magnetic repulsion scheme has been demonstrated, and we are completing the design of the retractor mechanism.

4.7.3 Pylon Motion Monitor

We have also developed methods to evaluate the performance of the pylon. We have tried to minimize flexing and vibrations of the pylon and target mount when the target is unshielded just before laser firing. To ensure that the target is within the $5\text{-}\mu\text{m}$ tolerance on its aligned position at the time of firing, we have built a modulated capacitance transducer. The operation of the transducer, as shown in Fig. 4-53(a), depends on the change in capacitance between two electrodes as their distance from a passive coupling plane changes.

The actual electrode pair is vacuum-deposited on an epoxy-fiberglass substrate. As illustrated in Fig. 4-53(b), the substrate has the shape of a portion of a cylinder, because the pylon surface that serves as the coupling plane is cylindrical. When this capacitance is included as C_{sense} in the simple circuit of Fig. 4-54, a change in electrode-coupling plane spacing produces a change in the dc voltage at the

Fig. 4-54. Schematic of transducer circuit.

output. A test circuit based on this principle, with a 10-V peak-to-peak, 10-MHz driving signal, has a sensitivity of $0.1\text{ mV}/\mu\text{m}$ and 0.05-mV noise. This is equivalent to an uncertainty of $0.5\text{ }\mu\text{m}$ in plane spacing. The frequency response had a 3-dB roll-off at about 7500 Hz.

4.7.4 Mach-Zehnder Interference Microscope

We have improved our optical system for evaluating the quality of the frozen DT layer. As described in last year's report,²⁷ we previously used a wedge interferometer for this purpose. However, when used with high-spatial-resolution optics, the wedge system is inadequate for characterizing spheres with diameters greater than about $500\text{ }\mu\text{m}$.

Thus, we developed the interference microscope shown in Fig. 4-55. Basically it is a Mach-Zehnder interferometer with microscope objectives added. The objective in the Dewar arm magnifies and focuses the microsphere image, while the compensating objective in the reference arm provides independent control of the interference pattern. By translating the compensating objective, a phase gradient is easily introduced for measuring

Fig. 4-53. (a) Schematic of modulated capacitance transducer. The capacitance between the two electrodes 1 and 2 changes as their distance Δd from a passive coupling plane changes (shown as d_0). (b) Cylindrically shaped electrodes, vacuum-deposited on epoxy-fiberglass substrate. The pylon (not shown), which serves as the coupling plane, lies inside the cylindrical electrodes.

the layer concentricity.³⁰ Using the white-light source and adjusting the optical path length with the pentaprism and wedge pair, the absolute layer thickness is also easily measured. A further advantage of using white light instead of laser light is that the interference pattern does not contain spurious interference fringes caused by laser coherence. In addition to making measurements easy, the interferometer can be readily adapted to the Shiva pylon because the length of the arms is not constrained.

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4.8 Target Factory Developments

The successful development of inertial confinement fusion requires a target factory capable of providing targets rapidly and economically. Reactor target designs cannot be specified on the basis of current knowledge. However, for this discussion, we

will choose a relatively complex target concept—a multilayer, multishell target with cryogenic fuel. The general concepts for automating the building of this specific target will be useful for other targets, and they illustrate one approach to the problem of developing a target factory.

Present and near-future targets for inertial confinement fusion can be fabricated by techniques that currently exist or are under development. Targets such as the simple ball-on-stalk can be manufactured individually at a relatively large cost in manpower and time. (They can cost several hundred dollars if they are well characterized and made from high-quality components.) The material cost of a ball is extremely low—as little as one millionth of a cent. The cost of the fuel in the glass ball is only slightly higher—0.1 cent for 100 ng of tritium and a negligible amount for the deuterium. The material cost of the glass stem on which the ball is mounted is probably less than 0.1 cent, and the cement used to attach the ball to the stalk is worth perhaps 0.0001 cent. Thus, the cost of the material in this simple but often-used target is perhaps 0.2 cent. Clearly, the cost of a finished target is the cost of the manpower to handle, select, fill, measure, and assemble the parts.

As a reasonable 1978 figure for manpower cost, let us assume \$25/h. Because inertial confinement fusion is still under development and every experimental target must be characterized individually (not statistically), several parameters must be measured accurately. Each of these parameter measurements and each hands-on operation is expensive. If a target requires one man-day for parts selection, preparation, manufacture, characterization, and assembly, its cost is approximately \$200. It is difficult to conceive of a well-characterized target that would require less than one man-day of effort. However, if inertial confinement fusion is to be an economically practical source of power, targets must be produced at high rates, must be of high quality, and may need to be produced at costs of less than about 50 cents each.

To approach the problems of economical target production, several aspects of the fabrication processes must be reconsidered:

- Fuel container production (glass, plastic, or metal shells, or the fuel itself as its own container).
- Layer coating.
- Surface and interface characteristics.

- Fuel state.
- Required production rate.

In evaluating target factory concepts, two approaches are apparent. One approach involves what we call individual processing, and the other uses batch processes.

In individual processing, we treat each target singly, and either actively control the process to ensure high yield or actively reject targets that do not successfully survive each processing step. This approach is useful if the processing steps are not well enough developed to allow uncontrolled processes with almost 100% yield. An example of such a process is a system that coats a single shell with a beam (for example, see Fig. 4-14). Control of the process would require monitoring the surface finish and coating thickness, perhaps in situ. Such processes will tend to be somewhat general with regard to materials and dimensions, allowing development of the techniques and evolution of reactor target designs to proceed independently. One may view this approach as an automated and refined version of the techniques we currently use to produce experimental targets.

The second approach uses high-yield batch processes that are well enough understood or of a nature that virtually every target meets required specifications. Such processes may depend on target materials and may require clever techniques for their success. An example of a proposed batch process is electroplating, which, when highly developed, may be a feasible high-Z batch coating process. The success of this process depends on the material being coated and on the substrate. The advantages of batch processes are that they tend to be less expensive, less sophisticated, and often more reliable than individual processes. The disadvantage is that they may require much more development before becoming useful. Also, it is not obvious that such processes can meet the high specifications attainable with the individual approach. Finally, batch processes may demand target design alterations that require operating at a lower power or lower energy yield per target.

The prototype reactor target factory will probably combine the individual and batch approaches. With early driver designs, we can expect that the yield of the target will be the most important consideration, and individual processing may be the only alternative. We view individual processing as the most straightforward approach to a

reliable, high-yield, high-tolerance prototype target factory. However, even in the earliest prototypes and certainly as development proceeds, we will substitute batch processing for previously individualized steps. (Currently, we batch-fill our experimental targets at very high yields.)

We have already begun to develop the individual processing techniques that may well constitute the prototype factory that provides the high-tolerance targets to reach breakeven.

For our example, specifications for a reactor-grade target factory are straightforward:

- Production rate: 1 to 10 per second.
- Cost: 10¢ to \$1 per target (the higher cost corresponds to the slower production rate).
- Surface finish: approximately 100 to 1000 Å at spatial wavelengths of 10 to 100 μm.
- Assumed target design: concentric multilayer shells with layer thicknesses of 10 to 200 μm and shell diameters of 100 μm to 1 cm.
- Either cryogenic or noncryogenic fuel fills.
- Yields greater than 90%, within specified tolerances.

The target factory transport system must deliver the targets accurately enough to allow optimum use of all the driver power. The last consideration is the tritium inventory. This inventory for any type of target is proportional to the number of filled targets. It can be reduced by filling the targets as late as possible in the production chain, or by shortening the processing time so that the number of filled targets is reduced.

4.8.1 Shell and Hemishell Fabrication

Shells of both high and low atomic number must be formed. The current glass shell technique shows the feasibility of a specific material and technique: rates of approximately 100 per second have been demonstrated at yields of about 80%. Extensions of this technology look promising for reactor application.

Hemishell fabrication is an area just being developed, and we are evaluating many complex technologies. Many of these techniques have counterparts in molding or integrated circuit production, but their extension to hemishell production is not straightforward.

4.8.2 Hemishell Assembly

Some targets require the nesting and assembly of hemishells. Advanced automated techniques to

support the inner shell can be conceived, but we are just beginning to develop and evaluate approaches for assembling the hemishells and for aligning the nested assemblies within a tolerance of a few micrometers.

4.8.3 Coating

Layering of the shells or hemishells is most easily done by a series of coating processes. Efforts in the area of traditional coating techniques (sputtering and evaporating) have centered on the surface finish problems associated with material-dominated defects and on the physics of coating morphology. Many coating materials have been generated in an amorphous state with surface finishes approaching those required for reactor-grade targets. We have also obtained acceptable surface finishes by using nontraditional approaches such as plasma polymerization. To improve control, we are now turning our effort from batch processes to individual processes. Extensions of these techniques have been proposed as candidates for prototype factory systems.

4.8.4 Cryogenics

In many of the proposed reactor target designs, the fuel fills are solid or liquid DT, which must be maintained at cryogenic temperatures to avoid destruction of the targets by high pressures. Design changes may eliminate this constraint, but we must still be prepared to handle targets at cryogenic temperatures. We have considered several techniques for producing and maintaining cryogenic targets, but further effort is required to evaluate each approach.

4.8.5 Target Transport

The transport of targets through the processing steps must be gentle enough to maintain the surface finish and to ensure physical and chemical cleanliness, thus preventing processing variations. Gas jets or electrostatic systems appear to be most effective. This year we have demonstrated the fundamental feasibility of both systems. Section 4.3.2 describes the gas jet levitator, which is being coupled to various processing steps to improve some of our coating methods. The flow of gas appears to be low enough to allow many vacuum coating techniques.

An electrostatic quadrupole levitator depends on the same principles as does the quadrupole mass spectrometer, which transports ions to the detector when the fields are adjusted for the proper charge-to-mass ratio. Such a system can also be used to transport and support targets during processing (Fig. 4-56). In the quadrupole-of-rotation levitator shown in Fig. 4-14, charging, microscopic inspection, and neutral beam coating are accomplished in the same chamber. Figure 4-57 shows a system that has levitated 0.5-mm shells in a quadrupole rail. Advanced versions of this system support targets of any material, at any pressure and at temperatures less than 650°C.

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