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(2) No 2043

UCRL-50021-79

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Laser Program **Annual Report ~1979**

Volume 1

Lawrence
Livermore
National
Laboratory

R283

Laser Program **Annual Report -1979**

Volume 1

Scientific Editor: Lamar W. Coleman
Publication Editor: John R. Strack
MS date: March 1980

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5285 Port Royal Road • Springfield, VA 22161 • \$16.00 per copy • (Microfiche \$3.50)

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FOREWORD

This report presents the unclassified activities and accomplishments of the Laser Program at the Lawrence Livermore Laboratory (LLL; recently renamed the Lawrence Livermore National Laboratory—LLNL) for the calendar year 1979. The classified work of the Program in 1979 is being reported separately. The Laser Program at LLL—comprising both Laser Fusion and Advanced Isotope Separation—is supported by the United States Department of Energy.

Our purpose in preparing this report is to present our work in depth for the benefit of the inertial confinement fusion and isotope separation communities. Accordingly, concepts, theoretical analyses, computational results, design and configuration of experiments, data, and results are presented in detail to allow critical technical evaluation and to make it possible to reproduce or extend any of the work presented here. In 1979 we realized significant scientific and engineering accomplishments in all areas of our program, highlighted by achieving a fusion target compressed-fuel-density milestone.

This report is published in three volumes: the major sections correspond to the division of technical activity in the Program. Section 1 in Volume 1 provides a Program Overview, presenting highlights of the technical accomplishments of the elements of the Program, as well as discussions of Program resources and facilities. Section 2, also in the first volume, covers the work of the Solid State Laser program element, which include systems operations, Nova, and research and development activities.

Volume 2 contains four sections that cover the areas of target design, target fabrication, diagnostics, and experiments. Section 3 reports on target design activities, plasma theory and simulation, code development, and atomic theory. Section 4 presents the accomplishments of the Target Fabrication Group, and Section 5 contains the results of our diagnostics development and applications activities for the year. Finally, Section 6 in Volume 2 reports the results of laser target experiments conducted during the year.

Volume 3 comprises three sections, beginning with Section 7 on Advanced Quantum Electronics. Both theoretical and experimental research and development activities on advanced laser concepts in the quest for high efficiency and high repetition rate are presented here. Section 8 contains the results of studies by the Energy and Military Applications Group, particularly those relating to electrical energy production by inertial confinement fusion systems. Section 9 presents results from some of the activities in the Advanced Isotope Separation Program.

Preparing a comprehensive technical report of this magnitude is a large effort that involves the work of many people. The overall content of this report is, of course, the result of the efforts of the entire staff of our Program. The names of authors and major contributors responsible for a particular piece of work appear at the end of the article describing that work. The authors had the added tasks of organizing and writing the material and patiently participating in the iterative editing, review, and proofreading processes necessary for final publication. The able and responsive assistance of the Section Editors in collecting and reviewing the articles was an especially valuable contribution to this report. The Program clerical staff and administrative assistants bore the responsibility for preparing the original manuscripts, in addition to their normal, formidable workloads.

The process of preparing and publishing this report required the talents and participation of many members of both the LLL Technical Information Department and other departments. I am indebted to all of them for their help and support in this task. Elsa Pressentin coordinated all aspects of production, keeping them under control and on schedule. Donald Cowden, Wilma Leon, William Fulmer, and Sharon Watson planned, guided, and coordinated the artwork and layout. Ronald Meogrossi brought considerable imagination and creativity to designing the general format and in preparing divider pages, section introductions, and cover. The tedious and exacting job of proofreading the material was capably done by Susan Gray, Bo Pitsker, and Solveig Shearer. Composition of the text was the work of Louisa Cardoza, Linda Davis, and Cathy Johnson. Charles McCaleb provided constant editorial support and overview, while the excellent job of editing complex technical articles was accomplished by John Strack, John Dervin, Thomas Elkjer, Gerald Grow, and Lee Taylor. Herman Teifeld and Richard Pond in the Classification Office have been responsive and supportive by their timely reviews of the material, and Olga Parker of the Laser Program Multimedia Group has devoted a great amount of time and energy in locating many of the illustrations used throughout the report. To these people, and all the others I have not mentioned by name, I offer my thanks for their hard work and for a job well done.

Suzanne Anderson, my assistant in preparing this report, merits my special thanks; her extremely capable and indefatigable help was an essential ingredient in every aspect of the generation and production of the report. It has been a pleasure to work with John Strack, the Publication Editor, throughout the production of this report. His enthusiasm, energy, and expert approach to getting the job done and his effectiveness in working with all the people involved in this effort have earned him a major portion of the credit for its production.

Lamar W. Coleman
Scientific Editor

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Laser Program Overview

Introduction

The principal components of the Laser Program at the Lawrence Livermore Laboratory (LLL) are laser fusion and advanced isotope separation. The goal of the Laser Fusion Program is to develop inertial confinement fusion (ICF) technology for both military applications, in the near term, and civilian energy production, in the long term. Through the mid-1980's, the focus of the Laser Fusion Program is the achievement of ignition conditions in a thermonuclear plasma, which is a necessary milestone along the way to either application of ICF technology.

The development of ICF technology requires the parallel investigation of several critical areas of research, and the organization of the Laser Fusion Program reflects this requirement: First, experimental facilities capable of achieving significant compression and heating of thermonuclear fuel must be established. Over the past seven years, a succession of glass laser facilities, of increasing power, energy, and cost effectiveness, has been developed at LLL. This development has been carried out by the Solid State Laser Systems and Technology program element. Two large laser facilities are currently operating: the two-beam Argus and the 20-beam Shiva. The Nova laser is currently under construction; when completed, it will be capable of achieving the ignition milestone.

The use of these facilities to conduct experiments ranging from fundamental plasma physics investigations to fully integrated target implosions is the responsibility of the Laser Fusion Experiments and Analysis program element. The development of new diagnostics technology—to meet the demanding requirements of spatial, temporal, and spectral resolution imposed by ICF research—represents a major portion of this activity.

Working closely with the experimentalists, the Target Design program element includes studies of plasma physics phenomena, energy transport by both radiation and particles, hydrodynamics, and high-temperature atomic physics. Extensive use is made of the computational capabilities of the LLL computer center, and the LASNEX code represents the most complete computational model of ICF target physics available anywhere.

The Target Fabrication Group has a dual responsibility: to provide experimental targets, for both plasma physics experiments and implosion studies, and to investigate new methods of target fabrication—including new processes, materials, and diagnostic techniques for characterization. The dimensional tolerances required for ICF targets are very demanding because stable implosion requires a high degree of uniformity in target composition and component size.

The Nd:glass laser provides a well-developed technology for use as a driver in experimental facilities. The use of frequency-multiplication crystals permits the generation of wavelengths from 1.06 μm to 0.26 μm with relatively high efficiency. The laser output can also be varied in pulse duration and modified to increase the spectral bandwidth. Thus the glass laser facilities afford the experimentalist a wide degree of flexibility.

For applications requiring either high repetition rate or high efficiency, an alternative driver is required. The development of alternative driver technologies is the objective of the Advanced Quantum Electronics program element. The principal areas of investigation include *pulse compression*—through both *angular multiplexing* (stacking) and *nonlinear optical techniques* (backward-traveling Raman amplifier)—for application to excimer lasers, and advanced concepts, including free-electron lasers and new solid state laser media.

For both military and civilian applications, it is essential that technology be developed in the context of its ultimate use. The programmatic objective of the Energy and Military Applications Group is to provide the program with this guidance. The High-Yield Lithium-Injection Fusion Energy (HYLIFE) converter design developed by this group is a complete ICF power-plant design centered on a unique reaction chamber concept: a liquid lithium shower that provides first-wall protection and tritium breeding, while also serving as a heat-exchange medium.

The objective of the Advanced Isotope Separation (AIS) Program, the second major part of the LLL Laser Program, is the development of the atomic-vapor laser isotope separation (AVLIS) process. This process, which demonstrated separation of macroscopic quantities of reactor-grade uranium in 1975, is economically and technically attractive, both for primary uranium enrichment and for processing tails from existing gaseous diffusion plants and from planned centrifuge plants. Capital costs for plants using the AVLIS process promise to be between 10 and 20% of those using other isotope separation methods. Additionally, AVLIS plants would require less power and lower operating budgets.

The Shiva laser became operational late in 1977. During 1978, much of the effort of the Fusion Experiments program was devoted to the activation of Shiva and the implementation of a full set of target diagnostics for the facility. Full-schedule operation as a target facility began in the last quarter of 1978. Early in 1979, Shiva experiments produced a record D-T fuel compression of 50 to 100 times liquid D-T density. This result was obtained as part of an extensive campaign devoted to the achievement of high-density implosions (see Fig. 1-1, which shows our

overall progress in achieving such implosions). Both the Shiva and Argus facilities operated reliably and productively during 1979. Shiva provided 228 target shots, along with an additional 47 shots for diagnostic characterization. Argus carried out 126 target shots at $1.06\text{ }\mu\text{m}$ and 31 at the second harmonic. Second-harmonic conversion efficiencies as high as 70% were obtained in a 9-cm-diam beam on Argus.

The Nova laser design was reoptimized to provide performance approaching 300 TW at 100 ps, and 300 kJ at 3 ns. The design calls for phased activation, with 10 beams operating in the first phase, each with an output-beam diameter of 74 cm. In Phase II, 10 more beams will complete the system. Construction began on the Nova laboratory and office building during 1979.

The achievement of intermediate density on Shiva is based on the use of the double-shell targets described in the 1978 *Annual Report*. During 1979, prototype double-shell targets were designed, fabricated, and tested. This is the first in a series of increasingly complex targets to be developed in order to reach high densities.

Major theoretical and experimental advances were made in our understanding of the plasma physics of laser fusion. Using the frequency-doubled capability of Argus, we ob-

Fig. 1-1

tained evidence of improved coupling at shorter wavelengths to confirm theoretical predictions. The frequency dependence of stimulated scattering and absorption processes was also determined.

In the final quarter of 1979, LLL was designated as "lead laboratory" for both Nd:glass laser development and experiments at $1\text{ }\mu\text{m}$ or less. The lead laboratory is responsible for the technical direction of all aspects of the Department of Energy (DOE) program in the designated areas of research. (The program includes projects at the US Naval Research Laboratory, KMS Fusion, Inc., and the University of Rochester.) This is the first of several lead laboratory designations in ICF, and it is unique in requiring coordination of significant in-house and extramural research activities in a single national program.

J. L. Emmett

Major Activities

In this *Annual Report*, we present Laser Program achievements and research accomplishments for the year 1979. The program represents the combined activities of more than 500 people, with a total operating budget of \$54.8 million in 1979. In this section, we present a summary of the major activities of the technical components of the program. The remainder of the section consists of a brief description of program resources and physical facilities.

Solid State Laser Systems and Technology

The Solid State Laser program is responsible for design, construction, and operation of existing and future laser systems at LLL that are used to perform fusion experiments.

During 1979, significant progress was made in all areas of the program (see Section 2 for details). The most important achievements during this period were as follows:

- Provision of reliable high-power laser systems (Argus and Shiva) to support the high-density experimental campaign conducted by the Fusion Experiments program.
- Completion of the optical design freeze for the Nova laser system.
- Authorization to proceed with the construction of Phase I of the Nova project following a final review by the Under Secretary of Energy in April 1979.

Improvements were achieved in the experimental and operational capabilities of both Argus and Shiva. On Shiva, an $f/14$ output spatial filter was in-

stalled to improve beam relay; this increased the peak power and energy capability to 30 TW and 15 kJ, respectively. Upgrading the Argus laser continued with the addition of an actively mode-locked oscillator and a planar-triode switchout system. Continuing modification of the Argus system includes conversion to the second and third harmonics, first with a 9-cm beam aperture, and then with a full 28-cm output aperture. Up to 70% conversion of $1.06\text{-}\mu\text{m}$ light to the second harmonic has been achieved in a 9-cm-diam beam.

Construction began on the Nova laboratory and office building during 1979; when completed, it will allow occupancy and integrated construction of the laser system. In September 1979, we completed a reoptimized Nova design that can produce an exceptionally flexible, versatile laser capable of performance approaching 300 TW at 100 ps, and 300 kJ in 3 ns. In the first phase of development, the laser will consist of 10 beams, each with an output stage composed of 46-cm-diam fluorophosphate disk amplifiers, followed by a 74-cm final focusing lens. For Phase II development, an additional 10 beams on the Shiva laser will be reconfigured to the Nova design, thus completing the full 20-beam Nova system.

In addition to reflecting our experience in operating Shiva, the new Nova design takes advantage of recent advances in optical technology. New optical coating technologies have led to significantly increased damage resistance in thin-film coatings. Furthermore, the development of phase-separated glass allows the design of nonreflecting, uncoated, graded-index surfaces (shown in Fig. 1-2) that are much less vulnerable than coated optics to optical

Fig. 1-2. Sample of phase-separated glass. The lower right half has been etched to provide a low reflection loss with higher optical damage threshold than conventional coated surfaces.

damage at "hot" points (e.g., input lenses on spatial filters).

Improvements in the Argus, Shiva, and Nova lasers result directly from achievements made in program research and development activities during the past several years. In addition to the achievements noted above, other advances in basic science and technology include the development of new techniques for the accurate measurement and analytical modeling of saturation in laser glass amplifiers, the application of photoacoustic techniques to the detection of weak absorption in solids and thin films, and the construction and testing of a prototype compensated-pulsed alternator under contract at the University of Texas.

Target Design

The design of maximum-performance targets for our 1000X (1000 times liquid D-T density), ignition, and high-gain milestones requires both development of faster, more sophisticated simulation codes and improved theoretical understanding of laser-plasma coupling (described in Section 3).

During 1979, several high-density target designs were successfully tested, including a prototype of the 100 to 1000X milestone target. Our theoretical understanding of laser-plasma coupling

increased significantly, and it received experimental confirmation in several important areas. Further, the capability and computational power of our simulation codes were substantially improved. We made major progress in the design of advanced targets for Nova and reactor-scale drivers (both short-wavelength lasers and ion beams).

Our plasma theory predictions of Raman scattering were confirmed in 2-ns disk experiments. We also predicted improved coupling with shorter wavelength light. This improved coupling was confirmed in Argus frequency-doubled experiments. In addition, we have made important theoretical progress in the area of nonlinear corrections to inverse bremsstrahlung, and our understanding of the critical issues of resonant absorption, filamentation, and Brillouin scattering has substantially improved.

The newly developed Cray version of our principal simulation code, LASNEX, currently offers twice the computing capability of its predecessor CDC 7600 version. In addition, the treatment of atomic physics, Brillouin backscattering, and multigroup diffusion in LASNEX has been improved.

Gold-disk experiments provide a test of our detailed understanding of laser-plasma interaction physics and of the LASNEX code. We have reexamined old gold-disk results, and have attempted to model the recent results at longer laser-pulse lengths, lower intensities, and frequency-doubled conditions. We find generally good agreement with experimental results. However, the small discrepancies we have observed might be due to neglect of significant physical processes. Refined experiments with more sophisticated diagnostics are required to explore these discrepancies.

Analysis of data from our 10 to 100X experiments also provides a test of our understanding. A series of experiments in the 10 to 20X liquid-density range, which were diagnosed by three independent techniques, were found to be consistent with LASNEX simulations. Detailed comparisons among calculated and experimental x-ray microscope images, argon-line images, and radiochemical analysis all agreed quite well. Relatively good agreement was also achieved between simulations and experimental data for the higher-density 30 to 100X targets, when the generation of hot electrons was delayed. This delay is predicted by theory and has been confirmed experimentally.

Initial tests of our 100 to 1000X prototype high-density target design yielded detectable neu-

trons. This is the first of a series of increasingly complex targets designed to reach higher densities.

Advances were made in the design of classified targets for 100 to 1000X compression with Shiva, ignition with Nova, and high gain with reactor drivers. In order to increase the accuracy of scaling from our current experiments, we formulated scaling laws and analytic approximations for a number of critical phenomena, and these formulas are in good agreement with the detailed experimental results.

Early in 1979, we derived the gains to be expected for reactor-scale targets, using more conservative ignition criteria and reduced burn efficiencies. These conservative factors represent our current understanding of thermonuclear ignition and burn. On the basis of these revised gain curves, we conclude that short-wavelength lasers with efficiencies of 7%—or ion beams with efficiencies of 15%—will require energies of 3 to 5 MJ to achieve gains high enough for economic power reactors.

In design calculations for our heavy-ion-beam reactor target, we have achieved high beam-to-target coupling efficiency. Our calculational capability in this area was improved by adding new ion-beam ray-trace physics modeling capacity to LASNEX.

Target Fabrication

In 1979, the major effort in target fabrication was devoted to the development and assembly of multilayer laser fusion targets and to the production of intermediate-density (100X) targets (Section 4).

Deposition on glass shells of high-quality layers of such materials as platinum and gold—or either high-Z or lower-Z polymers, such as fluorocarbon or hydrocarbons—requires that the glass surface be exceptionally clean and smooth. As the layers are deposited, any surface irregularities or dust particles seem to nucleate the growth of severe nonuniformities in the coatings. Through study of the physics of the coating process and careful control of the process parameters, we have been able to deposit excellent coatings on glass spheres: CH coatings more than 100 μm thick, CF polymers up to 35 μm , and several micrometres of gold, platinum, and beryllium.

We have also developed an apparatus for levitating glass spheres and multilayer shells on a

molecular beam, permitting them to be coated without damaging contact with support pans and plates.

Hemishells are assembled to form the second shells in multilayer targets of the type shown in Fig. 1-3. Machining the hemishell surface (500 μm diameter and 50 μm thick) to finishes of 100 to 1000 μm , with thickness variations $<1 \mu\text{m}$ is extremely difficult. However, using single-point diamond turning on air-bearing spindle machines, both Rocky Int'l and the L.L.L. machine shop have succeeded in producing hemishells that meet these specifications.

Characterization of spheres and layers has always been a time-consuming and difficult task. We have made strides toward reducing both the time and difficulty by developing automated handling and characterization systems. By manual manipulation and by observation through an interferometer, an operator can characterize a sphere in several hours. Our automated system can characterize a sphere over its entire surface (4 π characterization) to an accuracy of 100 μm ("altitude" or wall thickness) and a lateral resolution of 2 μm in about five minutes and can also provide a hard-copy contour map of the spheres.

We have produced spheres filled with diagnostic gases such as argon and bromine. Because the gases are put in the glass spheres during their formation, no drilled and plugged holes are necessary. Thus, the surface quality is maintained at the 100- to 200- μm level.

Glass shells of very high quality have been produced with diameters of more than 1 mm. In the past, yields of usable target spheres from commercial sources were very low: 1 in 10^7 to 10^{11} . However, up to 99% of the glass spheres produced by the droplet generator are of target quality (i.e., 100 to 200 μm surface finish, wall variations less than 1% of wall thickness).

Surface and material studies give insight into the physics and chemistry of sphere production and coating technology. Such information is vital to developing new fabrication processes. We have expanded our capabilities in this area with the addition of a scanning Auger microscope. This instrument allows us to analyze the composition of

Fig. 1-3. Major advances in target fabrication technology provide the basis for the fabrication of multishell targets.

material surfaces with a spatial resolution of $0.2\ \mu\text{m}$ and depth resolution of $2\ \text{nm}$.

Cryogenic fuel layers are expected to provide significant improvements in fusion target performance. We are experimentally testing several approaches for forming solid and liquid D-T fuel layers in targets and are developing theoretical descriptions of the layer characteristics. We are also engineering cryogenic delivery systems for placing these targets in the target chamber without disturbing the frozen-fuel layer.

Fusion Experiments and Diagnostics

The responsibilities of the Fusion Experiments program element are to plan and execute our laser fusion experiments, provide the necessary diagnostic instrumentation, develop new instruments for future experiments, reduce and analyze the data, and operate the systems (our 1979 work is presented in Sections 5 and 6). Through July 1979, Fusion Experiments comprised three groups: the Shiva Operations Group, the Laser Plasma Interaction Group, and the Diagnostics Development Group. The following month, the operations of Argus and Shiva were consolidated and transferred to Solid State Laser Systems. The Laser Plasma Interaction Group was split into three groups: Experiments, Laser Fusion Diagnostics, and Data

Management and Analysis. The role of the Diagnostics Development Group in providing the new diagnostic instruments and techniques remained unchanged.

The Data Management and Analysis Group was formed to improve the efficiency and accuracy of data processing and analysis. It will be necessary to purchase and install a new, data processing computer to handle the classified data generated by the Argus and Shiva systems. (Because neither system is a permanently cleared facility, we are unable to use their current computer systems for classified processing.) The new computer, a DEC 11/780 VAX, will be located in Building 381 and connected to the Argus, Shiva, and Nova systems by one-way data links. This system will make possible significant improvements in the quantity, quality, and timeliness of our data analysis.

We were able to use both Argus and Shiva for target experiments for the greater part of 1979. The output spatial filters/image relays were installed on Shiva during April and May. During this period, we also made diagnostic improvements. In June, we installed the new B-C spatial filter/image relays on Argus, and during September and October, we converted the south beam output to $0.532\ \mu\text{m}$ at an aperture of $9\ \text{cm}$. This represented our first capability to study the scaling of laser plasma phenomena at a wavelength shorter than $1.06\ \mu\text{m}$.

During the first quarter, Shiva experiments produced a record D-T fuel compression of 50 to

100 times the density of liquid D-T (Fig. 1-1). During our first series of high-density shots, variations in the target design produced densities from 10 to 100X. The fuel temperatures ranged from 0.5 to 1.0 keV, and the number of fusion reactions varied between 10^6 to 10^8 . These experiments are a significant step in our progress towards the 1000X compression required to explore the scientific feasibility of laser fusion. During the summer, we made three independent fuel-density measurements using a 10X target design that permitted us to increase our confidence in the earlier 50 to 100X results. The remainder of the Shiva experiments and all the target shots on Argus were used in experimental sequences to increase our understanding of laser absorption and scattering processes and energy-transport processes in our laser-imploded targets. The data from experiments at 0.532 μm are very encouraging; they support the theoretical predictions that the deleterious effects of collective absorption, stimulated scattering, suprathermal electrons, and transport inhibition are reduced as the wavelength decreases.

Our diagnostics research and developments efforts have continued to provide us with new instruments and capabilities. A Wolter x-ray microscope system with a resolution of 2 μm was calibrated and subsequently installed on Shiva (data will be recorded by one of our x-ray streak cameras). The microscope will operate in the x-ray shadowgraph mode, with one or more beams of Shiva serving as the x-ray backlighting source. Shiva experiments have demonstrated that sufficiently intense monochromatic sources can be generated to probe target pusher dynamics at increased density.

We have been developing the use of charge-coupled devices (CCDs) for 1.06- μm imaging, streak-camera data recording, and CRT transient digitizers. In this last application, we have collaborated with Tektronix in a demonstration of a 4-GHz transient digitizer based on their 7912 tube in which the recording Si target was replaced with a backthinned RCA CCD to provide increased sensitivity and bandwidth.

Advanced Quantum Electronics

The broad objectives of the Advanced Quantum Electronics (AQE) effort are to identify, demonstrate, and assess short-wavelength laser driver systems for fusion research and reactor ap-

plications and for use in advanced isotope separation. To carry out these responsibilities, we have assembled an integrated capability to conduct experimental, theoretical, and computational studies that span atomic and molecular collision physics, quantum electronic processes, and device and systems technologies.

Our 1979 effort in support of the Laser Fusion Program continues as a natural evolution of our activities in 1978 (see Section 7); it is directed along two complementary paths:

- Research, development, and further assessment of hybrid (angle-multiplexing and Raman) pulse-compressor laser systems as a baseline approach to fusion-laser drivers.

- A continued search for new laser media and pumping techniques capable of providing laser driver systems that operate with efficiencies greater than that projected for the baseline approach (e.g., >5%) and/or that use less complex and less expensive technologies.

The Raman Amplifier Pumped by Intensified Excimer Radiation (RAPIER) KrF pulse-compressor laser system tested (shown in Fig. 1-4) began operation in 1978 and continues to be the centerpiece of our baseline effort. The front-end and A-amplifier subsystems of RAPIER have been fully characterized, and we have used them to carry out experiments demonstrating backward-wave Raman pulse compression and angle-coded pulse stacking. By using the KrF discharge lasers of the front-end subsystem, we have measured the energy conversion efficiency from the KrF pump pulse to the backward-wave Stokes pulse as a function of pulse compression ratio at the second Stokes parasitic limit. We have demonstrated that pulse compression in methane gas agrees with theoretical models and code predictions, as shown in Table 1-1.

The A-amplifier, pumped by two opposing electron beams, has produced up to 35 J of KrF radiation when operated as an oscillator (compared with a design goal of 25 J). This device has also been operated with excellent performance both as an injection-locked regenerative amplifier and as a three-pass conventional amplifier. We have observed amplifier-power gains in excess of 1000X—again in agreement with theoretical and computational models. In addition, we have conducted

Fig. 1-4. The A-amplifier of the RAPIER system, driven by dual electron beams, is capable of producing up to 35 J output at 0.25 μm .

Table 1-1. Demonstrated pulse-compression performance in methane gas.

Compression ratio (K)	Conversion efficiency (%)	Stokes pulse width (ns)
25	30	1.2
10	50	3.5
5	70	7.0

a demonstration of the control of the spatial and spectral output properties of a KrF power amplifier with very modest input fluences. To develop KrF kinetics and laser amplifier/oscillator codes of the highest possible predictive accuracy, substantial experimental and theoretical studies have been conducted. These studies and principal results derived from them are described in detail in this *Annual Report*. To complement our state-of-the-art KrF kinetics and laser/amplifier models, we have made

significant progress in simulating the strong amplified spontaneous emission (ASE) characteristic of excimer gain media and the parasitic loss processes, which will ultimately limit aperture and energy-scaling of large KrF power amplifiers.

The array of models that characterize KrF gain media have been interactively exercised to establish preliminary conceptual designs of megajoule-class KrF pulse-compressor laser systems. One design that was based on pure angle-coding and pulse-stacking featured a compact optical configuration requiring only spherical optics. A second design combined this angle-multiplexed stacker concept with a backward-wave Raman compressor subsystem. Estimated project costs for these system designs included direct installed equipment costs; an engineering, design, inspection, and administration (EDIA) cost factor of 1.17; a contingency factor of 1.25; and an escalation factor of 1.3, based on a six-year construction period and a constant annual inflation rate of 8%. (Research and development costs for prototype components and systems were not included.) The project cost for a hybrid megajoule

system was projected at \$280 million, a total that was found to be independent of the energy output of the final power amplifier module over the energy range from 50 to 200 kJ. The project cost for the megajoule pure-stacker was projected to vary from \$250 million (using 200-kJ power-amplifier modules) to \$345 million (using 50-kJ modules). On the basis of these initial scoping studies, we have been able to identify high-leverage scientific and technological issues that are now undergoing intensive study.

In addition to our baseline effort on KrF pulse-compressor systems, we have made a small, but critical, effort to search for and make a preliminary assessment of alternative laser systems. During 1979, two distinctly different advanced laser concepts were explored in some detail. Together with several consultants, we have developed a concept for a single-pass, high-peak-power, free-electron laser (FEL) that shows promise as an efficient ($>10\%$) short-wavelength laser ($\lambda < 250$ nm). The design described in this *Annual Report* is based on high-current, linear-induction-accelerator technology currently being developed under the sponsorship of the Department of Defense in a separate program at LLL. The fusion FEL concept we are pursuing features the incorporation of an electron pre-buncher section and the use of a variable-wiggler power-amplifier section, both techniques that lead to the highly efficient conversion of electron energy to light energy. A particularly attractive feature of the design is that no ultraviolet optics are required to manipulate the output beam at high intensity.

A second advanced laser system concept is based on the solid state laser medium, vanadium-doped magnesium fluoride (V:MgF₂). This laser medium, which was first demonstrated in 1963, is characterized by a high-energy storage density (>500 J/litre), a long energy-storage time (2.3 ms), and operation at the relatively short wavelength of $1.1\ \mu\text{m}$. Amplifier and system performance analyses described in this *Annual Report* indicate that overall system efficiencies greater than 5% may be achieved by the use of xenon flashlamps, whose output radiation couples particularly well to the absorption bands of V:MgF₂. To support device and system design studies, we have begun to investigate crystal growth and laser parameters for V:MgF₂. Results from these studies have started to influence power-

amplifier designs that are based on the "axial gradient" configuration. We are continuing the search for alternative solid state gain media and excitation sources that might prove superior to the V:MgF₂.

In support of the AIS Program, AQE efforts have centered on two technical areas: research and development of rare-gas halogen closed-cycle, high-average-power laser pumps, and the theory of coherent pulse propagation in vapors with electronic transitions in near resonance with the electromagnetic wave. In 1979, we operated the closed-cycle rare-gas halide (RGH) laser testbed with various laser media. Output power up to 40 W with a pulse-repetition frequency of 525 Hz have been observed for XeCl, with run lifetimes greater than four hours. A maximum power output of 55 W at 600 Hz has also been attained. On-line mass spectrometry has been used in two efforts: to help characterize deleterious chemical species formed in the laser discharge over long periods and to provide information for the design of long-life, closed-cycle laser systems. Off-line test of the e-beam switch RGH discharge lasers has proceeded quite successfully, together with the prototyping of a pulse-repetition-rated electron-beam gun by Hughes Aircraft Company. In 1980, we plan to install this gun in the closed-cycle system testbed (CCTB) in order to assess its effectiveness under flow conditions.

Energy and Military Applications

The goal of the Energy and Military Applications Group is to develop detailed scenarios for the application of fusion drivers for both military and civilian energy objectives. For civilian energy production, a detailed design study for a 1000-MW_e generating station has been evolving for several years. The design is based on the HYLIFE reaction chamber, a particularly attractive concept that uses a liquid metal wall that converts the pulsed radiation output of the fusion reaction to heat, without suffering excessive wall damage. (A detailed description of the conceptual design of a HYLIFE-based generating station is presented in the 1978 *Annual Report*.)

This year, the design of a number of important subsystems of the power plant has been extended,

and an economic tradeoff analysis has been completed, for the integration of these subsystems into the complete plant (Section 8). Among the topics analyzed have been the effect of vibration on the stability of liquid metal jets; the response of the liquid wall to the deposition of x rays, target debris, and neutrons; and the subsequent thermal and mechanical response of the wall. This analysis has led to significant simplification of the HYLIFE design.

The conceptual design effort has also been expanded to include a short-wavelength laser system for fusion. Together with the AQE Group and an industrial team drawn from Bechtel National, Hughes Aircraft Company, and Physics International, Inc., the Energy and Military Applications Group arrived at a design for a KrF-driven stacker/compressor laser that will be extremely valuable in guiding our search for high-leverage areas to reduce cost, complexity, and technology-development time. We have incorporated near-term (1990) technology to design a 1.5-MJ system that would operate at two pulses per second over a 10^5 -shot lifetime and that would be suitable for an experimental test facility. With additional development and capital investment to achieve a longer lifetime, this modular laser facility could be expanded to the 3-MJ size characteristic of a full-scale fusion power plant driver.

Advanced Isotope Separation

The goal of the Advanced Isotope Separation (AIS) Program is the demonstration of a uranium isotope enrichment process for the production of light-water reactor fuel that is more efficient and more economical than current technologies. The specific enrichment process under development at LLNL is atomic-vapor laser isotope separation (AVLIS) in which the ^{235}U component in atomic uranium vapor is selectively photoionized by powerful tunable laser radiation. The resulting ions are separated from the neutral vapor stream and collected as enriched product.

In 1979, the AVLIS program recorded significant technical advances in several areas (see Section

9). We demonstrated the vaporization of substantial quantities of uranium at high energy efficiencies. We obtained high power outputs from new designs of both copper vapor and XeCl excimer lasers. Important physics tests were run on the uranium vaporization process, on several aspects of ion extractor designs, and—in cooperation with the Nuclear Division of Union Carbide Corporation—on materials for uranium product collection. The 32 copper vapor lasers in the Venus power amplifier facility were activated and used to meet single-aperture power-output milestone. We have integrated our existing lasers and process chambers to achieve significant uranium enrichment.

The effect of these achievements is to increase our confidence that AVLIS can meet its very low projected operating cost per separative work unit (cost/SWU) and capital cost/SWU. The key system components for the AVLIS process already exist. An aggressive development program could bring an AVLIS plant on line within the next decade.

An already developed AIS process can be employed in the nuclear fuel cycle on a current basis to strip from 0.25% to 0.075% ^{235}U both the already accumulated DOE tails stockpile and the tails from conventional enrichment plants. Future applications include the replacement of existing gaseous diffusion plants and meeting new demands for enrichment capacity. An analysis performed in 1979 indicates that the benefit-to-cost ratio for implementing AVLIS is greater than 6 for each of the individual sources of demand listed above and greater than 40 for all demands taken together. Considering both its present technical status and its estimated economic advantages, we believe that AVLIS is the most attractive long-term uranium enrichment option presently available to the nation.

Program Resources

The budget for the Laser Program during FY 1979 amounted to \$54.8 million in operating funds and \$5.3 million in equipment funds. An additional \$20 million was appropriated for Nova in 1979, bringing project funding to date to \$23 million, and allowing the start of construction of the laboratory and office buildings. Total internal program manpower, including the Nova project, was 538 employees. Table 1-2 shows the history of funding and

Table 1-2. Resources of laser fusion and AIS programs for FY 1979 in comparison with those of prior years.

	Fiscal year											
	1970	1971	1972	1973	1974	1975	1976	1976T ^a	1977	1978	1979	
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	40.6	
Advanced isotope separation	—	—	—	—	0.74	4.8	7.2	2.1	8.1	10.9	14.2	
Manpower												
Laser fusion	43	124	155	232	223	230	244	259	281	355	355	
Advanced isotope separation	—	—	—	—	23	70	90	92	94	116	131	
Equipment (\$ million)												
Laser fusion	0.1	0.4	0.9	1.1	1.17	2.0	2.4	0.5	2.8	3.6	3.1	
Advanced isotope separation	—	—	—	—	0.13	0.7	1.5	0.3	2.4	1.9	2.2	

^aTransition quarter.

manpower for the last 10 years for the Laser Fusion and Advanced Isotope Separation Programs.

Laser Fusion Program

Operating funds of \$40.6 million remained essentially constant from the previous year, which

Fig. 1-5. Operating costs and wage expense by fiscal year for (a) the Laser Fusion Program and (b) the Advanced Isotope Separation Program.

Table 1-3. Laser fusion program—FY-1979 costs and manpower by budget category.

Budget category	Manpower	Cost (\$ thousand)
Nd:glass laser development	53	7 190
New laser development	29	2 955
Pellet design and fabrication	121	14 115
Target-interaction experiments	111	12 300
Diagnostics development	29	2 690
Reactor systems studies	8	955
Heavy-ion source development	4	360
Total	355	40 565

represented a reduction in buying power. Because manpower remained constant at 355 employees, the proportion of external to internal spending was reduced. The divergence of the total operating costs and the manpower costs shown in Fig. 1-5(a), however, indicates that the long-term trend of increased industrial spending is being maintained. This has been a commitment of our program, and it will remain a central consideration in our plans for the future.

The distribution of funds and manpower by budget category (discipline) is shown in Table 1-3. The trend is to greater expenditures in the target design and fabrication areas as facilities such as Shiva are brought on line and as required target complexities increase. The program, however, is becoming limited by capital equipment funds: the growth of these funds is not keeping pace with the need both for new diagnostic and analytic techniques that are dependent on state-of-the-art instrumentation and for techniques that probe areas not previously explored.

Advanced Isotope Separation Program

In FY 1979, the operating budget for the AIS Program was \$14.2 million, and the equipment budget was \$5.2 million. The manpower figures reflect all LLL personnel in direct support of the programs: scientific, technical, nontechnical, clerical, and crafts. In addition to this in-house LLL manpower, we use non-LLL contract personnel for support of peak program loads. A breakdown of AIS programs by FY 1979 operating budget category and manpower is given in Table 1-4.

As Fig. 1-5(b) shows, the ratio of outside spending to manpower costs continues to increase, reflecting the total program commitment to use of private industry and university resources.

Table 1-4. Advanced Isotope Separation Programs—FY 1979 operating costs and manpower by budget category.

Budget category	Manpower	Operating cost, (\$ thousands)
Atomic-vapor process— Uranium isotope separation	124	13 600
Deuterium laser isotope separation	3	200
Advanced technology and system assessment	1	100
Advanced cycle-coal	2	200
Atomic-vapor process— industrial participation	1	70
	<u>131</u>	<u>14 170</u>

Program Facilities

Introduction

Program growth during 1979 led to the addition of new facilities and the continuing modification of those already in existence. (Figure 1-6 shows existing Laser Program facilities and those planned during the next five years.) Most new construction involved office and technician space; only one new laboratory building was under construction. Table 1-5 contrasts 1979 with 1978 and clearly shows the ongoing expansion of office space required by the program. The current total of 355 270 ft² represents

Table 1-5. Space distribution and 1978-79 comparison for Laser Program facilities.

Facility type	Space allocated (ft ²)		Increase (%)
	1978	1979	
Permanent office	50 930	50 930	0
Owned office trailers	42 047	68 247	31.1
Rental office trailers	6 016	7 456	23.9
Permanent laboratories	187 548	187 548	0
Technician support areas	34 609	38 929	11.1
Total	331 150	353 150	6.2

a 6.2% increase from 1978. In order for us to make accurate projections of our future facility requirements and to manage the growth in the program effectively, we have hired the firm of Royston, Hanamoto, Alley, and Ahey to help us develop a facilities master plan for the Laser Program. This firm provided the original LLL master facilities plan and will ensure that our plan is integrated with LLL goals, while serving us as a detailed planning guide. Although the plan will encompass the next 20 years, special emphasis will be placed on the next five years. This plan should be completed by mid-1980.

Construction costs at LLL continue to increase. In an effort to find more cost-effective construction techniques, we retained a consultant to advise us on the feasibility of using "tilt-up" construction for building laboratories. This method of construction employs concrete slab on grade, with concrete walls formed and tilted into place at the construction site. Thereafter, conventional roofs are supported by laminated wooden beams and steel columns. These structures are semimodular, relatively low in cost, and widely used in the electronics and light manufacturing industries. Most such buildings are turn-key projects. The results of our study were extremely encouraging and we believe that a completely equipped laboratory can be built for \$70 ft², rather than the current figure of >\$100 ft². We have changed the design of the Fusion Target Development Facility line item project to incorporate this concept and are confident that this widely used and cost-effective method of construction will be successful at LLL.

New Facilities Completed in 1979

Additions to Office Trailer Complex. The fourth and final wing of each complex (Trailers

Fig. 1-6. Laser Program facilities at L.L.L. Facilities currently in use, under construction, and proposed are shown as indicated.

3724, 3725, and 3726) was completed by the end of the year. Each wing can house approximately 25 people. The additional space will provide some temporary relief from the crowded conditions arising from the increase in both L.L.L. staff and contract engineers and designers.

Portable Buildings. A new 1080-ft² conference room was built to provide an uncluttered meeting area for 20 to 30 people. The building contains a main conference room, lobby area, and toilet facilities. Initial reaction to the finished project is good and the room is heavily used. Growth in the AIS Program necessitated the purchase of two 2160-ft² buildings to house mechanical technicians, contract designers, and a copper-vapor laser tube in-

spection area. In addition to the new facilities, two existing trailer units were refurbished and brought up to Laser Program standards for acceptable office and technician space.

Continuing Projects and Significant Accomplishments

Nova. Construction of the Nova laboratory building began in May, and the office building was started in October. (Figure 1-7 shows the layout of the laboratory and the relationship of the new office

Fig. 1-7. The Nova laser fusion facility. The building on the right houses the Nova laser. On the left is the office wing added to the existing Building 381. (Both facilities are currently under construction.)

Fig. 1-8. A model of the Mars building and electron-beam experiments.

building to Building 381, the current Laser Program office complex.) By the end of 1979, the laboratory building was 16% complete, while the office

building was less than 1% complete. Completion of the two buildings is projected for the third quarter of calendar year 1981.

Mars (Bldg. 175). Construction of the Mars building began in September 1979 and will end in

Fig. 1-9. An exterior view of the proposed Fusion Target Development Facility. This facility is expected to be complete in mid-1981.

February 1980. The building has increased in size from 4000 to 4400 ft². Design of the structure has been optimized for the Mars electron-beam experiment. (Fig. 1-8 shows a model of the building and the experiment.) Overall cost of the building has also increased to \$475 000 from \$440 000. Activation work will begin in March and will be completed by August 1980.

Fusion Target Development Facility (FTDF).

The FY 1981 line item to provide permanent laboratory space for target-fabrication laboratories has been changed from a 27 700-ft² addition to Building 391 to a 52 000-ft² building located northwest of Building 391. Total project cost is \$7.6 million, and construction will be phased to ensure early occupancy. We have received \$1.0 million in FY 1980 and plan to construct the building shell by October 1980, with all construction complete by March 1981. Activation of the building is scheduled to be completed in January 1982. Adhering to this rapid schedule is possible only through turn-key construction, using tilt-up techniques. (Figure 1-9 shows the exterior of the facility.) Construction of the project via this approach, rather than conventional methods, allows us to use the building one year earlier than planned. This in turn has enabled us to cancel a proposed 20 000-ft² trailer complex that would have housed target-fabrication laboratories. By not building the trailer complex, we have saved at least \$500 000 in utility development, rental fees, and laboratory activation.

Neptune. A new laser/electro-optical laboratory will be built. This \$750 000 project has been approved and funded and is now in the criteria-development stage. The present design is for a 6000-ft² structure that will house various lasers, optical

benches, and associated controls and data-acquisition equipment. Projected completion date for the new facility is July 1981.

Building 174 VAX Computer Installation. One of the VAX computer systems for the Nova project was purchased and installed in Building 174. This installation required extensive electrical and mechanical modifications to the building. The computer is located in the old Cyclops laser area and is now being used for Nova software development.

Overall Site Improvements. New landscaping near Building 177, increased bike-path lighting, and a new parking lot near Trailer 3724 highlight improvements in the area. New landscaping and path-lighting projects that will further improve the appearance of our facilities are in the planning stage and should be completed during 1980.

Future Projects

During 1980, facilities issues to be addressed include the following:

- Solving the problems of material storage for the Nova laser.
- Providing continued support for the Argus 2w experiments.
- Upgrading the technician areas in Shiva.
- Supporting the Nova prototyping in Buildings 174 and 611.
- Obtaining more office space to accommodate program growth.

In addition, continuing growth of the AIS Program will lead to a continuing requirement for

Fig. 1-10. A proposed facility for the Advanced Isotope Separation Program. This building, proposed for FY 1981, will provide 155 000 ft² for laboratory and office space.

new laboratory space. We have identified \$650 000 of General Plant funds for the design and construction of a new laboratory building during 1980 and 1981. This building will house RGH laser experiments and component-development laboratories. A tentative location south of Building 175 has been selected. The permanent facility for the AIS Program, the Advanced Isotope Separation Facility (AISF), is a proposed FY 1981 line item. If the project is approved, we will construct a 155 000-ft² office and laboratory complex to the east of the Nova

office building. Figure 1-10 shows the planned facility.

The next several years will witness considerable activity on behalf of program facilities. Construction and activation of the Nova office and laboratory buildings, and of the FTD and AIS facilities will constitute significant challenges to the program. Our overall goal remains transition from our remaining temporary or obsolete facilities to permanent laboratories and office buildings that meet the operational needs of the program.

Solid-State Laser Systems and Technology 2

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Solid-State Laser Systems and Technology 2

Introduction

The solid-state laser program is responsible for understanding, constructing, and operating solid-state lasers suitable for use in fusion research and development. To fulfill this responsibility, we have organized the program into four major groups:

- Operations Group.
- Nova Project.
- Research and Development Group.
- Basic Research Group.

The Operations Group manages the Argus and Shiva laser systems; the Nova Project, as the name implies, is responsible for developing and constructing the Nova laser facility; the Research and Development Group is responsible for developing prototypal Nova components, for general laser-materials development, and for improvements to operating lasers; and the Basic Research Group is responsible for long-range basic studies that are of interest to the laser community.

In 1979, the two most important goals of the solid-state laser program were to support the Shiva high-density target campaign and to freeze the design of Nova. The Shiva operational crew, by achieving a test rate of two completely diagnosed experiments per shot day since early 1979, succeeded in compressing deuterium-tritium (D-T) to approximately 100 times its normal liquid density. The Nova Project received a final review by the Under Secretary of the Department of Energy (DOE) in April 1979; subsequently, we were directed to proceed with the construction of Phase I, which includes the buildings and the first 10 beams of the Nova laser. In September 1979, we finished a sophisticated 20-beam laser design that fits within the Nova budget, that meets the design criteria of 200- to 300-TW short-pulse operations and 200- to 300-kJ long-pulse operations, and that also meets our goal of >100-kJ long-pulse operations with the 10 beams of Phase I.

Our Operations Group staff continued their activities in preparing and operating the Argus and Shiva lasers for fusion experiments and in improving and maintaining these lasers and their target-system hardware. The Argus laser team redesigned several spatial filters to reduce the damage sensitivity of the lenses, and they replaced the prototypal actively mode-locked oscillator with a newly engineered unit. They also added a more reliable planar-triode switchout system.

In a major policy decision, Argus was dedicated to obtaining plasma physics data at the harmonic frequencies of the Nd:glass laser. During initial testing, we achieved a 70% conversion of the primary Nd wavelength ($1.064\ \mu\text{m}$) to the second-harmonic (2ω) wavelength ($0.532\ \mu\text{m}$) by using an 80-mm-diam beam and a 100-mm-diam doubling crystal. Experiments at the third-harmonic (3ω) wavelength, using a 100-mm-diam beam, are planned for late 1980, and harmonics experiments are planned for 1981 that will use the full 280-mm output aperture of Argus.

In late 1978, Shiva was brought to operational maturity, and it is now operating routinely as a target irradiation facility with a program of coordinated experiments, scheduled maintenance time, and planned inventories. As mentioned above, Shiva, since early 1979, has been operated at a level of two fully diagnosed target shots each scheduled shot day.

The Shiva laser team installed an output spatial filter to improve the relaying, thereby raising the peak power to 30 TW and the maximum energy capability to 15 kJ. The team also created a video-computer link to automate alignment of the 120 spatial-filter pinholes, thus saving over an hour per day of system setup time. The Shiva system continues to be dedicated to achieving higher-density implosions (i.e., densities greater than 100 times normal liquid density of D-T).

Construction on the Nova project began in 1979. Ground breaking took place on May 14, after DOE recommended immediate construction of Nova Phase I, and provisions have been made to implement Nova Phase II when funding becomes available.

The original Nova baseline, with 40 beams through 500-mm apertures, was based on 1977-1978 optical manufacturing capabilities and was optimized for short-pulse operation (≥ 1 ns). Since the baseline was first designed, however, significant progress has been made in materials and component research, and much related experience has been gained from Shiva operations. Among recent developments are new types of optical coatings that can sustain more than twice the fluence of previous state-of-the-art commercial thin-film coatings without damage.

By mid-1979, it had become clear that larger-diameter beams with longer glass paths were possible and that, for the Nova design criteria, the operating costs of a 20-beam laser had become more favorable than those of a 40-beam laser. Hence, in September 1979, we reoptimized the Nova laser and produced an exceptionally versatile laser design capable of approaching 300 TW at 100 ps and 300 kJ in 3 ns. The important technical features of the current Nova baseline are discussed in detail in a later subsection.

Our research and development program and our basic research program have identified several areas of activity where major efforts will produce maximum benefit: surface damage, glass/crystal physics, harmonic conversion, pulse-power development, and propagation physics. Examples of important recent developments are the use of phase-separated glass to triple or quadruple the damage threshold of the surfaces; the detailed measurement and modeling of saturation fluences in glass, which have made

Fig. 2-1

fluorophosphate glass an attractive candidate as a long-pulse driver; the experiments that achieved 70% harmonic conversion on Argus; and the analysis supporting the harmonic conversion of Nova that would operate at > 50 kJ (Phase I) or > 120 kJ (Phase II) for small additional construction costs.

Several other important concepts were explored in 1979. Energy extraction from the compensated pulsed alternator was demonstrated at the University of Texas; propagation modeling with MALAPROP, including nonlinear self-focusing, optical noise, and local saturation, has convinced us that operation of a two-piece disk in the 460-mm Nova output amplifier is feasible; the glass structure at the laser ion site was successfully simulated by using Monte Carlo methods; and the usefulness of photoacoustics for detecting very weak absorption in solids and thin films and for investigating laser-induced damage processes has been demonstrated.

The above technologies, along with experience gained from the operation of Shiva and the design of Nova, have given us confidence that megajoule-class lasers are feasible. Figure 2-1 shows the cumulative effective apertures of glass lasers as we now understand them. The area of a single Nova beam is slightly smaller than the cumulative beam area of Shiva; Nova achieves Shiva-level performances by transmitting a higher fluence level per beam. As may be seen, a megajoule laser is not that much larger than Nova in cumulative area (based on 15-ns damage values at 1.064 μm); consequently, the experience and technology developed for Nova will also be applicable to any megajoule laser (gas or solid).

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Argus and Shiva Laser Facility Operations

Overview

The primary responsibility of the Operations Group is to provide for the daily operation of the Argus and Shiva facilities. This includes the ongoing performance of target experiments as well as the maintenance and upgrading of facilities. Presently, the Operations Group employs a staff of 90 people, with diverse training and educational backgrounds, to operate and maintain the Argus and Shiva systems on a two-shift basis. Approximately one-half of the staff are full-time LLL employees; the remaining members are provided by private industry. The Bendix Field Engineering Corporation and Digital Equipment Corporation provide on-line technical support in the operation of the facilities. Off-line maintenance of oscilloscopes and transient digitizers is provided on site under contract with Tektronix. Additional technician and drafting support required for short-term projects is provided through contract personnel.

During the first three quarters of 1979, Argus was used as a 1.064- μm target irradiation facility

and performed very reliably. During the last quarter, modifications were completed for experiments at harmonics of the fundamental frequency. By year's end, both crystal conversion efficiency and target irradiation experiments were conducted at the second harmonic (0.532 μm).

The most significant accomplishment of the year was the maturing of Shiva into a reliable target irradiation facility; two fully diagnosed target shots per two-shift day are now routinely conducted. The various upgrades and system improvements that have contributed to Shiva's success are discussed in the sections which follow.

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Argus

Operations Summary. At the present time, implosion experiments are conducted on Shiva while Argus has been devoted to target physics experiments. The major experiments conducted on Argus at 1.064 μm during the first nine months of 1979 were

- Investigation of physics issues relating to performance of complex targets.

Fig. 2-2. Argus focusable energy as a function of the 25-mm drive energy. Spread of the data indicates the reliability and stability of Argus system performance.

Fig. 2-3. Photograph of the new 85- to 200-mm spatial filter containing an uncoated positive meniscus input lens with an 85-mm aperture and an antireflection-coated output lens with a 200-mm aperture.

- Brillouin and Raman scattering studies.
- Transport inhibition.
- X-ray backlighting characterization.

During the last quarter of the year, we conducted conversion-efficiency tests of frequency dou-

bling and experiments on target physics at 2ω ($0.532 \mu\text{m}$). Initial data from our experiments emphasize the importance of crystal alignment. In all, 157 target shots were performed on Argus during 1979. Of these, 126 were performed with $1.064\text{-}\mu\text{m}$ irradiation and the remaining 31 were per-

Fig. 2-4. Photograph of the new portable vacuum system which permits fast pump-down of spatial filters in event of beam-induced lens damage.

formed with $0.532\text{-}\mu\text{m}$ light. An additional 157 shots were used primarily for 2ω setup and conversion efficiency measurements.

See Fig. 2-2 for a plot of the laser's output energy vs the energy exiting the 25-mm aperture rods. This figure illustrates the reliability and stability of Argus system performance.

System Improvements. During early summer, we upgraded Argus to enhance operational efficiency by making the following system improvements (see Figs. 2-3 to 2-9):

- Installed a new oscillator and single pulse device.
- Installed a new Pockels cell driver (see section on "Fast Pulse Development").
- Improved the 85-mm aperture beam diagnostic station.
- Improved the 85- to 200-mm aperture spatial filters.
- Designed, built, and used a new portable vacuum station for the spatial filters.
- Improved water coolers for the rod amplifier.
- Designed and procured 280-mm f/1 lenses and lens positioners.
- Implemented a DEC 11/34 computer and Shiva-compatible software for target diagnostics (see section on "Target Diagnostics - Upgrades").

Beam diagnostics (energy and beam photography) are obtained at a station preceding the third 85-mm aperture amplifier in each arm of Argus. Prior to June 1979, beam photography was of little value for diagnostic purposes because of interference fringes introduced by reflections from the imperfect antireflection-coated surfaces of the beam

Fig. 2-5. Photograph of the 280-mm $f/1$ lens positioner.

splitter. This problem was remedied by installing new, 2% reflecting splitters oriented at Brewster's angle. To obtain photographs on the existing tables, we changed the sense of rotation of two Faraday rotators, the orientation of one polarizer, and the orientation of one disk amplifier. These changes, in turn, altered the beam position (height as well as north-south location). To accommodate this change, we installed a pair of mirrors following the

25-mm amplification stage to adjust height, pointing, and centering of the beam.

In June one-piece 85- to 200-mm aperture spatial filters were installed to replace the existing two-piece, three-lens spatial filters. The new spatial filter contains an uncoated, positive meniscus input lens with an 85-mm aperture and an antireflection-coated output lens with a 200-mm aperture. See Fig. 2-3 for an illustration of the new spatial filter. The input lens is the most damage-prone element in the chain; leaving it uncoated raises the damage

Fig. 2-6. Schematic of the frequency-doubling addition to Argus showing the three-mirror system which diagnoses the incident $1.064\text{-}\mu\text{m}$ beam and directs it into the frequency-doubling leg.

threshold. Following this installation, certain optical components preceding the filter had to be repositioned to protect them from light back-reflected and focused by the uncoated input lens.

A new portable vacuum system (see Fig. 2-4) was added for faster pump-down of the spatial filters in the event a lens had to be replaced because of beam-induced damage. This system pumps the largest spatial filters to 10^{-4} Torr in less than an hour. It is semi-automatic and consists of a Leybold-Heuruss 14.5 cfm roughing pump, a

5000 lps turbo molecular pump, and a 2500 lps cryogenic pump.

During reassembly of the system in June, we noticed that the collimation of the beam was fluctuating ($\pm$ a few mrad at the 25-mm rod amplifier positions). This problem was traced to the water chillers which were cycling the temperature of the rod amplifiers and inducing "lensing" in the rods, thereby influencing the beam collimation. Changing

Fig. 2-7. Photograph of the Argus target room with the 2ω addition in place.

the chillers corrected the problem and minimized beam-divergence fluctuations.

Lenses were purchased and lens positioners built to operate Argus with $f/1$ optics at 280 mm (see Fig. 2-5). The weight of the lens positioners (≈ 150 lbs) necessitated the construction of fixtures specially designed for safe installation. These lenses and positioners are ready when Argus resumes 280-mm operation.

2ω Modifications. Several laboratories have produced efficient conversion of 1.064- μm laser beams to the second, third, and fourth harmonics.^{1,2} The following features motivated us to use Argus for studies of target interactions with large-aperture (≥ 50 cm²) frequency-doubled and -tripled beams:

- High-conversion efficiency.
- Increased target absorption ($\leq 80\%$).³

- Decreased high-energy electron production at shorter wavelengths.

The target-interaction studies are divided into two phases:

- Phase I: Small-aperture (80-mm diam beam), single-arm 2ω and 3ω target-irradiation experiments.

- Phase II: Full-aperture (280-mm diam beam), two-arm 2ω and 3ω target-irradiation experiments.

The first phase was limited by components on hand or which could be purchased in a short period of time (< 6 months). The second phase will include a careful study of doubling and tripling requirements to optimize system performance. Complete beam diagnostics are included in both phases.

The transport optics for the 2ω target-irradiating pulse, including the three-mirror system that diagnoses the incident 1.064- μm beam and directs it into the frequency doubling leg, are shown in Fig. 2-6. Figure 2-7 is a photograph of the Phase-

Fig. 2-8. Second-harmonic beam diagnostics: (a) incident beam diagnostics, (b) reflected beam diagnostics, (c) transmitted beam diagnostics.

1 Argus 2ω addition on the south arm. The 280-mm, $1.064\text{-}\mu\text{m}$ beam is demagnified to 80 mm and passed through the doubling crystal (100-mm diam, Type II, KDP²). The unconverted $1.064\text{-}\mu\text{m}$ light is rejected from the beam by a dichroic mirror (99.7% reflective at $1.064\text{ }\mu\text{m}$, 95% transmission at $0.532\text{ }\mu\text{m}$). The beam is then directed by mirrors 2, 3, and 4 (Fig. 2-6) to the target chamber. (A half-wave plate is located between mirrors 3 and 4 to rotate the beam polarization to match that of the $1.064\text{-}\mu\text{m}$ beam of earlier target experiments; 104°

clockwise with respect to the vertical.) The 2ω beam is focused onto a target by a 175-mm focal-length, 95-mm clear-aperture ($f/2.2$) lens. A debris shield following the focusing lens protects the lens from target debris.

The 2ω beam diagnostics consist of incident beam diagnostics (IBD), reflected beam diagnostics (RBD), and transmitted beam diagnostics (TBD).

- IBD includes: calorimetry, near- and far-field photography, and an alignment TV (see Fig. 2-8a).

- RBD includes: calorimetry, far-field photography, a streak camera, and an alignment TV (see Fig. 2-8b).

- TBD includes calorimetry, far-field photography, and an alignment TV (see Fig. 2-8c). The temporal characteristics of the incident 2ω pulse are measured by directing the leakage through mirror 2 (see Fig. 2-6) to the RBD streak camera via fiber optics. The main use of the TBD is in target alignment and focal-spot size selection.

A $1.064\text{-}\mu\text{m}$ cw laser, a frequency-doubled cw YAG laser, and low-intensity system shots are used to align the optical train and targets for 2ω experiments. The $1.064\text{-}\mu\text{m}$ cw beam aligns the 280- to 80-mm demagnifying telescope and the 2ω pointing and centering mirrors (mirrors 2, 3 and 4 in Fig. 2-6). In this procedure, the dichroic mirror used to reject unwanted $1.064\text{-}\mu\text{m}$ light during target shots is replaced by a transmitting optical element of the same thickness and tilt angle as the dichroic mirror.

The frequency-doubled cw YAG laser provides the alignment beam for the IBD, RBD and TBD beam diagnostics and the target chamber lenses. The beam path, including the removable mirror pair (a-b) used to direct the $0.532\text{-}\mu\text{m}$ alignment beam into main beam transport optics, is shown in Fig. 2-9.

In practice, we found it necessary to do final collimation of the diagnostic telescopes and adjustment of the target chamber spot size with the 2ω pulsed beam. This additional step is necessary because the collimation of the 2ω cw laser fluctuates with time and, thus, does not insure that the collimation of the 2ω cw and pulsed beams are the same.

The alignment of the doubling crystal is done with low-intensity pulses using a method that samples a range of angles on each shot.⁴

High conversion efficiencies (in excess of 70%) to the second harmonic were obtained only after careful and tedious alignment of the crystal. The target experiments being conducted in Phase I do not require these high conversion efficiencies (50% is quite acceptable). This lower conversion efficiency is easy to obtain and maintain over an ex-

Fig. 2-9. Schematic of the $0.532\text{-}\mu\text{m}$ cw alignment set-up showing the removable mirror pair (a-b) that directs the alignment beam into main beam transport optics.

Fig. 2-10. Second-harmonic conversion efficiency. The solid curves are theoretical predictions using phase mismatch angles interior to the crystal.

Fig. 2-11. Intensity profile of the focused 2ω beam at $500\text{ }\mu\text{m}$ and $40\text{ }\mu\text{m}$. (a) Enlarged photograph of the focused 2ω beam at $500\text{-}\mu\text{m}$ diameter. (b) Line scan of a focused beam at $500\text{-}\mu\text{m}$ diameter. (c) Enlarged photograph of the focused 2ω beam at $40\text{-}\mu\text{m}$ diameter. (d) Line scan of a focused beam at $40\text{-}\mu\text{m}$ diameter.

tended period of time. (After the crystal is aligned, no realignment is necessary for several days.) The conversion efficiencies measured on the south arm using a Type II KDP are shown in Fig. 2-10.

The energy we have been able to place on target at 2ω (Fig. 2-11) is limited by optical damage of the

dichroic mirror used to reject unconverted $1.064\text{-}\mu\text{m}$ light. Damage has occurred for a single shot at $2\text{ J}\cdot\text{cm}^{-2}$, $3\text{ GW}\cdot\text{cm}^{-2}$, (combined $1.064\text{-}\mu\text{m}$ and $0.532\text{-}\mu\text{m}$ energy); at lower energy densities a slow degradation of the coating has been observed. Thus,

reliable beam diagnostics have been performed only at the lower power densities of 2 GW/cm^2 . Near-field photography indicates that the 2ω beam modulation is greater than that of the incident $1.054\text{-}\mu\text{m}$ beam. However, theoretical considerations indicate that at higher conversion efficiencies and power densities the 2ω beam modulations should be less severe.

The focused 2ω beam has been photographed using the multiple image camera in the IBD arrangement. Figure 2-11 compares the intensity profile of a $500\text{-}\mu\text{m}$ focused spot with a $40\text{-}\mu\text{m}$ focused spot. The beam modulation of the smaller spot is markedly worse than that of the larger spot. The increased beam modulation attributable to the poor quality of the target focusing lens will be corrected in Phase II.

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Shiva

Operations Summary. During 1979, we fired 275 shots with the Shiva laser system. These included 228 target irradiation experiments and 47 laser characterization and performance tests. Laser output energy was as high as 9.7 kJ for 0.6- to 2.0-ns

Fig. 2-12. A histogram showing the number of Shiva shots performed each month from January 1978 through December 1979. Laser system shots are those in which one or more arms of the laser are fired for beam characterization or propagation studies. Target shots are those in which beams are aligned to a target in the target chamber and target diagnostic data are collected.

pulse durations; output power was as high as 28 TW for shorter 100- to 200-ps pulse durations. Figure 2-12 shows the number of shots performed each month from January 1978 through December of 1979.

We began the year by continuing experiments started in late 1978 to achieve compressions of 100-times normal liquid density in fusion targets.⁵ Most experiments in this series done during January, February, and March required laser energies of 7.0 to 8.0 kJ at a pulse duration of 600 ps. Fuel density of approximately 100-times liquid density was achieved in the best performing targets irradiated during this series.

In April and May target shots were suspended for installation of the f/14 output spatial filters.⁶ Following this installation, we determined the

characteristics of system performance with 100-ps pulses. We measured a substantial decrease in self-focusing induced-beam modulation on high-power beams at the target chamber.

In June we resumed target experiments with high-power, short-duration pulses. A record yield of 3.3×10^{10} neutrons was obtained from a 23-TW target shot in this series. Another series of shots followed in July and early August to measure the fuel density achievable with 200- to 400-ps duration pulses on intermediate density design targets. Densities of up to 10-times normal liquid density were measured.

From mid-August to mid-October we performed a series of experiments designed to gain further understanding of the operation of high-density targets with 600-ps pulses. During October we also

Fig. 2-13. Peak power output from Shiva vs pulse duration. Limits shown are those imposed to ensure a long lifetime for thin-film coatings on beam-line optical components.

Fig. 2-14. Energy output from Shiva vs pulse duration. The flatness of the curves above 0.6 ns results from the very slow change in damage threshold of thin-film coatings with pulse duration.

began routinely aligning the spatial-filter pinholes with the computer-controlled automatic alignment system.

We finished the year with a series of experiments to study the scaling of target response with pulse duration. Most experiments in this series required 5.0 to 8.0 kJ from Shiva in 2-ns pulses. Performance of this series required reconfiguring the spatial filter pinholes to prevent closure during the 2-ns pulse.

In order to devote as much time as possible to target experiments, system maintenance during the year was integrated with target experiments. We monitored the performance of each subsystem and took corrective measures when performance fell below established criteria. System maintenance, in-

cluding monitoring, preventive, and corrective activities, required a level of effort comparable to target experiments.

System Performance. As noted in the preceding section, we operated Shiva with a variety of pulse lengths in the range from 100 ps to 2.0 ns, FWHM. Figures 2-13 and 2-14 summarize the laser power and energy delivered to the target for the full-system shots fired through December of 1979. The large range of energies and powers at each pulse duration result from the values requested for individual experiments and not from scatter in the laser output. Full-system energy predictability is within $\pm 5\%$ and pulse width repeatability is within $\pm 5\%$. The routine operating limits set to prevent optical damage to thin-film coatings and to insure a long lifetime for the optical components are shown in Figs. 2-13 and 2-14.⁷ Operation below these limits has resulted in

Fig. 2-15. A schematic illustration of a Shiva laser chain. Labels on each amplifier give the nominal clear aperture. The number in parenthesis after each spatial filter gives the magnification of the beam diameter by that spatial filter.

virtually no optical damage induced from the incident laser beam. Optical damage which did occur in shots below these limits was caused mainly by unanticipated back reflections or focused reflections from inadvertently misaligned components. Also shown in the figures are maximum operating limits for selected cases in which it was decided to take a higher damage risk to obtain more energy or power on target. We have conducted a few experiments of this type at the shorter pulse durations.

To set up the system for target shots, we fire the system through the rod amplifiers and measure the energy output from the beta-rod amplifier in each arm. See Fig. 2-15 for a schematic illustration of the chain. Rod amplifier output energy is adjusted with

the gain control in the preamplifier to give the desired input energy to the disk amplifiers in each chain. Figure 2-16 shows the measured average chain output vs the average beta-rod amplifier output for the system shots fired since the installation of the f/14 output spatial filters. The solid line in the figure is from a system modeling calculation using a saturation flux of 4.0 J/cm² and neglecting B-induced (beam breakup integral) losses.⁸ The three high-energy points are maximum single-arm energies obtained from selected beam lines at 600-ps pulse duration.

Fig. 2-16. Average output energy of Shiva beams is shown vs the output energy from the beta-rod amplifier in each arm. The solid curve is the result of system simulation calculations. The three high-energy points are single-chain maximum energy outputs at 600-ps pulse duration.

Table 2-1. Intensity modulation on Shiva beams at input to the target chamber.

Beam No.	Energy (J)	Power (TW)	Peak/Av modulation
1	145	0.24	1.28
2	319	0.53	1.20
3	377	0.62	1.22
4	292	0.48	1.36
5	288	0.48	1.33
6	332	0.55	1.28
7	312	0.52	1.31
8	431	0.71	1.22
9	546	0.90	1.18
10	412	0.68	1.14
11	328	0.50	1.36
12	545	0.84	1.16
13	308	0.47	1.35
14	313	0.48	1.40
15	296	0.45	1.60
16	313	0.48	1.27
17	296	0.45	1.34
18	311	0.48	1.24
19	310	0.48	1.35
20	293	0.45	1.27
Av			1.29 ± 0.10

Near-field beam quality of Shiva output beams has improved as a result of the $f/14$ spatial-filter installation and the continual component maintenance and alignment monitoring. We periodically take near-field photographs of the beams at the input to the target chamber at low power and at operating power to assess the beam intensity modulation⁹ and alignment. Table 2-1 summarizes the beam modulation of Shiva's twenty beams. These were determined from such a set of near-field photographs with output power of most arms between 0.45 and 0.90 TW. The average spatial modulation of the 20 beams was 1.29 with a standard deviation of 0.10. Figure 2-17 shows the data from beam 9 (one of the best beams) at an output power of 0.90 TW.

The beam modulation increases substantially as the power is increased above 1.0 TW. Installation of the $f/14$ output spatial filters, which complete the image relay to the target chamber and provide additional filtering, has significantly reduced this effect. The input lens is uncoated to decrease the damage threat at long-pulse length and high-beam fluences. The pinhole filtering properties reduce the beam modulation of the output beam to a level permitting antireflective coating of the output lens without damage. An output lens positioner (i.e., beam collimation, lens centering, and lens tilt) allowed the filters to be assembled and aligned in situ on the target spaceframe. The alignment experience gained during this installation is important because similar techniques are proposed for spatial filter alignment on the Nova laser. Figure 2-18 reproduces a figure taken from last year's annual report showing the high intensity spikes present in beam 6 at 1.5 TW output before installation of the output spatial filters. Also shown in Fig. 2-18 are similar data for beam 6 taken at 1.5 TW output after installation of the output spatial filters. The intense spikes are no longer present and the peak-to-average beam modulation has been reduced from a ratio of 12-to-16:1 to a ratio of 3-to-4:1.

One series of experiments required operation of the system at 2-ns pulse duration. We generated these pulses by delaying and coherently adding two 1-ns pulses in the preamp section. To minimize pulse distortion from the bleachable dye cell, this "pulse stacking" followed the ASE dye cell. To avoid spatial-filter pinhole closure with these long pulses, we modified the spatial-filter staging

Fig. 2-17. Near-field photograph of Shiva beam 9 at 0.9 TW output. The relative intensity plot was generated by computer reduction of the densitometer scan along the diameter marked on the photograph.

Table 2-2. Spatial filter pinhole sizes used on Shiva at various pulse durations.

Spatial filter	f/No.	Pinhole diameters (μm)		
		100- to 400-ps operation	0.6- to 1.0-ns operation	2.0-ns operation
α rod - β rod	50	1500	1500	1500
α rod - β disk	10	300	300	400
β - β	10	300	600	None ^a
β - γ	10	300	600	600
γ - δ	10	400	600	None ^a
δ - δ	14	800	800	1500

^aPinholes were removed for long pulse operation.

slightly. The beta-disk to beta-disk and gamma-disk to delta-disk spatial-filter pinholes were removed and the diameter of the pinholes in the delta-delta (output) spatial filters was increased from 0.8 mm to 1.5 mm. We found that a 1-mm-diam pinhole in the gamma-delta spatial filter would remain open for the 2-ns pulse, but most shots in the series were done with no pinholes in this spatial filter. Table 2-2 shows the pinhole sizes used for 100- to 400-ps, 0.6- to 1.0-ns, and 2-ns pulse durations. Operation with the 2-ns pinhole configuration was possible because

of the low total chain-B value for 8-kJ outputs at this pulse duration.

Maintenance Procedures. To perform the primary task of ICF target irradiations efficiently, the Shiva operating crew must perform a number of secondary tasks. These include:

- Implementing system modifications to meet changing experimental requirements.
- Maintaining current timing and calibration for all diagnostics.
- Implementing system improvements to increase capabilities.
- Maintaining the system operation at a high performance level.

In order to maximize the time available for experiments, we integrate as many of these secondary activities as possible into the shot schedule. The shot schedule is interrupted only for major modifications or maintenance tasks.

To aid maintenance of the laser and diagnostics systems, the operations crew follows a regular sequence of laser performance monitoring. Near-field beam photographs are taken regularly at several locations in each chain to monitor dirt.

Fig. 2-18. Shiva beam quality before and after $f/14$ spatial filter installation. Shown are near-field photographs and densitometer scans taken of beam 6 at an output power of 1.5 TW.

optical-component damage, and beam alignment. The power-conditioning crew monitors the correct firing of all flashlamps in the system at least once per week with the waveform analysis data system (WADS). The laser-diagnostics crew monitors beam energies at several locations in each chain to track amplifier chain and component gains. If these monitoring techniques show a sub-standard condition, maintenance is concentrated to correct the difficulty. This strategy has enabled us to maintain

good beam quality and beam-energy balance while dedicating most of system operating time to performing the shot schedule and implementing system improvements.

To operate the facility in this way requires that adequate manpower always be available to carry out the maintenance and upgrading tasks. During the day shift a senior technician is assigned the responsibility of coordinating the maintenance activities with the shot schedule. Operations, clean-room, and engineering-support technicians are assigned to carry out these tasks, as the requirements arise. A level of effort comparable to that

needed to execute the shot schedule is required to maintain the system in good working condition.

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Component Maintenance Summary. During the past several years of laser operation, the value of having optical surfaces that are clean, damage-free, and void of diffraction-noise sources has become well established. We have taken a systemized approach to ensure operation of Shiva¹⁰ within acceptable levels of noise-induced beam modulation.

● All beam-line components were designed and assembled to minimize contamination. We

assemble and rework most laser components in a class-100 clean room.^{10,11}

● Optical surfaces were polished or coated to provide high-damage thresholds consistent with the present state of the art.

● The operating laser is monitored closely to detect dirt and damage on optics so that corrective action may be taken promptly before the resulting noise produces additional system degradation.

● The laser bays are maintained as class-1000 clean rooms to minimize the contamination during system operation.

Table 2-3 shows the damage-level criteria we established for cleanliness of the Shiva laser system. This criteria requires a total-beam obscuration of less than $5 \times 10^{-3}\%$ of the surface for chain optics and less than 0.5% of the surface for target-room turning mirrors and focus lenses. The beam line is monitored by taking near-field photographs frequently. These are reviewed to determine if modulation produced in an assembly or component exceeds permissible levels. During the past year we identified and eliminated several causes of surface damage that resulted in such scattering amplitudes from surfaces. As a result of our experiences, we have made a number of mechanical modifications to correct the causes of mechanical misalignment that can result in damage to optics.

Table 2-4 gives a summary of the Shiva optical component replacement history as a result of optical damage. A significant cause of rod-amplifier

Table 2-3. Maximum acceptable damage site or particle concentrations on damaged optical components. Criteria are based on achieving an average beam obscuration of 5×10^{-4} /surface ($5 \times 10^{-3}\%$ /surface) for chain optics and a maximum obscuration of 5×10^{-3} /surface (0.5%/surface) for target optics.

	Alpha rod	Beta rod	Beta lens	Beta disk	Gamma lens	Gamma disk	Delta lens	Delta disk	20-cm Focal optics
Maximum counts/cm ² > 10 μ m	—	—	—	—	—	0.5225	—	—	1.44
Maximum counts/cm ² > 100 μ m	—	—	—	—	—	0.1854	—	—	0.51
Maximum counts/surface > 10 μ m	3	10	40	90	92	209	164	383	452
—or—									
Maximum counts/surface > 100 μ m	1	3	15	32	33	73	58	135	160
—and—									
Counts/surface > 1 mm	0	0	0	0	0	0	0	0	57
Counts/surface > 5 mm	0	0	0	0	0	0	0	0	0

Fig. 2-20. Concentration of damage sites as a function of the number of amplifier firings for the Shiva laser system. The data were collected during routine maintenance of the system over the past two years. They represent only those amplifiers damaged enough to warrant rebuilding. The 1% line represents the damage level that would cause a 1% loss of power if all 1000 disk surfaces were damaged to the same extent.

of substandard operation. The high numbers for the rod amplifiers resulted from the retrofit to correct the design flaw causing the leaking o-ring. Data in Fig. 2-19 show the number of active laser-component overhauls by arm number. The distribution of overhauls by arm is not related to operational procedures or the average energy in a particular arm. Figure 2-20 summarizes the concentration of damage sites on disk amplifier surfaces as a function of amplifier firings. We expect this failure rate to improve as design and operational flaws are identified and corrected.

The damage and replacement rate of optics in the Shiva system is within the original design specifications with the exception of the rod amplifiers. Drawing upon this experience for the Nova design, the reliability of Nova should be better than Shiva.

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Automatic Pinhole Alignment System. During the latter part of 1979, automatic closed-loop spatial-filter pinhole alignment became operational. This required adding a video digitizer interfaced to the alignment system PDP 11/34 computer and writing the software to communicate with the new and existing hardware. The operator controls, with their various options, and a typical automatic pinhole alignment sequence are described below.

The major operator interface for the automatic pinhole program is a plasma touch panel (Fig. 2-21). The touch panel is divided into three sections: beam-line selection, system status, and command controls. The top half contains a map of the beam lines and is used to activate the alignment sequence on a beam or a group of beams. The center section contains displays which indicate the status of a beam line and consists of a command (cm) line and a status (st) line. The first block in the cm line shows the command that is being issued to the beam line. The following blocks show the command being issued to each spatial filter in that beam line. The st line shows the alignment status of the beam line and each of its spatial filter pinholes. The bottom section contains the command process (cp) control line. The cp block on the left controls the entire beam line and the blocks on the right allow command of individual spatial filters. Table 2-6 lists the

Table 2-6. Command options.

	Explanation
BLANK	Clears display
IDLE	Idle operation on a chain
CROSS	Enable for cross-coupling determination
CNTP 1	Align center point 1
CNTP 3	Align center point 3
IBDREF	Enable for IBD pinhole reference determination
FREEZE	Enable for prevention of any motion
CRSHR	Display crosshair on video screen
SUCCESS	Operation successfully completed
GOTO 1	Slew to center point 1
GOTO 2	Slew to center point 2
GOTO 3	Slew to center point 3

Fig. 2-21. PLASMA TOUCH PANEL with the automatic spatial filter alignment page displayed. The operator simply points at the item to be activated, and the block reverses the video (ACTIVE, TRACE) with an audible beep.

commands presently available and a brief explanation of each. The last two lines of this section of the plasma panel provide the additional commands described in Table 2-7.

Other displays aid the operator in using the system. Two color monitors (Fig. 2-22) display the status of the alignment operation and the current position of all the spatial filter pinholes. A black and white monitor near the display panel displays

the analyzed video image from the video digitizer. A Hewlett-Packard (HP) terminal (Fig. 2-23) monitors the program status. If the plasma panel is in the trace mode, the HP terminal displays each executed command in the executive program. The HP terminal also allows us to interface the PDP 11/34 directly for installing or restarting programs.

The 120 spatial filter pinholes (6 in each arm) are aligned automatically using the same procedure as the manual alignment described in previous

reports.^{13,14} This consists of acquiring the best focused spot on a reference as seen on the IBD sensor, back illuminating the pinholes, aligning one pinhole at a time to that reference, and finally verifying the alignment.

To determine the reference for auto-alignment, we set up the IBD using its control panel. We first set the filter levels to obtain proper illumination of the focused beam on the IBD TV monitor, remove the IBD far-field energy pinhole, and insert the IBD reference cross hair. The IBD vidicon lens is slewed

to get the best focused spot and the motor position is declared zero. The best focused spot is moved onto the IBD reference cross hairs using the beam diagnostic routing mirror (BDRM) and the BDRM's motor positions are declared zero. Last, the IBD cross hair is removed and the auto-pinhole program is run in the IBD reference mode. This program stores an x and y coordinate for each beam run.

The system is next set up for back illuminations of the pinholes. First, the cham input alignment (CHIP) sensor is taken out of closed-loop operation because the pinhole illuminating lens is inserted between the CHIP sensor and the CHIP driven gimbal. Next, the pinhole illumination lenses are driven into position in the beam line. The lens increases the beam size in the pinhole plane and decreases the intensity on the IBD vidicon, so the filter level must be readjusted.

We next activate the auto-pinhole program for the desired pinhole position: 1 (large), 3 (small), or 2 (open). The beams to be aligned and the desired pinholes are selected using the touch plasma panel. If all six pinholes in a beam are being aligned, this operation takes about one minute per beam.

To verify the results, we drive the IBD reference cross hairs into the beam and visually check that the cross hair appears centered on the pinhole silhouette. When all of the pinhole silhouettes are aligned to the reference cross hairs, the

Table 2-7. Spatial filter page.

Commands	
The large blank areas allow space for machine replay messages.	
HELP	Will give an explanation of the current command
FILE	Not used
SIMULT	Send no commands to the motors
STATUS	Not used
EXAM	This plus "Touch a Chain" will display this beamline in the status section
ACTIVE	Must be active before you can issue commands
HOLD	Will stop program until released
TRACE	Causes the HP terminal to list each command
MENU	Return to menu
SKIP	Skip the chain that is being processed now
REFRESH	Rewrite the plasma screen

Fig. 2-22. COLOR STATUS MONITORS used to monitor the automatic spatial filter alignment. The left display shows the status of the alignment operation and the right display indicates the current position of the spatial filter pinholes.

Fig. 2-23. HEWLETT PACKARD VIDEO TERMINAL is used to monitor the program status in the trace mode by displaying each executed command. This terminal provides an interface to the alignment PDP 11-34 computer enabling the operator to restart programs.

sometime during the auto-pinhole alignment sequence.

IBD filters are increased, the pinhole illumination lenses removed, and CHIP is put back in closed loop. The focused beams are checked for centering on the IBD cross hair by viewing the IBD vidicon. If the focal spot is judged to be too far from the reference cross hair ($>20\%$ of the pinhole diameter), the pinholes are aligned again. This is a very infrequent occurrence which can usually be traced to movement of the beam diagnostic routing mirror

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Alignment Control Subsystem. The Shiva alignment control subsystem was fully operational at the time the decision was made to develop an automatic pinhole alignment system. Although the control system was not specifically designed to support this task, the flexibility of its distributed computer architecture was well suited to incorporating such a major functional enhancement. To implement automatic pinhole alignment, use of the same sensor employed by laser operators to manually align the pinholes (the IBD vidicon) provides the most reliable, verifiable, and flexible approach.

Our major effort was focused on which types of image analysis techniques could perform sufficient image processing on each sensor "query" to allow extraction of position information, irrespective of substantial fluctuations in image noise, background variations, or contrast while not exceeding the computational capability of the alignment subsystem's single PDP-11/34 minicomputer.

The primary objective of our *design criteria* was to implement a computer-driven automatic alignment system for the 120 pinholes which would reduce both the manpower and time required for alignment as well as improve the consistency of pinhole alignment by eliminating qualitative interpretations of the video images. Design criteria included:

- Analysis of each sensor image must be completed in an average time of less than two seconds using the alignment subsystem's PDP-11/34 computer.
- The image analysis results must be insensitive to variations in contrast, focus, background intensity, image defects, and random noise.
- The image analysis algorithm must be biased so as to minimize the probability of accepting an inadequate image (e.g., a partially illuminated pinhole) as valid (pinhole present and discernible), at the risk of rejecting marginal, yet valid, images.
- Sufficient operator controls and status feedback mechanisms must be made available to allow the operator to monitor and verify correct operation of the system.

The subsystem *architecture and hardware* contains a PDP-11/34 minicomputer which provides high level operator interaction and control functions. It interconnects the alignment subsystem components using Shivanet network links employing fiber optic communication paths to 27 LSI-11

microcomputer control processors. Figure 2-24 illustrates the automatic pinhole alignment subsystem components. Operator commands and subsystem status display are processed directly by the PDP-11/34 minicomputer.

Efforts to implement the automatic pinhole alignment system included minor hardware upgrades to the existing alignment subsystem equipment, plus a substantial software effort to provide the three fundamental functions of automatic control, operator input, and operational status. A Quantex video digitizer with 512×512 resolution was interfaced to the PDP-11/34 to capture and digitize the analog video sensor data. To select which video sensor is to be examined, we implemented a channel selection interface to the Shiva video switching system.

The major *pinhole alignment software* elements developed for the alignment subsystem's PDP-11/34 (Fig. 2-25) included:

- Focused spot analysis: an image processing algorithm designed to reliably determine the location of a focused spot on the image.
- Pinhole analysis: an image processing algorithm which determines the center location of a backlit pinhole as imaged onto the IBD vidicon (appears as soft-focused disk).
- Translation matrix: determines the relationship between the X and Y motion of the motors connected to a given pinhole stage and the distance and direction of travel as imaged on the IBD vidicon by offsetting each pinhole a known amount from a centered position and measuring the resulting displacements in the video image.
- Reference point determination: applies focused spot analysis to determine the reference point for pinhole alignment.
- Pinhole alignment: controls sequencing and alignment operations for the actual pinhole alignment procedure.
- Plasma panel control: accepts operator commands to the pinhole system.
- Color status display: displays status of each pinhole stage.
- Function control: interprets operator commands and dispatches functions to appropriate program sections.
- Video ID control: sends commands to disable the generation of TV network channel numbers

Fig. 2-24. Shiva alignment subsystem.

(the video switching system normally inserts these identifiers into the video image, obscuring part of the display).

- **Video selection:** sends commands to the panel processor which selects the video sensor channel to be fed into the video digitizer.

We employ two different *video analysis* schemes depending on the image being analyzed: focused spot or backlighted pinhole disk. Each algorithm met three criteria:

- **Speed.** With only one video processor in the system, analyses must be performed quickly and have relatively low computational requirements

compared to traditional image processing applications.

- **Contrast/Noise Independence.** Since each of the 20 sensors and illumination levels is different, the algorithm must be independent of wide variations in random noise, beam irregularities, and contrast ratios.

- **Accuracy.** Each algorithm must include checks to verify that the correct image has been analyzed and processed.

A focused spot provides a sufficiently high contrast image so that we are able to use intensity populations and coordinate averaging to determine the location of the center point.

Pinhole analysis presents a more difficult problem. Pinholes are imaged on the IBD vidicons

Fig. 2-25. Software elements in pinhole alignment.

as disks by inserting a beam expanding lens at the input of each laser arm. The images are often poorly focused and show low contrast on a non-uniform background. Variations in the image arise due to occlusions in the beam (damage spots on glass), intensity variations in the illumination laser, and damage in the vidicon itself. Changes in the background intensity often result in large areas which can be more intense than portions of the pinhole itself. A color enhancement of a typical pinhole image (Fig. 2-26) indicates a large background area (green) with intensity equal to portions of the left edge of the pinhole image. Applying the intensity distribution technique for focused spots to such images would yield center-point positions which are substantially biased by these background levels. In Fig. 2-27 we see that a horizontal sample line of this pinhole shows significant differences in intensity at the pinhole edges. High-frequency noise variations are also evident, as are large low-frequency variations within the

Fig. 2-26. Intensity variations in a typical pinhole image.

Fig. 2-27. Horizontal scan of large pinhole.

pinhole itself, due to interference effects on the coherent alignment beam.

For these images we use an edge detection algorithm which eliminates high-frequency noise effects, is insensitive to intensity fluctuations internal to the pinhole, and satisfies the speed requirement. Figure 2-28 illustrates the fundamental concept used in the edge detection algorithm. A "window" wide enough to eliminate high-frequency noise effects but sufficiently narrow to capture low-frequency edge variations samples elements in a vertical or horizontal scan line. The sum of intensities in one half of this window is subtracted from the sum in the other half at each sample location. This yields a difference value with a maximum or minimum as the window passes over an edge. The

Fig. 2-28. Sliding difference window.

Fig. 2-29. Edge detection scan lines.

calculation is performed using a horizontal and vertical sample grid scaled with the expected pinhole diameter to yield a fixed number of scan lines intercepting the pinhole (Fig. 2-29). This adjustment is performed to minimize the time spent processing large pinholes where high-resolution scans would be inappropriate.

A plot of the difference vector, using a typical window width, is shown in Fig. 2-30. High-frequency variations have been reduced and large peaks corresponding to the outside pinhole edges are observed, as well as a substantial peak within the pinhole itself. At this point, a threshold is determined by finding the minimum and maximum difference values. Scans are then executed from each end of the grid line to find the two outermost peaks exceeding a fixed percentage of this threshold. The coordinates of these peaks become the designated

Fig. 2-30. Sliding difference for horizontal scan.

pinhole edges for the given scan line. This procedure ensures that peaks within the pinhole are not observed and thus falsely detected as edges. As part of an integrity check, edges separated by less than 25% of the diameter of the pinhole are rejected to eliminate lines in which no pinhole, or just a small portion of the pinhole, appears.

A scan is also rejected if both edge peaks do not exceed an internally stored threshold, τ . This is one of the most important parameters, as it controls whether the scan operation accepts low intensity background variations as part of a pinhole image. The correct value of τ for a given image varies according to image contrast, edge definition (focus), and the degree of intensity variation within the pinhole itself. If too few or too many lines with seemingly valid edge intercepts are found for a particular pinhole, the value of τ is adjusted downward or upward, and a rescan is performed. This continues for a given image until either a suitable number of intercepts is found or no threshold adjustment is successful.

Newly adjusted values of τ are retained according to chain number. Since contrast for a chain remains constant for each pinhole, the value of τ calculated for the first stage analyzed will in general be correct for succeeding stages, enhancing the speed of operation. Video feedback, including centerpoint, size, and edge intercept information, is presented for each pinhole analyzed (Fig. 2-31).

Pinholes are aligned starting from the earliest stages on all enabled arms simultaneously. The

Fig. 2-31. Annotated pinhole image.

pinhole algorithm benefits in speed from overlapping the analysis of an image on one arm with the slewing of motors on the others.

In summary, the automatic pinhole alignment system has met the technical objectives of speed, accuracy, and verification by utilizing a series of algorithms and analysis techniques designed to minimize computational requirements while maintaining sufficient information content to ensure valid processing of the images.

This is the first use of video sensors as part of an automatic laser alignment system at LLL, and proves the feasibility of the concept. We have demonstrated, in particular, that video images with substantial variations in quality can be processed efficiently and reliably over long periods of operation. This approach will form the basis for all Nova alignment control systems.

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Target Diagnostics

Target diagnostics responsibilities comprise the operation and maintenance of the electronics data acquisition system and the target chamber systems. A description of these systems may be found in previous annual reports.^{15,16}

Table 2-8 summarizes the status of the data of the acquisition system at the end of 1979 and compares it to that at the end of 1978.

Table 2-8. Target diagnostics electronics data acquisition system summary.

Component type	Total number on line	
	1978	1979
CAMAC CRATES	7	11
7912 Transient digitizers	17	28
7903 Oscilloscopes	14	10
7844 Oscilloscopes	0	4
Integrator channels	62	89
Calorimeter channels	48	62

Our activities in 1979 included conducting six target campaigns: 100-times density, high neutron yield, 10-times density, physics study, high density, and 2-ns absorption. The two most significant results were the approximately 100-times liquid density compression of the target fuel and the new world record of 3.3×10^{10} 14 MeV neutrons produced.

Diagnostics Fielded. Table 2-9 summarizes the complement of Shiva target diagnostics existing at the end of 1979. Basically, the implementation of diagnostics for new experiments fell into four measurement categories: density, neutron yield, x-ray spectrum and energy balance.

The radio chemistry diagnostic provides our prime means for assessing compressed fuel density. Neutrons at the 14.1-MeV level activate silicon in the glass microballoon and the target debris is caught on a foil. An automatic system transports this foil out of the target chamber to the detector station where the decay products are counted. (A more complete description of this and other individual diagnostics and results is presented in Sections 5 and 6 of this report, "Diagnostics Technology" and "Laser Fusion Experiments and Analysis.")

Independent diagnostics for determining fuel density include an argon line imaging crystal spectrometer (ALICS) and silicon line imaging crystal spectrometer (SILICS).¹⁷ Here we resolve x-radiation from the compressed hot target in energy and space. A measurement of the compressed volume can then be obtained.

A silver activation detector was installed to supplement the lead detector for measuring low D-T neutron yields. This addition also enhances our capability to measure D-D neutrons which

Table 2-9. Shiva target diagnostics.

Type of diagnostic	Type of detector	No. of detectors	Type of measurement	Month/year activated
Neutron				
Yield	Scintillation/PM	3	Time resolved	Jan. 1978
Time of flight	Scintillation/PM	2	Time resolved	Jan. 1978
Yield	Cu activation	2	Counting	April 1978
Yield	Pb activation	1	Counting	Oct. 1978
<i>pr</i>	CR-39 track	4	Multichannel proton counting	Oct. 1978
Yield	Dioxane activation	1	Counting	Dec. 1978
<i>pr</i>	Si activation	2	Counting	Jan. 1979
Yield	Ag activation	1	Counting	March 1979
Interval	Fluor/microchannel plate	1	Time resolved	March 1979
X-ray				
3X Microscope	Film	4	Spatially resolved, time integrated	March 1978
Zene plate	Film	3	Spatially resolved, multispectral, time integrated	April 1978
8X Microscope	Film	4	Spatially resolved, time integrated	June 1978
2-5KeV Spectrograph	Film	1	Spectrally resolved, time integrated	June 1978
Hard streak camera	Film	1	Time resolved	Sept. 1978
Angular high-energy	Fluor/vacuum photodiode	9	Time resolved	Nov. 1978
Pinhole camera	Film	1	Spatially resolved, time integrated	Dec. 1978
Dante S	XRD-31 Diode	10	Spectrally resolved, time resolved	Jan. 1979
Filter fluorescer	Fluor/PM	17	Spectrally resolved, time integrated	Jan. 1979
Argon spectrograph	Film	1	Spatially resolved, time integrated	March 1979
Silicon spectrograph	Film	1	Spatially resolved, time integrated	March 1979
Dante M	XRD-31 Diode	6	Spectrally resolved, time resolved	July 1979
Calorimeter	LC-29	1	Time integrated	Sept. 1979
Sub-KeV spectrograph	Film	1	Spectrally resolved, time integrated	Sept. 1979
Plasma/ion				
energy bal	LC-27 Calorimeter	34	Time integrated	Jan. 1978
Zone plate	Cellulose nitrate	1	Spatially resolved, time integrated	May 1978
Energy bal	LC-38 & LC-39 Calorimeters	3	Time integrated	May 1979
Laser Light				
Energy bal	LC-21 Calorimeter	21	Time integrated	Jan. 1978
Energy bal	Pin diode	38	Time integrated	Jan. 1978
Energy bal	Box calorimeter	24	Time integrated	Oct. 1979
Brillouin scattering	Spectrometer/diode array	1	Spectrally resolved, time integrated	Nov. 1979

previously rested only on the yield scintillation detectors. We used this additional capability on one set of experiments in 1979.

With the activation of the Dante S, Dante M, and Filter Fluorescer systems, our capability to measure target x-radiation now extends over a wide

spectral range. Both the Dante S and Dante M diagnostics time-resolve the low-energy part of the spectrum by utilizing fast XRD-31 diodes and R7912 transient digitizers. We measured the impulse response of these systems by irradiating a ball target with a 100-ps laser pulse. Integrated photo-multiplier signals from the Filter Fluorescer system are used to measure high energy x rays. We elec-

trically calibrated the recording system to improve system accuracy.

In addition to fielding the sub-KeV spectrograph and LC-29 x-ray calorimeter, we increased the number of angular high-energy x-ray detectors from 3 to 9. This angular x-ray measurement directly supplements the Filter Fluorescer diagnostic.

We activated the Brillouin scattering and box calorimeter diagnostics. The Brillouin scattering diagnostic was implemented with a stand-alone electronics system. Since the box calorimeter shadowed nearly all of the existing diagnostics, we physically rearranged the normal calorimeter system to enable addition of these new channels. Unfortunately, target-induced shock damage to the inner light shield necessitated removal of this diagnostic after only a few shots.

We deactivated the alpha spectrometer, 7-shooter (a 7-channel x-ray spectrum diagnostic), and one-half of the neutron scintillator detector yield diagnostics because new experiments made these measurements no longer necessary. Both the alpha and 7-shooter systems were completely removed; however, only the recording instruments were reassigned in the neutron yield case and the diagnostic could easily be reactivated (i.e., as in the case of D-D neutron measurements). The Sentry system¹⁸ was removed from the target chamber after the f/14 spatial filter installation when we determined that it was no longer required to protect the laser from damage if the target fell off the stalk.

We directed a substantial amount of preliminary effort into fielding the soft x-ray streak camera, optical pyrometer, Raman spectrometer and Dante N diagnostics. We expect these instruments to be on line during the first quarter of 1980.

Upgrades. We not only implemented and operated existing and new diagnostics throughout the year but made significant system advances in three areas: software, electronics instrumentation, and vacuum pumping capability.

Software improvement to the target acquisition, control, and instrumentation (TACAI)¹⁹ system code allowed us to begin using a new version which corrected a number of problems that had existed previously. No errors have been found in the new version, allowing us to isolate and correct system problems more rapidly.

TACAI currently is controlled by two LSI-11 microcomputers connected in a master-slave relationship. The master serves as the system con-

troller and user interface. The slave serves as a data base containing all pertinent parameters and calibration factors required for system operation, and as a "smart" controller for the CAMAC hardware served by the system.

Due to the limited memory of the LSI-11 microcomputers, adding to or improving the system as currently configured has become increasingly difficult. To accommodate new operational requirements and improve the maintainability and reliability, the slave will be linked directly to the PDP 11/34 target diagnostics subsystem processor which exercises the functions of the master. The PDP 11/34, in addition to more memory, offers a more powerful and flexible operating system, RSX-11M.

The portion of the software for system control and interfacing to the user was rewritten in the Fortran IV Plus language, under RSX-11M, using a multiprogramming approach similar to that used for the subsystem processors. Of particular importance are the elimination of floppy discs for the transfer of shot data and the ability to link the operation of target diagnostics with the operation of the other major subsystems. The physical links between the PDP 11/34 subprocessor for target diagnostics and the slave LSI-11 have been installed for both the Argus and Shiva facilities.

In order to achieve simpler software maintenance, the PDP 11/40 computer system used for target diagnostics within the Argus facility was replaced with a PDP 11/34 computer system configured the same as the one used for target diagnostics within the Shiva facility. Identical data acquisition and quick-look data processing software packages can be used for both lasers, resulting in lower support costs and increased performance reliability.

Based on Argus experience, we anticipated that x-ray-induced noise in the recording instrumentation might be a problem on the Dante diagnostics (as it later turned out to be). About halfway through the first high-density campaign, we installed a 3-in.-thick lead shadow shield for our R7912 transient digitizers. No significant decrease in target generated noise (approximately 1 volt peak-to-peak) was observed. Subsequent testing revealed that an approximate 100-times reduction in this

Fig. 2-32. A noise reduction of approximately 100 times may be seen when comparing upper and lower instrument traces. The upper trace was taken on a 7904 oscilloscope located outside the target room. This oscilloscope viewed the same signals as the 7912 transient digitizer, lower trace, located on the target spaceframe approximately 10 ft from the target chamber. These signals are representative of either instrument in the two locations.

noise could be realized by placing the transient digitizers in the basement outside of the Shiva target room. We believe that this noise is induced in the instruments by scattered x rays or EMP effects. Based on the results of this testing (Fig. 2-32), we implemented an eight-rack instrumentation station in the basement room. We began installing the Dante S and Dante M R7912's there at the end of the year.

In constructing this station, the racks were isolated and a single-point ground installed. We provided isolated clean power, isolated the trigger line, and linked the two CAMAC crates to the main data acquisition system via our fiber optic serial

highway. We also installed a total of 40 half-inch air heliax signal cables to the east and west side of the target chamber along with 20 new high-voltage cables. This station is capable of future expansion.

Our vacuum pumping capability also increased substantially with the completion of the auxiliary vacuum system. This system, shown in Fig. 2-33, complements the target chamber system and consists of a mechanical pump, a 2-stage roots blower, a turbo pump, appropriate valving and manifolds above and below the target chamber. We now evacuate diagnostics with large lines of sight such as the Dante and Filter Fluorescer systems independently of the target chamber. This system has also been used to evacuate the $f/14$ spatial filters more quickly and smoothly.

Other target diagnostic upgrades include:

- Fiducial timing pulses were added to the Dante systems. These pulses, generated by detectors placed in IBD packages, provide a means for determining relative timing shifts between x-ray pulses from several detectors.

- We moved the Cu activation (for neutron yield) counting system from the target room basement to the STARS²⁰ area on the mezzanine to improve our operational capability. After each shot, copper disks must be manually transported as quickly as possible from the target chamber to the counting detector system. Our disk transport time was reduced from $\sim 2\frac{1}{2}$ to $\sim 1\frac{1}{2}$ minutes. This time reduction increased the capability of the Cu system when used to measure neutron yields near its lower threshold.

- We changed the location of the communications link to the neutron time-of-flight facility. The longer run necessitated pulling an improved fiber optic cable and installing higher powered transmitters in our CAMAC serial highway modules. In addition, we improved the performance and reliability of this link. At the same time, we changed the STARS area ground from the ground rod outside the building to the ground bus within the target room with no detrimental effects.

- We moved two STRIPES²⁰ packages away from the vicinity of the target chamber to reduce the effects of target generated noise and to open space for new diagnostics. This noise, as previously noted, affects only high-speed amplified instrumentation; slow-speed or integrated measurements do not respond detrimentally to it.

Fig. 2-33. The auxiliary vacuum system as shown on a model of the Shiva target spaceframe.

● In expanding the electronics data acquisition system from 7 to 11 CAMAC crates, we experienced serial highway problems that limited the size of the system. By reducing the highway clock frequency from 500 to 250 kHz and by adding U-Port adapters (we used none previously) to regenerate the data and clock signals in phase, we solved our size problem and improved the system reliability. The total data acquisition time increased by less than 10%.

● We completed fabrication, checkout, and installation of vacuum controllers for the Dante S, Dante M, Filter Fluorescer, radio chemistry diagnostics, and for the auxiliary vacuum system. Several mechanical modifications to the original radio chemistry extraction system design reduced the foil transfer time from 25 to 17 s—a significant improvement when working with elements which have 2.24 min half-lives. The design was completed and fabrication started for the soft x-ray streak camera controller.

● We installed stainless steel compressed air and N₂ manifolds around the target chamber to service the growing number of experiments with their many valves. This replaced an unreliable maze of initially installed polyflo tubing. Check valves and quick disconnects prevent inadvertent pressure loss.

● We increased the size of the bypass orifices on the gate valves isolating the large line-of-sight experiments from the target chamber in order to protect the fragile filters from pressure surges. Our testing determined that the original orifices limited the rate of evacuation so that too large a pressure remained when the main gate valve opened. This pumpout scheme, together with the auxiliary vacuum system, gave us two methods to bring these diagnostics on-line.

● To improve our ability to adjust the target viewing systems, we made several modifications to increase accessibility to the adjusting mechanisms. We also added a lock-nut modification to remove play in the instrument mounting mechanism caused by normal wear. We changed the position of the lower viewer retro-reflector from the 8X x-ray microscope to its own holder which can be inserted or removed as desired. By moving it out of the way for each shot, we no longer need to replace it after

each shot and, thus, eliminate vacuum cycling of the target chamber.

● We continued to have periodic problems with the target inserter ball valve assembly which allows target insertion without bringing the chamber up to atmospheric pressure. A new design was made, prototyped, and fabrication started.

● We fabricated new hardware for mounting a laser on the target chamber for aligning experimental apparatus. By using this laser as an illuminator for a nylon surrogate target, which is positioned at the center of the chamber, we provide a diffuse alignment source to supplement the existing fiber optic technique. It is much easier to implement this source than the fiber optic one. We plan to pursue an even smaller target to simulate a point source.

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20. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), pp. 3-22.

Engineering Summary and Update

The major modifications and their effects on the operation of our lasers have been discussed above in separate sections dealing with each laser and with target diagnostics. In addition to these changes, numerous additional modifications were made to improve operation, decrease turnaround time, and improve system reliability. The majority of the upgrades were concerned with system integration and software improvements within the controls

system. Hardware modifications were made to the laser diagnostics systems, the power conditioning system, and the mechanical subsystems. A hardware redesign effort was also completed for the master oscillator electronics. The master oscillator change is required to improve the oscillator noise immunity and provide for precise timing of multiple oscillators, a capability required to support the upcoming x-ray backlighting experiments.

Over the past year the electronic systems have performed well. More than 1000 shots were taken through the β rods and over 200 full system shots were fired. Approximately 1% of the full system shots resulted in lost targets due to system malfunctions, and 10% were not up to full system performance due to a single ignitron not firing (approximately a 5% system energy loss). Minor aggravations in the system performance also delayed some shots, but in general these shots went off on the scheduled day. These continuing problems were attacked by increasing our system diagnostic capabilities, by identifying specific failure modes, and by implementing other means to improve system reliability. In addition, while these activities were continuing, additional system capabilities were being added.

The major laser diagnostic improvement has been the waveform analysis data system (WADS).²¹ Other improved diagnostics include the ignitron diagnostics and the safety interlock system improvements.

Improvements in system reliability were made on several fronts, especially by increasing redundancy. For example, an additional "quad port memory" and a spare power supply were installed as well as the PDP 11/70 backup system. Other improvements include reducing the number of system components (deletion of a power supply), reducing the use of certain components (spark gap trigger), and monitoring components not previously monitored (ignitron diagnostics).

Finally, significant improvements were made in system capability through the automatic pinhole alignment system, new charge-coupled device (CCD) diagnostics, and computer operating system upgrades. These topics are discussed in further detail in the following articles.

Author: P. R. Rupert

Reference

21. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), p. 2-46.

Control System. During the construction of Shiva, bringing an operating laser on line in the shortest time was of the greatest importance. To meet this goal, the initial control system was designed for easy installation with demonstrable functions. The easiest way to accomplish this was to install stand-alone systems in the laser bay. Although this satisfied the requirement for an operational laser system it resulted in fragmented operation. Alignment of the laser under these conditions was slow and gathering data from stand-alone systems after the shot had to be accomplished by hand. Human error could result in component damage during system operation and maintenance was more expensive because it depended on manual checks of the hardware to find faulty components. We are striving towards an optimal control system which should:

- Provide automatic alignment.
- Gather all the data for the system and concentrate it in one location in an easily accessible manner.
- Provide status of all components for maintenance purposes.
- Notify the operators of improper configurations before firing the laser.
- Maintain shot and experiment histories for the operators.
- Allow for easy addition of added functions.
- Allow all these functions to take place in one location for easier management.

At the beginning of this year, the power conditioning and beam diagnostics systems were performing most of their control functions from the control room, but the alignment and target diagnostics control functions were still being performed in the laser and target bay. The power conditioning and beam diagnostics systems, although more centralized than the other systems, still could not perform functions for the operators, such as performing trigger checks on the beam diagnostics system or telling the power conditioning operator the exact problem when the sequence was

aborted during a shot. The computers being used for control contained much data on the system which was either being lost, archived by hand, or ignored due to its sheer volume. As a result, the year's activities have been directed towards correcting these difficulties.

Efforts in the Shiva control area were oriented in four directions:

- Adding functions to the existing system.
- Enhancing speed and utility of the existing functions.
- Moving system controls from the laser bay to the control room.
- System integration.

The control functions are divided into four subsystems:

- Laser alignment control.
- Laser beam diagnostics.
- Power conditioning.
- Target diagnostics.

Each of these subsystems uses a PDP 11/34 minicomputer for its operator interface and to command one or more LSI-11 microcomputers exercising local control of a subsystem function. In addition, program development, data logging, processing, and archival are carried out on a PDP 11/70. (This can also replace a PDP 11/34 in the event of a failure.) This architecture is described in the next article and has been discussed in detail previously.²²

System integration was accomplished by improving the communication capability between the four control systems while simultaneously increasing the number of tasks a PDP 11/34 can handle. A serial link patch panel was installed which, together with the common memory that the PDP 11/70 shares with the power conditioning subsystem, allows the 11/70 to duplicate most of the functions of each subsystem controller. Presently the power conditioning subsystem can be totally controlled from the 11/70 by the execution of an indirect command file. Work is in progress to correct software problems, after which the 11/70 will be capable of replacing any one of the four PDP 11/34s.

A new version of the Shivanet utility, the master-master version, is capable of routing messages to nodes not controlled by the PDP 11/34 on which the message originates. A major advantage of the new master-master Shivanet is that

message exchanges can now be initiated from formerly subordinate programs down the line from the master program. This allows the master program to reduce its polling activity since it can now be notified by the front end processors (FEP) of any status changes.

Of the four subsystems, three were originally brought on line with control panels and LSI-11 microcomputers within the laser bay controlling laser functions locally. Each LSI-11 used the REBEL/BASIC language.²³ The power conditioning subsystem was developed using one pair of redundant LSI-11s controlling a hardware operator panel in the control room and a single Q-bus running throughout the laser bay and capacitor bank areas.

We completed transfer of control of the laser alignment, laser beam diagnostics, and power conditioning subsystems to the PDP 11/34 computers in the control room in early 1979 and we are presently accomplishing a similar transfer with the target diagnostics subsystem.

Only a few complex functions on the power conditioning subsystem are controlled by the LSI-11 microcomputer, but timing is critical. For this reason, the LSI-11 and the PDP 11/34 (and the PDP 11/70) share four kilowords of memory. A command written in the appropriate section of the common memory is placed by the LSI-11 on its Q-bus every tenth of a second, and input data from the Q-bus is written into the same section of common memory with the same frequency. The LSI 11 also updates, in the common memory, a table of changes which it has detected on the Q-bus. These are logged by the PDP 11/70.

The laser beam diagnostics subsystem controls many photodiodes and calorimeters. These measure laser energies at various stages of the laser chain including the incident beam and reflected beam diagnostics packages (IBD and RBD). In addition, the subsystem drives stepping motors used to control attenuators, filters, and pinhole and crosshair positioners, and generates a data set for each shot which is used for later analysis. The functions of this subsystem have been reviewed extensively.²⁴

The alignment control subsystem controls many stepper motors which position attenuators, mirrors, and pinholes for balance, alignment and spatial filtering of the beams. The target diagnostics subsystem controls diagnostic instruments attached

to a CAMAC highway in the target chamber and gathers large amounts of output energy data for each shot. At present this subsystem is controlled by two LSI-11 computers, one the slave of the other. When the PDP 11/34 is brought on line, it will assume the functions of the master LSI-11.

The last three subsystems use Shivanet, a locally written utility for transmitting messages over serial links between computers. A typical message on the alignment control subsystem, for example, is a message from the PDP 11/34 to the chain output pointing (CHOP) front end processor which mimics a laser bay panel command to position a pointing mirror. In this way, a limited number of operators can control the laser from one location, viewing status on PDP 11/34 driven CRT displays and manipulating console switches to issue commands to the appropriate station over either a serial or Q-bus link.

Operating system upgrades are being performed by Digital Equipment Corporation on the present RSX-11M (version 3.2) system. Under the old operating system the indirect command file processor was used in a batch processing mode. Thus, it was unaware of the success or failure of programs that it was executing, and questions had to be inserted for the operator to answer in order to control processing. Under the new version, the utilities are "smarter" and can send to the indirect command file processor an exit status so that procedures are more automated. Software programs are also aware of the execution of other programs. For example, one program can suspend itself until a resource used by another program is freed by termination of the second program. A third improvement is the "Stop" bit. The "Stop" option enables a program to be shuffled out of memory when it has nothing to do, thereby making more efficient use of the memory. This should improve the operation and response speed of the subsystems.

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22. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), p. 2-22.

23. M. C. Zarnstorff and J. R. Greenwood, *REBEL BASIC: Language, a User's Guide*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-52668 (1979).
24. *Laser Program Annual Report—1978*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-78 (1979), p. 2-31.

Power Conditioning. We have concentrated our software modification efforts in three areas:

- Preshot setup.
- Postshot processing.
- Display of the waveform analysis data

system (WADS) data.

We have pursued a philosophy of adding functions through the use of a programmable switch panel along with the use of a CRT for displaying status and data. This makes implementation of new functions easy and reduces the choices available to the operator to only those matching his particular situation.

We added new sequences for maintenance and alignment functions. Two timing channels were added for controlling an additional stage of pre-amplification required by the insertion loss of pulse stacking optics. A special sequence was implemented to charge and fire the chain through this stage repeatedly at 1 Hz for pulse alignment purposes. Another channel was added to control the triggering of a high-resolution spectrograph for recording optical scattering and optical emissions from the target plasmas. A total of nine sequences are now available which the operator can dynamically load from the control panel; each uses approximately 70 channels of the 128 available.

We implemented a set of routines to check the subsystem configuration and provide CRT displays of the configuration for the operator. This configuration check can include either determining that the hardware answers its bus addresses, or verifying that the hardware state selected by the operator matches the functions indicated by the sequence he has loaded. Several displays are available for maintenance of the subsystem. The state of all beam blocks, including beamline shutters, insertion box cross hairs, dye cell status, and oscillator status can now also be displayed. The shot sequence now halts on any non-standard configuration and queues a display of the offending hardware status. In addition, a display (Fig. 2-34) shows the operator which components he has selected for a shot, assisting him

Fig. 2-34. Selected device display. The power conditioning status colors are green (go) and red (no-go). This diagram indicates that the operator has selected to fire 10 of Shiva's arms.

in setting up special configuration shots. During a shot sequence, a display histogram (Fig. 2-35) shows the charging of the power supplies, and upon a "pre-fire" (conduction of current by the ignitron switches prior to reaching shot voltage), indicates the faulty power supply in a special color. Other faults, which can occur with a "pre-fire" (such as overcurrent or overvoltage tripping of the power supply circuit breakers), have their own special colors on the histogram.

After the shot, WADS data is collected. This system, the primary diagnostic improvement, is comprised of individual current monitors on each flashlamp and rotator circuit.²⁵ The data, which are digitized and analyzed for anomalies, contain information about the state of the flashlamps, the condition of the capacitor which charged them, and the timing of the charge relative to the shot time. The data were frequently useless in the past due to the

vast size of the data set (over 1200 waveforms) and because the environment introduced noise into the data. We have implemented a procedure which, at the time of collection, analyses the data with integral and RMS slope numerical algorithms, filters noise out of the data, masks the channels against the known patterns to see if any waveforms are missing, and tests each set of waveforms to see that each lamp presents the same load to the capacitor. From these tests, a summary display is produced for each stage of laser amplification. If a fault is shown in the summary, the operator can select a display of the individual set of waveforms. Finally, the operator can print the summary file for off-line maintenance.

As shown above, our analysis capability has improved from a technician looking individually at each waveform to a sophisticated analysis program which flags all system anomalies. As a result, the system picked out a capacitor with an internally shorted pad and approximately 30 bad flashlamps. Detecting the capacitor failure early prevented it

Fig. 2-35. Power supply charging histogram. The power supply charge histogram dynamically indicates the voltage supplied to the flashlamp capacitors during the two minutes required for a shot sequence. When faults are detected, this screen is also used for pictorial representations of the situation or for printing short error messages at the bottom.

from deteriorating to a catastrophic failure. To our knowledge, this is the first time such a failure has been detected in a large operational capacitor bank before the capacitor failed completely.

This diagnostic system also verifies the proper operation of the electronics system when low-laser chain gain is observed. This allows corrective action to be taken in the offending subsystem in a more directed and immediate fashion.

Hardware modifications to the system have been made to improve system reliability and provide added system capability.

Due to inadequate quality control, many of the original current transformers used in WADS fail when a fault occurs in the primary load. This led to failure of the diagnostic package and 30% of this system is currently not on line. Continued effort was devoted to replacing these current monitors. A vendor was selected who can meet the 20 kV isolation specification and a contract awarded to him to replace the faulty transformers.

Reliability has been increased through the use of redundancy this year with the addition of a DEC quad port memory. This procurement and reconfiguration eliminated the last single point failure in the power conditioning controls. The system is now capable of running from either LSI-11A or B, each with a separate quad port memory connected to the PDP 11/34 and the PDP 11/70.

Another increase in system redundancy was made when the spare 100 KVA power supply was placed on line and debugged. This supply had not been brought on line during initial system activation for operational reasons. Our procedures and operational maturity have developed to the point where we felt confident in implementing this redundancy.

The number of components required for a system shot was reduced (and thus reliability increased) by the removal of a 100 KVA power supply

Fig. 2-36. Preamp YAG addition schematic. The YAG preamp required the addition of a modified 5 kV power supply and a low-dielectric-stress pulse-forming network.

and its associated ignitron from the system. This reduced the number of power supplies required for a systems shot from 29 to 28 and the ignitron switch assemblies from 73 to 72. The capability given up for this reduction was the ability to set the gain of the amplifier rods on the preamp table independently. This feature had not been used on any target shots. Since wave plates controlled through the oscillator alignment system are now used for gain setting on the preamplifier, we see no future requirement for this capability. The combination of the two rod preamp table loads also improved the reliability of the remaining ignitron switch. Previously the load was so low that after a few hundred shots, the size-D ignitrons would start to prefire due to dirty cathodes. With the addition of another circuit we have not observed this problem.

Reducing the use of the pulse pack which triggers the spark gap also improved reliability. This function previously operated even when the Pockels cells were not in use during 1-Hz oscillator operation. By providing remote capability and bringing the function into the control system, we activate it so that it only works when the Pockels cells are actually required for a system shot. This increased the pulse pack life expectancy by orders of magnitude.

Reliability was also increased by improving our diagnostics capability. Additional diagnostics and feedback have been added to the ignitrons switch

assembly and the safety interlock system. A diagnostic audio peak detector was added to the interlock chain to insure that the automatic system announcements had been made on the public address system (PA) prior to completing the interlock. As these announcements are an important part in our overall safety and interlock strategy, it was necessary to insure that a PA system failure does not occur prior to laser operation. Diagnostic temperature sensors have also been installed on the heat lamps in the ignitron switch assemblies to provide information to the computer on the 142 lamps in the system. These single temperature closures have not yet been connected to the control system.

Other modifications made to increase our overall system capabilities were the addition of a new Nd:YAG preamp to compensate for insertion losses during pulse stacker use, and the addition of two additional front end processors to control the new output spatial filters. The new FEP's control the 60 stepper motors for positioning the spatial filter pinholes. Two new fiber optic serial links were made and connected to the spatial filter master processor. Only software modifications to recognize a new spatial filter pinhole position and display it were required. Fiber optic links provided the required 50 kV isolation between the target and laser bay.

The addition of the Nd:YAG preamp capability made up for the 10-dB insertion loss when

Fig. 2-37. Preamplifier YAG pulse forming network chassis.

the long pulse oscillator or pulse stackers are installed. The control section of an existing 5 kV power supply was removed and a spare Shiva power supply control chassis modified to operate as a single phase controller. This approach automatically provided the necessary computer interface.

A new design was also required for the pulse forming network (PFN) to improve capacitor life in this application. Previous supplies of this type had only been used with 240 μf , 5 kV capacitors in various PFN configurations, and usage was restricted to system shots. However, this amplifier is required to operate at 1 Hz to provide sufficient gain to point the beam with the oscillator alignment

system. Therefore, to improve capacitor life at a high repetition rate, the PFN was redesigned to reduce the dielectric stress on the capacitors. Figure 2-36 shows the basic circuit layout; it has been packaged in a 19-cm rack chassis as shown in Fig. 2-37. The system is interfaced with the power conditioning bus and has fired the Nd:YAG for 8 h at 1 Hz without failure.

The power conditioning software is shown in Fig. 2-38, and the power condition bus is shown in Fig. 2-39.

Recently, we have added (on the PDP 11/70) an RT-11 system build capability, with the special requirement of mapping into a global common.

Fig. 2-38. Software structure of power conditioning. Each function commandable by an operator is carried out by a "page" program. Each page queued by the traffic manager also monitors errors and queues the error processor on detection. The common memory is divided into bus data, pointers and bus status, transfer buffer, flags, and change data. The LSI-11 is commanded through the flags, which are also used by the LSI-11 to post its responses, errors, and system state. Post-shot data collection and preshot sequence loading use the buffer reserved for that purpose in the common memory.

This facilitates updating the LSI-11 code and recording code changes and allows easy adaptation of routines from the LSI-11 for the PDP 11/34 and vice versa.

Authors: P. R. Rupert and R. W. Carey
Major Contributor: E. H. Padilla

Reference

25. *Laser Program Annual Report—1978*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-78 (1979), p. 2-37.

Shiva Alignment System. In target alignment, it is necessary to verify the alignment of all 20 beams on the target. The cumulative errors of centering the beams on the focusing lenses, focusing on the surrogate target, and replacing the surrogate target by the real target are too large for accurate alignment

by simply offsetting the beams after they are aligned to the surrogate. In practice, after commanding the lenses to move to the offset position, we verify all beam positions on the real target using the TV cameras in the PFC/RBD packages. Corrections of a few tens of microns are usually necessary for several beams.

Central control became a reality in 1979 with the *alignment control subsystem*. In the control room two LSI-11 microcomputers and a PDP 11/34 minicomputer collaborate to accept commands for either manual or automatic alignment of the laser chain optics. The PDP 11/34 accepts commands through a programmable touch panel²⁶ displaying a menu of options which the operator can activate by touching the appropriate item on the screen.

In addition, the central alignment console was augmented with two newly developed programmable switch panels intended to provide tactile feedback not possible from the menu-driven touch

Fig. 2-39. Three-level Shiva control system, consisting of a distributed network of approximately 50 computers and microprocessors grouped into four major subsystems. Connections between processors are made with fiber optic serial data links. A highly isolated (50-kV) extended computer bus connects a large number of devices for power conditioning control to the central computer. A new patch panel allows switching of serial links between computers.

approximately 50 computers and microprocessors
ber optic serial data links. A highly isolated (50-
2 control) to the central computers. A new patch

Analysis, development, & mass storage

- 176 Mbyte disc drives
- 5 Mbyte disc drives
- 2.5 Mbyte disc drives
- 500 LPM printer/plotters
- 75 IPS tape drives

Print & mass storage

Legend

Fig. 2-40. The alignment control room functions. Automatic functions are queued on command from the plasma panel. Manual operations are carried out from the programmable switch panels which also provide views of the beams and the target during operations.

panels. The panels are divided into three parts. Task specific labels and information are displayed at the top with dot matrix displays. In the middle, two CRT's provide images of the beam or target at eye level. At the bottom, the operators can drive remote stepper motors with programmable switches. Hard switches, i.e. single function only, were avoided to reduce clutter and operating complexity and also to permit easy additions of new functions as they are needed.

Each panel is driven by an LSI-11 microcomputer which provides a custom set of labels and panel configuration for each task. The panel configuration and other parameters are commandable either from the panel itself or remotely from the PDP 11/34. Operators use the console for alignment of laser components by manually activating remote stepper motors while viewing the effects on the CRT image.

The programmable panel features multi-function alphanumeric displays. Each switch or display has a primary label and up to three secondary labels that can be flashed twice per second. For example, the motor slew switches are labeled with an axis name as the primary label but are also labeled with the two limit switch alarms and an alarm indicating other interface trouble. Normally only the

axis label is displayed. Upon receipt of remote status, an appropriate secondary label can be made to alternate with the axis to reduce the quantity of extraneous information presented to an operator. As a further extension, the switch panel driver suspends operations after a period of disuse and presents only the label "suspended" to the operator to avoid distraction. Manipulating any switch will then reactivate the console. Functions currently installed and operating in the programmable panels are target viewing and positioning, beam diagnostic routing mirrors, penthouse rotators, waveplate attenuators, spatial filters, and TV selection for automatic pinhole alignment.

Automatic pinhole alignment capability was added to increase the shot rate. The addition of this new feature required three peripheral changes. First, eight additional motor control channels were added to the control system to regulate the four-aperture insertion assembly.²⁶ These additional channels were necessary to remotely control the diffuser lens used to backlight the spatial filter pinholes. Second, a Quantex video digitizer was added to the alignment PDP 11/34. Third, switching capability and control of the central TV network from that PDP 11/34 were implemented. Figure 2-40 shows the additional control system interfaces.

Fig. 2-41. This color diagram is generated by the alignment control PDP 11/34 and shows the status of the chain output pointing systems for each of the 20 arms of Shiva. This display is updated every five seconds.

During the course of the automatic pinhole alignment, the PDP 11/34- and LSI-11-driven panels coordinate in presenting progress information. The operator monitors the quality of the alignment by viewing the beam image presented on the hardware switch panel CRT. Color CRT displays driven by the PDP 11/34 display status for spatial filters, pinhole alignment, oscillator alignment, CHIP, and CHOP (as shown in Fig. 2-41). The flow of central alignment control software is indicated in Fig. 2-40.

A major speed advantage was achieved on several LSI-11 controlled functions by switching from REBEL/BASIC, running under RT-11, to

FORTRAN-IV Plus, running under the RSX-11S operating subsystem. This subsystem also supports downline booting from the PDP 11/34 over a serial link.

Hardware improvements included computer-driven insertion of the four-aperture remote translation stage lenses for backlighting the pinholes during the alignment session. These are presently controlled by a laser bay FEP but control will be transferred to the plasma panel programs in the future.

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Major Contributors: R. D. Boyd and P. J. Van Arsdall

Reference

26. *Laser Program Annual Report—1978*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-78 (1979), p. 2-41.

Laser Diagnostics System. The previous method of diagnosing beam energy at mid-chain relied on light reflected from a polarizer in the Beta Pockels cell polarizer assembly. This measurement was subject to variations that were eventually traced to humidity changes.²⁷ Figure 2-42 shows that the ratio of reflected to transmitted light from a polarizer varies inversely with humidity, with the greatest change being in the reflected light.

To achieve a stable energy diagnostic and a beam photograph, we developed the package shown in Fig. 2-43. Two beamsplitters, mounted at Brewster's angle and coated on the first surface for 1% reflection, are mounted to yield both a near-field photograph and the energy diagnostic. The prototype proved the energy measurement stable to within 3%. Figure 2-44 is a photograph of the beam taken with this diagnostic. The photograph is free of modulation because there is no reflection from the second surface of the beamsplitter at Brewster's angle.

In addition to the foregoing mid-chain diagnostic work, a prepulse detector and an output streak camera have been added to Shiva. The prepulse detector is installed on the oscillator preamp table and can directly detect prepulse levels

Fig. 2-42. Varying humidity produces a varying R/T ratio. When the humidity in the control volume was varied at constant temperature, the reflected-to-transmitted signal ratio experienced large changes in response to the humidity changes.

Fig. 2-43. Mid-chain beam diagnostics. Two beam splitters mounted at Brewster's angle provide a stable signal for beam energy measurements and a modulation-free near-field photograph.

Fig. 2-44. Near-field beam photograph taken by the mid-chain diagnostic package.

-60 dB below the oscillator switched-out pulse. The same detector measures the extinction ratio of the preamp table dye cell. This small-signal attenuator (typically -30 dB) yields an indirect prepulse measurement which ensures the prepulse level is less than the oscillator pulse by equal to or greater than

Fig. 2-45. A prepulse deliberately induced by mistiming the switchout. The main pulse signal goes off scale.

Fig. 2-46. The noisy streak produced when a fiber optic cable is coupled directly to the input slit of a streak camera. The noise is due to variations in camera sensitivity over its input surface.

90 dB. Figure 2-45 illustrates a prepulse signal deliberately induced by mistiming the switchout electronics; the main pulse goes off scale.

To record the output pulse, a streak camera was installed at one of the output beams. A fraction of the beam entering the IBD is recollimated, passed through an etalon, and focused into a fiber optic

Fig. 2-47. The streak produced when a ground glass diffuser is inserted between the fiber optic output and streak camera input. Variations in streak camera spatial sensitivity are averaged out without affecting temporal resolution.

cable. The 62- μm diameter graded index glass cable carries the signal 3 m to the input of the streak camera. By coupling the fiber directly to the input slit of the camera, a noisy trace was produced (see Fig. 2-46) due to the nonuniform response of the camera. This noise problem was reduced by moving the exit surface of the fiber optic cable 1 cm from the slit and placing a ground glass screen between them. This diffuses the beam to a 5-mm width on the slit. When the film data are reduced, the signal is averaged over a 2-mm width which averages the

fluctuations in camera response without affecting the temporal resolution. Figure 2-47 compares the streak record obtained at the end of the chain with the pulse measured in the preamp section. These data indicate we are faithfully recording the output pulse.

A splitter was designed to be used in the converging beam inside the IBD to provide a photographic image of the beam in a plane near the final focusing lenses. A prototype was fabricated and is awaiting installation and evaluation.

An interface unit for analog-to-digital conversion of the preamp streak camera output and its

storage in local computer memory was built and installed; initial tests indicate it functions properly. This device eliminates the need for photography of the preamp table streak camera output and hand reduction of the data to obtain the pulse length.

An output prepulse measurement package has been assembled and installed, and is awaiting final alignment and checkout. This package will provide a direct measure of the prepulse level during a shot at the output of a chain.

A CCD array and a local 160K word memory are being prepared to replace the film now used to record the streak camera output pulse shape. The CCD and memory will be interfaced to the control room via the power conditioning bus and will provide real time data reduction.

The IBD and RBD controller software was reorganized. Stepper motors in the IBD and RBD packages²⁸ control variable density attenuators, ND filters, and pinhole and cross-hair positioners. Originally there was no position sensing feedback to verify the actual result of a computer or operator generated command; results were estimated from the command sequences generated by the stepper motor control software. This resulted in excessive error due to mechanical hysteresis of the stepper motor and driven assemblies. As a result, cams were mounted on the stepper motor shafts and their rotational positions, sensed by cam-riding microswitches, were read by the control software. When two cams were mounted on the same shaft, the microswitches could not be aligned with sufficient accuracy to assure that the cam riders would make and break the switches in synchronism. Therefore, we modified the software to provide ambiguity windows during which microswitch sensing was verified by multiple readings for a valid indication of state.

During this cam modification, separate control software packages for the IBD and RBD LSI-11 microcomputers were combined into one package running under the DEC RSX-11S operating system. Different functionality is distinguished by parameters in a common data base. The data base was reorganized so that a file of laser input parameters from each shot is available in a format suitable for appending to the output parameters file produced by the target diagnostics subsystem. Using these data, a set of programs calculate an energy balance for each shot.

Authors: R. G. Ozarski and S. R. Morris

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27. R. G. Ozarski and J. Prior, *Polarizer Reflectivity Variations*, Lawrence Livermore Laboratory, Livermore, Calif., UCID-18588 (1980).
28. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977), pp. 2-162 and 2-168; *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), p. 2-36.

Pulse Generation A simple four-mirror, passive pulse stacker was developed and implemented on the Shiva laser. The stacker, which produces 2-ns pulses (FWHM), is illustrated schematically in Fig. 2-48. A 1-ns input pulse is split into two approximately equal parts which travel two separate paths differing in propagation time by roughly 1 ns. The delayed and undelayed pulses are then optically recombined to produce the desired 2-ns output pulse. To assure constructive interference between the two pulses in the (temporal) overlap region, an adjustable etalon is incorporated into the delayed (longer) path. This etalon controls the relative phase of the delayed pulse so that coherent addition is maintained, i.e., no "dip" appears in the center of the output pulse.

This straightforward approach to "long" pulse generation was used for several reasons. First, the present Shiva oscillator²⁹ is not capable of producing pulses longer than about 1.3 ns without extensive modifications. Second, alternate approaches, such as double etalon (P-M-S-type) pulse stackers³⁰ or active (e.g. Pockels cell) pulse shaping,³¹ would have required major modifications of the Shiva front end (oscillator + preamplifier) staging to compensate for their substantial insertion losses (~20 to ~30 dB). Insertion loss for the four-mirror pulse stacker is ~0.38 dB (energy), ~0.68 dB (intensity). Third, the short time available for fabrication, installation, and debugging strongly favored a simple approach to the problem.

The hardware package for mounting and adjusting the stacker optics consists of four stainless steel micrometer-driven gimbal mounts for the splitters and turning mirrors and a separate fine-adjust gimbal mount for the etalon. The gimbal mounts are attached to a 35- × 45- × 0.6-cm super Invar

Fig. 2-48. Shiva four-mirror pulse stacker. The output pulse is generated by coherently adding delayed and undelayed portions of a 1-ns input pulse. An adjustable etalon varies relative phases of the 1-ns pulse to obtain constructive interference when they are recombined. The stacker energy insertion loss is given by $T_1 T_4 + R_1 R_2 R_3 R_4 = 0.42$ (-0.38 dB). R_2 is less than 100% to make $T_1 T_4 R_1 R_2 R_3 R_4$, which results in a time-symmetric output pulse.

plate. The plate, in turn, is built onto a 5-cm thick honeycomb base kinematically mounted to the Shiva preamp table. Kinematic mounting permits relatively easy switchover between "long" pulse and "standard" operation of the system. The pulse stacker hardware package is placed on the Shiva preamp table immediately after the ASE dye cell.

Preliminary alignment is accomplished using the Shiva automatic oscillator alignment system³² to coincidentally point and center the two beams from the short and long stacker arms. With the oscillator operating at a 1-Hz repetition rate, the output pulse shape is optimized by performing fine adjustments on the long path etalon while monitoring the output pulse on a high-resolution streak camera. Final adjustment is complete when constructive interference is observed. Figure 2-49 shows an example of typical input and output pulses as they appear on the streak camera display.

Reasonable precautions were taken in the design, fabrication, and installation of the stacker to achieve stable operation. One does not expect long-

term range stability from an open structure of this type, when interferometric (i.e., fractional wave) relative alignment and length tolerances between the two paths must be maintained. Nonetheless, the thermal and mechanical stability of the Shiva preamplifier table environment (i.e., minimal vibration and air flow) have proven adequate for short-term operational stability of the stacker. Experience to date indicates that moderately frequent attention and adjustment are required to maintain optimal performance of this stacker for target shots. Thus, this stacker configuration is not an adequate long-term solution for routine operation with longer pulses. As a result, a new long pulse oscillator will be incorporated in the system next year.

New controls for the Shiva oscillator were designed, constructed, and debugged off-line in 1975. They will be moved into Shiva along with a new oscillator in early 1980.

Figure 2-50 is a block diagram for the oscillator electronics. The new controls were consolidated into two chassis, one containing the computer interface circuits and the other containing the high-frequency controls circuits.³³ The computer inter-

face chassis provides low-frequency control signals to initiate and control an oscillator firing sequence. It sequences the lamp firing, does coarse gating of the RF, and determines which fiber optic triggers will be launched. A switch on the front panel determines whether the controls will be computer driven or locally generated. During computer operation all local panel controls are overridden to increase operational reliability. Under local control the computer has no influence; this will simplify troubleshooting and setup. The computer interface circuits are redundant so that either of the power conditioning computers can monitor or control the oscillator. All circuits in this chassis are CMOS to ensure compatibility with the power-conditioning bus interfaces and high-noise immunity. Many circuits in the chassis provide the status of the oscillator controls; their outputs are displayed locally and monitored by the computer for setup data archival.

The high-frequency control chassis performs the precise gating of the RF to the Q switch and generates accurately synchronized optical fiber triggers for remote devices, such as the switchout and ASE Pockels cells. This chassis reduces interconnections and noise problems by consolidating several components from previous systems and by employing optical fiber triggers. The delay settings of the trigger units and the levels of the RF outputs are monitored and transmitted over a fiber optic link to computer interfaces in their chassis. This allows the computer to monitor these settings as a laser operating parameter.

These controls can also provide timing signals for multiple oscillators. Thus, as additional oscillators are incorporated into Shiva, the control system will be duplicated for each one.

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Fig. 2-49. Streak camera records of input (a) and output (b) pulses from four-mirror pulse stacker. A 2-ns output pulse is generated from a 1-ns input pulse. Vertical display is linear in intensity. Slight dip in center of pulse indicates the stacker is slightly off optimum alignment.

Fig. 2-50. Block diagram of the Shiva oscillator controls.

Mechanical Systems. Several new items have been added to facilitate alignment, improve sub-system performance repeatability, reduce maintenance costs, simplify the means to record beam quality, and implement status monitoring equipment to ensure an operational and safe system. Status switches on all equipment now provide an output to the LSI-11 computer display to ensure there is no equipment in the beams prior to a target shot. The equipment was designed to minimize contamination and provide protection to the optics in the laser chains. These items were "human-engineered" for minimum effort of operations per-

sonnel and to provide rapid, reliable output data via the computer.

The ladder alignment crosshairs provide rapid remote insertion and removal of crosshairs at the top and bottom of each of the four ladders at the front end of the laser spaceframe. A typical ladder, with the alignment crosshairs, is shown in Fig. 2-51. The ladder comprises a series of beam splitters which direct the laser pulse into the laser chains. Covers over the beam splitter optics for contamination control remain intact during the alignment checks. Previously, the covers were removed and cross hairs installed manually. Alignment verification is performed by sighting through windows in the covers with IR viewers.

The crosshair mechanism consists of a crosshair mounted on an arm attached to the output

shaft of a rotary pneumatic actuator. The crosshair is commanded into or out of the beam (optical axis of the ladder) via a 4-way solenoid-driven air valve. Only 85 degrees of rotation of the 90-degree excursion of the actuator are used to ensure that positive pressure exists between the crosshair arm and its fixed mechanical stop for the in-beam mode. The fixed stop is used as a status switch. The out-of-beam mode has redundant status switches. Local control exists at each ladder and additional control from the LSI-11 computer is currently being implemented.

A beam profile fixture is used to align photographic film on a 20-cm diameter collimated laser beam just before the beam gets to the focusing lens on the target chamber. These near-field photographs are used to diagnose beam-induced

Fig. 2-51. Typical ladder with crosshair assemblies.

damage in the laser chain optics. The fixture is secured to the beam tube and is aligned to ensure that the entire area of the laser beam is recorded, without clipping. It comprises a movable and lockable interface carrier plate with registers for viewing screens, neutral density filters, film magazines, calorimeters, and protective covers. Figure 2-52 shows the fixtures installed in one of the upper 10 beams. Covered enclosures large enough to accept a calorimeter for IBD energy calibration are used on the upper 10 fixtures since the geometry dictated installation in the beam tubes.

The safety of operations personnel is of paramount importance. A series of catwalks and stairs was engineered to provide personnel access for alignment and maintenance on the upper inner arms (beams 11, 12, 19, and 20). Cross-over catwalks provide access to the two Pockels cell spark gaps and the up-leg relay to the penthouse. The penthouse optics are also accessible.

The installation complies with OSHA standards. A similar set has been installed on the target space frame. In addition, jibs with sliding trollies and electric hoists are integral with the catwalks for removal and replacement of beta-rod amplifiers and the alpha-rod to beta-rod spatial filters. Removal of a beta-rod amplifier via a jib/trolley is shown in

Fig. 2-52. A beam profile fixture after installation in one of the upper 10 arms.

Fig. 2-53. The amplifier is then transferred to the bridge crane hook to be removed from the laser bay.

Protection to lasers, related optics, and diagnostics on the oscillator and preamplifier tables was completed with the installation of enclosures. Clear panels of high strength Lexan in a commercial aluminum extrusion framework were installed. The side panels slide on roller channels for access.

Finally, a new Beta Pockels cell splitter assembly was designed for improved mid-chain beam diagnostics (see section on "Laser Diagnostics System"). One Beta Pockels cell splitter has been installed and system tested satisfactorily; the remaining 19 units are currently being assembled.

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Fig. 2-53. Removal of a beta-rod amplifier using one of the catwalk jibs and sliding trolley.

Fig. 2-54. Portion of the top level integrated schematic. This level schematic provides an overall view of the system, its major components, and its major interfaces.

Documentation. The Shiva laser requires a high level of documentation in order to troubleshoot and solve system problems in a timely manner (Figs. 2-54 and 2-55). The documentation from which the

laser was built does not allow a timely progression from observed system symptoms to identification of component failures for several reasons.

Fig. 2-55. Portion of a typical detailed integrated schematic. This level schematic presents on a consistent form the details of system interconnection and function. Each off-page reference is shown cross referenced by page and zone.

- We do not have adequate cross references between component level schematics.

- From a logic flow standpoint, the schematics were presented from the component rather than the system point of view.

- Some systems and components were built without formal documentation.

- We do not have physical location drawings which are helpful in finding equipment in a system as large and complex as Shiva.

As a result of these problems, integrated schematics are being produced. This system of drawings is designed so that a technical person, with no direct knowledge of the system, can quickly gain the understanding necessary to troubleshoot the system. This understanding is gained by starting

with the system flow charts and block diagrams which are progressively subdivided and amplified until component level schematics are detailed. This procedure allows one to grasp the overall system logic. Anytime a signal departs the page or detail amplification is on another page, that page and zone are noted. Great care is taken to ensure that functional component groups remain grouped and that all logic flow is left-to-right and/or top-to-bottom. When the integrated schematics are completed no other schematics will be required to solve system failures.

The integrated schematic reference-oriented page numbering system starts with a top drawing that depicts the entire system with each system element marked with a letter of the alphabet to indicate the system it is associated with (see Fig. 2-54).

Each letter designator is shown in more detail on a separate drawing used to organize the components into a system. Each of the blocks are assigned to a separate sheet for more detail. If the component level drawing is not reached, this drawing is again divided into blocks titled with this page number plus another number separated with a decimal point. (This allows more than nine subdocuments at any level, such as P7.16.23, and the number of sub-levels to be unlimited.) The detail grows until the component level schematic is reached (see Fig. 2-55). The page reference number created by this process allows one to regress to a higher level drawing at any point by ignoring the last number group of the sheet being used and turning to the page with the remaining number. The higher level drawing will show the block and how it is related to surrounding units.

Another aid for cross referencing is the reference bubble. When a signal path is broken the drawing and zone number at which it continues are shown by a bubble as shown below.

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Introduction

In early 1979, the Nova Project was reviewed by the Energy Systems Acquisition Advisory Board (ESAAB) of DOE; this review was conducted as part of DOE's requirements for acquiring a major system. Originally, the project had been viewed as a \$195-million single-line-item construction task; however, following the review, DOE requested that the Nova Project be organized into two independent phases: Phase I, estimated at \$137 million, in which the Nova laboratory building, office building, and a 10-beam laser system would be constructed; and Phase II, estimated at \$58 million, in which the building space presently occupied by the Shiva laser system would be reconfigured to accommodate an additional 10-beam Nova laser system, and the two 10-beam systems would be combined to form the full 20-beam Nova laser system. The Phase I 10-beam system is projected to have a performance of 80 to 120 kJ at 3 ns, while the full 20-beam system is projected to have a performance of 200 to 300 kJ at 3 ns.

Following the ESAAB review, we were authorized to start construction of the Phase I portion of the project. In addition, it was decided by the Under Secretary of DOE that another review will be made before the Phase II construction is begun. Following DOE authorization of Phase I, we began construction on both the office building and the laboratory building, and we started procurement action on long-lead-time laser components. These activities were possible because we received the \$56-million funding that we had requested for FY 1980.

In the fall of 1979, we froze the optical design of Nova. The selected Phase I laser configuration consists of 10 linear laser chains, each with a final-output-amplifier aperture of 460 mm and with focusing optics that are 740 mm in diameter. The final Nova laser system will consist of 20 of these linear chains.

The 20-beam laser configuration represents a significant change from the original 40-beam

design, which would have used an output-amplifier aperture of 340 mm for each beam. The decision to use fewer beams with larger apertures is a result of two main factors: first, the lower number of beams will reduce maintenance costs; and second, the larger (460-mm) segmented-disk amplifiers are more cost effective when total system costs are considered.

The selected Nova laser configuration uses an isofluence staging technique, which drives an amplifier's output beam fluence up to the damage limit of uncoated optics. A spatial filter then expands the beam and reduces the modulation to a fluence level that is below the damage limit of coated optics. This technique is described in more detail in "Laser Chain Design and Performance," below. At the time when the optical design was frozen, we reaffirmed the selection of fluorophosphate laser glass for the large-aperture amplifiers of the Nova system.

During the past year, the management structure of the project was formalized, and staffing was accomplished for the design phase. The primary management tools that will be used are described in "Project Management Systems," below.

To accomplish the Nova project without significantly impacting Laboratory manpower, we are using outside design and engineering capabilities for many aspects of the project. Following an evaluation of solicited bids, we selected the Advanced Technology Division of Kaiser Engineers, Inc., and the Research and Engineering Operation of Bechtel National, Inc., to provide onsite design and engineering in the areas of alignment, target subsystem, electrical engineering, and mechanical engineering. At present, there are 13 engineers and designers from Kaiser and two engineers from Bechtel onsite. This use of contractor personnel achieves two main purposes: first, it allows us to accomplish the Nova project without staffing up at the Laboratory; and second, it represents a first step towards transferring fusion technology to those companies that might become involved in the design and engineering of a prototype reactor and, later, of commercially oriented facilities.

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Fig. 2-56. Schematic of one Nova amplifier chain. Following the 460-mm amplifier stage, a spatial filter expands the beam diameter of 740 mm for transport to the final-focusing lens. Baseline components are indicated by solid lines. The dashed lines represent amplifiers that could be added for increased system performance.

Laser Chain Design and Performance

Introduction. During 1979, the design of the Nova laser chain underwent a significant change as a result of developments in our laser-glass and optical-coating evaluation programs. Two aspects of the glass development program deserve emphasis: first, vendor qualification for production of fluorophosphate laser glass progressed satisfactorily, and there is a reasonable expectation that vendors can meet the glass specifications within the Nova schedule constraints; and second, recent gain-saturation measurements have shown that the saturation fluence of the fluorophosphate glass is larger than previously supposed ($\sim 5.5 \text{ J/cm}^2$) and is, in fact, somewhat larger than that of the Shiva silicate glasses. Hence, Nova performance should be satisfactory for pulses in the range of 3 ns and

longer. For pulses in the 1-ns region, the fluorophosphate-glass chain will provide performance superior to that of a silicate-glass chain because of the low, nonlinear index of refraction of fluorophosphate glass ($\sim 30\%$ that of silicate). Because fluorophosphate glass has superior characteristics, we chose to base our design on the use of this glass in our chain.

Listed below are several key design and performance features of the Phase I Nova bas-

- 90 kJ and 90 TW at 1 ns,
- 110 to 137 kJ at 3 ns,
- 140 TW at 100 ps,
- Two opposing clusters of 8 (total 16 beams in all), with flexible open-cone geometry.

- Fluorophosphate laser glass,
- 460-mm split-disk output amplifier

if filter expands the beam to a diameter
s. The dashed lines represent amplifiers

in the driver section, a fluorophosphate glass disk will be used for performance reasons. The beam will be expanded because of the refractive index of the disk (silicate glass). However, the disk exhibits such distortions that a chain design must be used for the amplifiers. The design and performance of the baseline system: 900-mm-dia. output aperture.

output aperture of 5 beams (10 beams for cone irradiation)

split laser glass.
split-disk output amplifier.

- 740-mm output and focusing optics.
- f/3 final-focusing lens.

The full Nova system will comprise 10 additional beam lines of identical design, which will be located in the Shiva system bay, making up a full complement of 20 laser amplifier chains. As discussed below, the performance per chain may be significantly enhanced over the baseline levels.

Nova Design Considerations. Figure 2-56 shows a schematic of one Nova optical chain; 10 such chains will be used in the Phase I Nova system. Each chain comprises a driver section followed by 315- and 460-mm-dia. clear-aperture output-amplifier stages; the laser beam will be expanded to the full 740-mm output diameter after it leaves the last amplifier stage. In the output-amplifier stages, each head will hold two fluorophosphate-glass disks. The

design of these heads will be "340-mm prototype box at Development," below). The disks in the 315-mm stage will be 315-mm-dia. disks. Spacing of the two additional heads in each stage (see Fig. 2-56) could be adjusted to optimize the grading of the system beam. The driver section has no spatial filters and may use five mirrors will route the beam to the driver section, where it will be focused with an f/3 final-focusing lens.

As shown in Fig. 2-56, the beam will be focused at a point following the 2

- 740-mm output and focus
- f/3 final-focusing lens

The full Nova system will consist of 20 additional beam lines of identical design located in the Shiva system bay, making a complement of 20 laser amplifier chains. As discussed below, the performance per chain is significantly enhanced over the baseline.

Nova Design Considerations. Figure 2-55 is a schematic of one Nova optical chain. Six chains will be used in the Phase 1 Nova system. Each chain comprises a driver section and two amplifier stages; the laser beam will be expanded to full 740-mm output diameter after it leaves the amplifier stage. In the output-amplifier stages, each head will hold two fluorophosphate-glass disks. The

design of these heads will be similar to that of our 340-mm prototype box amplifier (see "Amplifier Development," below). There will be a total of eight disks in the 315-mm stage and six disks in the 460-mm stage. Spacing of the components is such that two additional heads in each stage (dashed elements in Fig. 2-55) could be added should a future upgrading of the system be desirable. Final design of the driver section has not yet been completed; however, it will use some Shiva amplifiers and spatial filters and may use phosphate glass. Four or five mirrors will route the output beam to the target chamber, where it will be focused onto the target with an f/3 final-focusing lens.

As shown in Fig. 2-56, each chain will be folded at a point following the 208-mm spatial filter. The

Fig. 2-57. Sizes and spacings of spatial filter and relay elements for Argus, Shiva, and Nova. Aperture sizes shown are in mm.

folded chains, including their final spatial filters, will be located within the Nova laser bay. It is tentatively planned to drive all chains by a common oscillator/preamplifier stage, as in Shiva. The output of this stage, if it is used, would first be split two ways at a 50-mm-diam aperture, and each channel from this division would then be split five ways, again at a 50-mm-diam aperture. Splitting losses would be recovered through the use of 50-mm-diam rod amplifiers in the two-way and five-way channels. However, a final decision to drive the Nova chains in this manner has not yet been made, and alternative drive schemes are being evaluated.

The Nova chains will be spatially filtered and fully relayed. The object plane of the relay will be a "hard" aperture (i.e., an aperture without graded edges) placed at the entrance to each chain, with successive image planes occurring at the input lens of each spatial-filter/relay element and at the final-focusing lens. Figure 2-57 compares the sizes and spacings of the Nova spatial-filter/relay elements with those of Argus and Shiva. Table 2-10 gives the filter/relay parameters for the Nova baseline chain.

The pinhole diameters were chosen so that the beam intensity at the pinhole edge does not exceed 10^{11} W/cm² at the nominal performance of 10 TW

Table 2-10. Parameters of spatial-filter/relay elements in the Nova chain.

Filter/relay diameters (mm)	f/No.	Pinhole diameter (mm)	Angular acceptance aperture (μ rad) ²
460/740	20	3.3	360
315/460	20	1.5	340
208/315	25	1.0	190
146/208	20	0.75	250
92/146	11	0.3	300
92/92	11	0.3	300
42/92	18	0.76	1000
27/42 ^b	66	1.3	730

^aFull angle.

^bThis relay is not shown in Figs. 2-56 and 2-57. It follows the apodizing input aperture of the chain.

per chain with a 1-ns pulse. Higher beam intensities at this pulse length would cause closure of the pinholes by a high-temperature plasma created from the edge material of the pinholes. Pulses shorter than 1 ns will create higher beam intensities, but the beam will propagate through a pinhole before it closes. For longer pulses, wave-front retardation (B-value) decreases, thereby reducing pinhole loading. Calculations of pinhole sizes depend, of course, upon the noise model used. In our calculations, we used a model that gives good agreement with the

Table 2-11. Nova design limits (J/cm^2) for optical damage to AR-coated and uncoated optical surfaces.

	AR-coated surfaces			Uncoated surfaces		
	100 ps	1 ns	3 ns	100 ps	1 ns	3 ns
A-fluence (Median damage threshold for today's surfaces.)	1.6	5	5.5	5.1	16	28
B-fluence (Damage threshold for best of today's surfaces.)	2.5	8	8.5	6	19	33
C-fluence (Best super polish.) (Laser polish/graded index.)	3.8	12	12.5	11	35	61

noise spectra observed for the Argus and Shiva lasers.

Fluence Limitations. The performance of Nova (and other glass-laser systems) is limited largely by the threat of beam-induced damage to optical components. The most vulnerable components (i.e., those most susceptible to beam-induced damage) usually are the antireflection (AR) coatings on the input lenses of spatial filters and on the final-focusing lenses. To increase the performance of Nova, however, we will use uncoated spatial-filter input lenses while retaining the coatings on the spatial-filter output lenses and on the final-focusing lenses. Therefore, both uncoated and AR-coated surfaces will pose potential damage limitations in Nova operations, although the AR-coated surfaces are about 3.2 times more susceptible to damage than are the uncoated surfaces (see the guidelines, below). Other types of surfaces in the laser system (e.g., coated polarizer and high-reflection surfaces and bulk-material surfaces) typically have higher damage thresholds than do the AR-coated surfaces and should not limit performance of the Nova laser system.

To assess the threat of surface damage and to develop guidelines for Nova chain design, we evaluated currently available damage data and adopted the following guidelines:

- Bulk-glass damage and high-reflectance-coating damage are not limiting factors at present.

- For 1-ns pulses, uncoated surfaces are damaged at a median fluence of $16 \text{ J}/\text{cm}^2$, with 70% of the surfaces tested being damaged at fluences between 14 and $19 \text{ J}/\text{cm}^2$. At other pulse lengths (0.1 to 3 ns), uncoated surface damage appears to follow a $\sqrt{\tau}$ dependence, where τ is the laser-pulse duration.

- For 1-ns pulses, AR surfaces are damaged at a median fluence of $5 \text{ J}/\text{cm}^2$, with 80% of the sur-

faces tested being damaged at fluences between 4 and $7 \text{ J}/\text{cm}^2$. In addition, damage thresholds appear to increase slightly between 1 and 3 ns and scale as $\sqrt{\tau}$ for pulses shorter than 1 ns.

- There is a reasonable expectation that damage thresholds will increase as a result of recent progress with graded-index AR surfaces, superpolished AR coatings, and laser polishing of uncoated surfaces (see "Damage Studies," below).

Using these guidelines, we established three damage-threshold fluence groups for the baseline Nova design: the A-, B-, and C-fluence groups. Table 2-11 shows the damage thresholds for coated and uncoated surfaces in each group.

The thresholds in the A-fluence group represent the median values obtainable for currently available production coatings and surfaces. More specifically, the 1-ns values are the median values obtained by examining a large amount of data taken at this pulse length. Threshold values for other pulse lengths are scaled as $\sqrt{\tau}$, as discussed above.

Thresholds shown for the B-fluence group represent the highest values obtainable for currently available production coatings and surfaces. Again, values have been scaled from the 1-ns data as described above.

The C-fluence group represents an estimate of the damage threshold values that may be obtainable in the future if one or more of several advanced surface-preparation techniques can be brought into production. Presently, graded-index surfaces look the most promising, and two contractors (Corning Glass Works and Owens-Illinois) are mounting significant development efforts on this type of surface. Less-developed techniques of surface preparation are laser polishing and superpolishing of substrate surfaces. Laser polishing (burnishing the surface with a directed CO_2 laser beam) has been

Table 2-12. Properties of fluorophosphate laser glasses.

Glass	Vendor	λ_p	$\sigma(10^{-20} \text{ cm}^2)$	$\tau_R(\mu\text{s})$	$(\Delta\lambda)_{\text{eff}}$	n_0	n_2	$E_s(1\text{-ns})$
LGH-10	Hoya	1.051	2.6	475	31.3	1.45	0.58	4.9
E-309	O.I.	1.051	2.5	510	31.3	1.43	0.54	5.1
LG-810	Schott	1.051	2.6	495	31	1.43	0.49	5.1
ED-2 ^a	O.I.	1.064	2.7	359	34.4	1.56	1.41	4.5

^aSilicate glass.Fig. 2-58. Saturation fluence vs output fluence from a test sample of E-309 fluorophosphate glass. Test data were taken at 1- and 9-ns pulse durations. The center wavelength of the probe pulse was 1.053 μm . The solid curve represents the values that are used in Nova performance-simulation codes.

shown to significantly increase the damage threshold of a bare surface. Superpolishing (finishing the substrate with a bowl-feed process) has apparently increased the damage thresholds of AR coatings applied to the polished substrates. However, both laser polishing and superpolishing techniques are presently in a very elementary state of development and must be viewed as long-term approaches.

Our greatest short-term hope for increasing the damage thresholds of laser optics is to develop graded-index components suitable for laser operation at B-fluence levels.

Glass Properties. The choice of fluorophosphate glass for Nova optics was predicated upon the following considerations:

- Fluorophosphate glass has a low, nonlinear index of refraction.

- The saturation-fluence parameters of fluorophosphate glass are competitive with those of silicate glasses.

- There is a reasonable expectation that vendors can manufacture the fluorophosphate glass to our specification.

Listed in Table 2-12 are some important physical properties of three fluorophosphate glasses and ED-2 silicate glass, the latter of which has been used extensively in previous laser systems. The saturation fluence, E_s , shown in Table 2-12 corresponds to a value for which the output fluence from the glass test sample was $5 \text{ J}/\text{cm}^2$.

Recent experiments (see "Gain Saturation Properties of Laser Materials," below) have shown that saturation-fluence parameters are dependent

Table 2-13. Specifications for bulk properties of production fluorophosphate glass.

Attenuation (cm^{-1})		Homogeneity		Damage fluence ^a (J/cm^2)	
Min	Goal	Min	Goal	Min	Goal
0.002	0.0015	$\pm 1.5 \times 10^{-6}$	$\pm 1 \times 10^{-6}$	23	35

^aMeasured normal to beam in air. Actual fluence in a (tilted) disk is reduced by the index of refraction, n_D .

upon the fluence level. This relationship is shown in Fig. 2-58 for E-309 fluorophosphate glass. In the saturation experiments, all test samples were pumped to approximately the same initial small-signal and net gains, so the saturation parameters shown in Table 2-12 provide a valid comparison. From the data, we conclude that the saturation behaviors of fluorophosphate glasses are better than those of silicate glasses of similar cross section over the range of fluences tested. The variation of E_s with fluence is accounted for in our performance calculations.

Table 2-13 lists the specifications for bulk properties of production fluorophosphate glass; these specifications have been submitted to the three vendors listed in Table 2-12. We currently anticipate that production-quality samples of this glass, in the form of 315-mm- and 460-mm-diam disks, will be delivered between February and June 1980.

Amplifier Design. New box-amplifier designs (see "Amplifier Development," below) have been adopted for the 208-, 315-, and 460-mm disks. The 208- and 315-mm designs will follow from the 340-mm prototype amplifier that has been evaluated over the past year. Both the 208- and 315-mm heads will use standard Shiva lamps (1117.6-mm arc length) mounted longitudinally with respect to the axis of the amplifier. The 460-mm head will use short lamps (482.6-mm arc length), similar to the lamps used on Shiva rod amplifiers, mounted transversely, to the axis of the amplifier; other aspects of the design will be similar to those of the 315-mm head.

Table 2-14 summarizes some important design characteristics of the 315- and 460-mm amplifiers.

Isolation. The power-amplifier portion of the Nova chain is protected from self-oscillation by 94-mm-, 208-mm-, and 315-mm-diam Faraday rotators. For the baseline design, the round-trip small-signal gain between the 50-mm Pockels cell that precedes the 94-mm stage and the output of the 460-

Table 2-14. Design parameters for 315- and 460-mm Nova amplifiers using fluorophosphate glass.

Clear aperture	315-mm	460-mm
Thickness	49 mm	38 mm
Disks per module	2	2
Small-signal gain per module	1.65	1.65
Gain coefficient	4.3/m	5.4/m
Energy density	300 J/l	400 J/l
Glass volume per module	15 l	24 l
Bank energy per module	300 kJ	800 kJ
Gain coefficient $\times$ disk diameter (αD)	2.5	2.5

mm amplifier stage is about 70 times (assuming 100% return). Therefore, total distributed losses must exceed 98.6% to suppress oscillation. (This loss criterion is not severe. If we imagine, for example, that the loss can be modeled by partially reflecting mirrors placed at each end of that portion of the chain considered above, then the reflectivity of each mirror could be as high as 11.8%.)

For the fully expanded chain design, including twelve 315-mm disks and ten 460-mm disks, the margin of safety is small. In this case, the round-trip gain is about 3500 times, and an equivalent mirror reflectivity of less than 1.7% would be required. A reflectivity of this value could be produced by, for example, a bad AR coating on a Pockels-cell window. Therefore, care must be taken that such surfaces are not aligned normal to the beam line.

Since the last Faraday rotator in the chain is placed at the input to the 315-mm amplifier stage, the Nova chain is particularly vulnerable to light retroreflected from the target. For p-wave polarization at short pulses (small-signal-gain regime), the returned fluence is amplified by about 150 times in passing from the output of the 740-mm spatial filter through the 315-mm amplifier stage. This means that a retroreflection of several percent at the target

Fig. 2-59. Calculated energy and power performances for the baseline Nova chain. Lower- and upper-curve boundaries correspond to performances achieved by using the A-fluence and B-fluence damage limits shown in Table 2-11.

could, for example, endanger the AR coating on the 315-mm rotator glass. To prevent possible damage from retroreflection, Nova will have a fast triggered-plasma shutter to block the pinhole of the last spatial filter. This shutter will produce plasma at the critical density for 1.064- μm light ($\sim 10^{21}$ ions/cm³) for a time sufficient to absorb light returning from the target or from an opposing amplifier chain. Details of the plasma shutter development and implementation are discussed in "Plasma Shutter," below.

Nova Performance. Figure 2-59 shows calculated energy and power performance for one chain of the Phase I baseline laser. The lower boundaries on the curves are values that can be achieved within

the A-fluence limitations; the upper boundaries are values corresponding to B-fluence limitations. The curves suggest that, at B-fluence levels and long pulses (1 ns or longer), performance is limited by gain saturation and energy storage of the amplifiers as much as by damage thresholds. However, detailed calculations for pulses longer than 3 ns have not been made. With short pulses (i.e., pulses shorter than 1 ns), performance is limited primarily by small-scale, self-focusing effects (ΔB), with concomitant loss at spatial-filter pinholes, and by growth of spatial-filter bandpass modulation over long propagation paths. Additional 315- and 460-mm amplifiers will not significantly contribute to increased performance for either short or long pulse: under B-fluence limitations. However, if damage thresholds can be increased (e.g., to C-

Fig. 2-60. MALAPROP-calculated fluence values along the Nova baseline chain for 3-ns pulses. The solid lines represent peak values of the modulated beam; areas of average values are denoted by the symbol M. U = uncoated surface; C = coated surface. All values were obtained by using the B-fluence damage limits shown in Table 2-11. Also indicated is the component that first reaches the B-fluence limit.

fluence limits), the addition of amplifiers should lead to increases in performance for pulses longer than 0.5 ns.

Figures 2-60, 2-61, and 2-62 show MALAPROP calculations of fluence levels throughout the baseline Nova chain for 3-, 1-, and 0.1-ns pulse durations, respectively. The symbol M is used to denote average fluence levels, while the solid lines show peak levels of the modulated beams. All calculations were made using the B-fluence limitation.

For a 3-ns pulse (Fig. 2-60), the damage threshold was reached at the coated output lens of the penultimate spatial filter, which is located between the 315-mm and the 460-mm amplifiers (see Fig. 2-56). Nonlinear effects become less important for long-pulse operations than for short-pulse operations, and the ratio of input to output fluences at the spatial filters approaches the geometric expansion ratio ($\sim 2:1$). Since this ratio is less than the

damage-threshold ratio of uncoated optics to coated optics ($\sim 3.2:1$), the threshold of the coated output lens tends to be the limiting factor for long-pulse performance.

Reducing the pulse width to about 1 ns appears to produce a switch from a coated-surface threat to an uncoated-surface threat, as can be seen in Fig. 2-61.

At very short pulses (less than 1 ns), the long propagation path from the output of the last spatial filter to the final-focusing lens causes the damage threat to move to the coated surface of the latter element, as shown in the 100-ps run of Fig. 2-62. The major factors contributing to damage in this very-short-pulse case are the modulation created by the split disks in the final amplifier and the nonlinear-pathlength contribution of the 50-m nitrogen-and-air-filled beam tube.³⁴ With nitrogen removed, the

Fig. 2-61. MALAPROP-calculated fluence values along the Nova baseline chain for 1-ns pulses. All elements in this figure are defined as in Fig. 2-60.

short-pulse damage limit remains at the final-focusing lens, but the chain output power can be larger.

Figures 2-63, 2-64, and 2-65 show performance curves for the baseline Nova in relation to A-, B-, and C-fluence limits, respectively. In Fig. 2-63, curve (A) represents the hypothetical Nova performance obtainable with an unmodulated beam with an area that is 70% of the clear-aperture area (0.7 fill factor), while curve (P) shows the Nova performance that is calculated to be actually attainable. Separation of the two curves is a measure of the peak-to-average intensity ratio for the modulation in curve (P). As this curve shows, the modulation begins to increase rapidly for pulses shorter than 1 ns, but the damage threat remains at the uncoated elements, not at the coated surfaces. For pulses longer than 1 ns, beam modulation results largely from linear diffraction and, therefore, remains relatively constant. The long-pulse threat remains at

the coated spatial-filter output lens, as described above.

The calculated performances for B-fluence limitations, shown in Fig. 2-64, are qualitatively similar to those shown in Fig. 2-63 except that, for pulses near 1 ns, the threatened element shifts, as noted before, to the uncoated lens of the penultimate spatial filter.

In Fig. 2-65, which shows performance curves for C-fluence limitations, the nonlinear effects dominate over a much wider range of pulse durations, and the damage threat remains at the coated elements throughout the performance range shown. By extrapolating from calculations of B-fluence performance limitations, we estimated that increasing the damage thresholds to C-fluence limitations would provide only a modest increase in performance, ranging from about 6% at 0.1-ns pulses to about 20% at 1- and 3-ns pulses. However, detailed MALAPROP runs have not yet been made on these extended performances.

As noted above, short-pulse performance for all three fluence groups is currently limited by the

Fig. 2-62. MALAPROP-calculated fluence values along the Nova baseline chain for -ns pulses. All elements in this figure are defined as in Fig. 2-60.

damage threshold of the AR coating on the final-focusing lens. This limitation results from the long propagation path acting on modulation arising from the split disks in the output amplifier. If this coating threat could be removed (e.g., by apodization, by replacement of N_2 with Ar, or both), then the Nova baseline performance would be limited largely by intrastage wave-front phase retardation (ΔB) considerations.

Historically, we have limited ΔB to values of about 3.5 rad because of the appearance of a temporal dip in the output pulse. With a fully relayed chain, we expect that increased values of ΔB could be tolerated, which would lead to an improvement in laser performance. Recently, the temporal dip as observed in early Argus experiments, was successfully modeled with the MALAPROP code. Similar calculations for Nova suggest that, indeed, ΔB s much higher than previously tolerated may

well be possible. The effect of higher ΔB is shown in Fig. 2-66, which shows the results of MALAPROP calculations that were performed, with the threat of damage to the output lens removed for the purpose of calculation, for A- and B-fluence levels. Also shown in Fig. 2-66 is the calculated performance with the "traditional" ΔB requirement imposed. As may be seen, the curves suggest that rather impressive performance improvements may be possible if the damage threat to the output lens is removed.

Long-pulse performance of the baseline Nova chain may actually be better for all fluence groups than has been projected by MALAPROP calculations to date. The reason is that gain saturation is modeled "globally" (i.e., as if the whole beam experiences the same saturation gain) by MALAPROP, whereas the real-system beam saturates

"locally"; consequently, intensity peaks experience less gain than do valleys, so that the actual peak-to-average intensity ratio is reduced relative to that calculated by MALAPROP (as shown in Fig. 2-60, for example).

To establish a quantitative measure of this local effect, we developed an upgraded version of MALAPROP (see "Damage Studies," below), which provides detailed modeling of gain-saturation effects on two-dimensional beams. The differences between global- and local-saturation modeling are illustrated in Fig. 2-67, which shows anticipated fluences under both modeling systems for the Nova baseline chain operating at 3 ns. (The upper curve in Fig. 2-67 is the same as that shown in Fig. 2-60.) It is apparent from Fig. 2-67 that local-saturation modeling predicts a damage threat to the critical component (the coated output lens of the penultimate spatial filter) that is about 10% less than that predicted by global-saturation modeling. Thus,

Fig. 2-63. Calculated output power and energy for the Nova baseline laser system for A-fluence limitations. Curve (P) corresponds to calculated performance values expected to be obtained when A-fluence damage limitations are imposed. Curve (A) corresponds to hypothetical performance values obtainable within A-fluence limitations if there were no spatial modulation on the beam. The separation between these curves is a measure of the peak-to-average intensity ratio for the modulation in curve (P).

Fig. 2-64. Calculated output power and energy for the Nova baseline laser system for B-fluence limitations. Curve (P) corresponds to calculated performance values expected to be obtained when B-fluence damage limitations are imposed. Curve (B) corresponds to hypothetical performance values obtainable within B-fluence limitations if there were no spatial modulation on the beam. The separation between these curves is a measure of the peak-to-average intensity ratio for the modulation in curve (P).

at long pulse durations, local-saturation modeling with a modified version of MALAPROP indicates that there is an additional performance margin for Nova, in terms of optical-damage threats, relative to that shown, for example, in Fig. 2-64.

Amplified Spontaneous Emission (ASE). Each laser amplifier is a source of fluorescent "noise" created by spontaneous emission from the inverted population of ions. This noise is subsequently amplified by succeeding stages to produce a net amplified spontaneous emission (ASE) from the laser chain. Much of the ASE arrives at the target before the main irradiating pulse and, consequently, represents a damage threat to vulnerable targets.

Table 2-15 shows calculated ASE values for the Nova system. Since one option for reducing ASE in Nova is to develop a 100-mm-diam Pockels cell for incorporation into the laser chain, two sets of calculations are presented in Table 2-15: one set that assumes a 100-mm-diam ASE-isolation Pockels cell placed after the second 100-mm-diam (beta) amplifier in the laser chain (in Fig. 2-56, this amplifier is denoted as a 94-mm amplifier, which is the clear aperture of the amplifier); and another set that

Fig. 2-65. Calculated output power and energy for the Nova baseline laser system for C-fluence limitations. Curve (P) corresponds to calculated values obtained when C-fluence damage limitations are imposed. Curve (C) corresponds to hypothetical performance values obtainable within C-fluence limitations if there were no spatial modulation on the beam. The separation between these curves is a measure of the peak-to-average intensity ratio for the modulation in curve (P).

assumes no Pockels cell in this location. We currently consider the latter situation to be the baseline design. Further conditions and assumptions used in the calculations presented in Table 2-15 are:

- Amplifier gains are chosen to produce peak laser performance at 3 ns, and B-fluence-limited performance is assumed.
- 100-mm Pockels cells are assumed to have a contrast ratio of 30:1.
- The amplified fluorescent pulse width is taken as 300 μ s at chain output, and the spectral line shape is that given in the LLL handbook on laser glass.³⁵
- All Pockels-cell time-interval gates are set at 50 ns.

With reference to Table 2-15, several broad observations can readily be made. First, the total ASE energy for the baseline system with the Pockels cells closed seems low (5.0 mJ/chain), and the largest contribution to ASE occurs when the cells are opened. Second, the ASE energy density on axis and in the focal plane of the final-focusing lens is very

Fig. 2-66. Calculated power performance of one Nova baseline laser chain. The upper two curves correspond to values obtained when A-fluence and B-fluence limits for optical damage are imposed. The bottom curve corresponds to performance limits imposed by nonlinear phase retardation with concomitant growth of spatial instabilities (B-fluence limit). A ΔB of 3.5 rad for the incremental phase retardation accumulated between each pair of spatial filters has been imposed on the calculations leading to the bottom curve.

high; therefore, target surfaces should not be located in this plane. Third, the energy density drops rapidly as a function of distance from the focal plane, but the energy density is still high (28 J/cm²) when the Pockels cells are open for 50 ns. Finally, addition of 100-mm Pockels cells to the Nova system reduces ASE by a factor of about 10 when the cells are closed, but this reduction has only a small impact on the total ASE accumulated during the gate interval. (Table 2-15 shows only the "open-gate" values obtained without the 100-mm Pockels cell.)

Figure 2-68 shows, for a single chain, both the temporal variation of ASE energy density at a location 1 mm forward of the focal plane and the total ASE energy. Three temporal regions are identified. In region I, the Pockels cells are closed and the ASE increases slowly (150 μ s) to an energy density of 2.5 J/cm² and total energy of 2.5 mJ. At this point, the Pockels cell switches are opened (note time-scale change), and the ASE values climb rapidly until the

Fig. 2-67. Calculated fluence values at spatial filters along the Nova Phase I chain for 3-ns pulses. The solid lines represent peak values of the modulated beam fluence; the upper line is the same as that shown in Fig. 2-60, while the lower line includes the effects of gain saturation in a realistic model. The areas of average fluence are designated by the symbol M. U = uncoated surface; C = coated surface.

Table 2-15. Calculated values of ASE in Nova. Calculations assume B-fluence-limited performance at 3 ns, a 30:1 contrast ratio for the 100-mm Pockels cell, 50-ns gate widths for all Pockels cells, and a 300- μ sec FWHM of the amplified fluorescent pulse at the output of the amplifier chain.

	All Pockels cells closed		
	Without 100-mm Pockels cells (baseline)	With 100-mm Pockels cells	All Pockels cells open (50-ns gate without 100-mm cell)
ASE energy per beam	5 mJ	550 J	24 mJ
Total Nova I ASE energy (10 beams)	50 mJ	5.5 mJ	240 mJ
Peak energy density in focal plane (single beam)	84 J/cm ²	7.7 J/cm ²	(2.5)10 ⁴ J/cm ² ^a
Peak energy density 1 mm from focal plane (single beam)	5.3 J/cm ²	0.48 J/cm ²	28 J/cm ²
Peak power density in focal plane (single beam)	(2.8)10 ⁵ W/cm ²	(2.6)10 ⁴ W/cm ²	(5)10 ¹¹ W/cm ² ^a
Peak power density 1 mm from focal plane (single beam)	(1.8)10 ⁴ W/cm ²	(1.6)10 ³ W/cm ²	(2.6)10 ⁸ W/cm ²

^aDiffraction-limited spot.

switches are closed 50 ns later. Typically, the laser pulse arrives at the center of the Pockels-cell gate (here shown at $t = 0$), so only the additional ASE

arising between switch-open time and pulse-arrival time (region II) is of concern in the operation of the laser. With the pulse at gate center ($t = 0$), the ASE values climb to an energy density of 14 J/cm² and a

Fig. 2-68. Calculated time evolution of ASE energy density and total energy for a single Nova baseline chain. (Assumptions: B-fluence; 3-ns drive; 300- μ s FWHM fluorescent pulse; 50-ns Pockels cell gate.) The energy density is calculated at a plane 1 mm forward of the best focus for the f/3 final-focusing lens. In region I, all Pockels cells are closed. In region II, the Pockels cells are open but the main laser pulse has not yet arrived at the target. In region III, the Pockels cells remain open but target irradiation has been completed.

total energy of 12.0 mJ over a time of 25 ns for the baseline system (i.e., no 100-mm Pockels cell). While the ASE fluence at this point seems high, the time scale over which it arrives is so short that it may not represent a damage threat.

The ASE in region II can be reduced by moving the pulse-arrival time closer to the switch-on time. It is reasonable to expect that, at least for the small Pockels cells in the preamplifier section, where much of the ASE originates, this arrival time could be reduced to 10 ns, which would reduce the ASE energy density to about $7 \text{ J}/\text{cm}^2$ and the total energy to about 6.0 mJ per chain.

Region III is simply the postshot ASE, which appears to be of little consequence with regard to target damage unless the main pulse should fail to be switched out—a situation that seldom occurs with our reliable pulse-generation systems (see "Control System," below).

Figure 2-69 shows the spatial distribution of ASE in the focal plane when the Pockels cells are closed. The structure of this "spot" arises from the changing angular aperture of the spatial filters along the beam line from the preamplifier to the

Fig. 2-69. Calculated ASE power distribution from a single Nova chain at the focal plane of the f/3 final-focusing lens. For these calculations, all Pockels cells remain closed. The rectangular step-like distribution arises from the superposition of individual, uniformly illuminated spatial-filter pinholes.

final output filter. Each rectangular portion of the spot shown in Fig. 2-69 represents the image of an individual spatial-filter pinhole. Forward of the focal plane (i.e., toward the beam source), this rectangular structure will wash out, and the spot is then better approximated by a uniform distribution, which was assumed for calculations of the energy densities shown in Fig. 2-68 and in rows 4 and 6 in Table 2-15.

The estimates of ASE for the baseline Nova system rely largely on theoretical calculations, suitably normalized to experimental measurements on Shiva, and to single-rod ASE experiments (see "Theory and Design Analysis," below).

Target Irradiation. For Phase I of Nova, each of the ten 740-mm output beams will be focused onto the target with a single-element f/3 focusing lens having a focal length of 2.2 m. The irradiation geometry is that of two opposing clusters of five beams each. Within the limitations of single-beam irregularities ($\pm 25\%$), this geometry allows irradiation of a sphere with the same uniformity that is

Fig. 2-70. Final focusing geometry and calculated intensity at best focus for a single cluster (5 beams) of the Phase I Nova baseline laser.

provided by a 12-beam dodecahedral geometry, while maintaining the geometry with which we are familiar in Argus and Shiva. The beams in each cluster are arranged as an open cone, the cone angle of which can be varied between 80° and 110° by relocating lenses and turning mirrors. Figure 2-70 depicts the geometry for a single cluster having a cone angle of 90° . This figure also shows the five-beam focal spot size ($150\ \mu\text{m}$) and the image size of the final spatial-filter pinhole. The focal spot size for an individual beam was estimated to be a pulse of 1-ns duration by using MALAPROP; the composite spot size of $150\ \mu\text{m}$ results when alignment

tolerances are included (see "Alignment and Beam Diagnostics," below). A peak intensity of about $5 \times 10^{17}\ \text{W}/\text{cm}^2$ is obtained at a 1-ns pulse if all five beams are brought to best focus.

Authors: W. W. Simmons, J. A. Glaze, J. B. Trenholme, and W. F. Hagen

Major Contributor: W. E. Warren

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Optical Pulse Generation

All of the front-end functions for Nova—initial pulse generation, preamplification, temporal and spatial shaping, and prepulse isolation—will be done in a separate room in the Nova laboratory building. We have located this room—the master oscillator room (MOR)—in the basement, adjacent to the control room and beneath the optical switchyard. The MOR will be a class 10 000 clean room (less than 10 000 particles larger than 0.5 μm per cubic foot of air) and will be isolated electrically from the main laser bay. The controls for the MOR will be totally separate from the main control room so that MOR setup and maintenance can proceed independently of the laser chains.

Two new developments have required a major rework of the MOR layout. First, improvements in our understanding of ASE and improvements in fast Pockels-cell drivers (see "Fast Pulse Development," below) have made possible the elimination of a bleachable dye cell. Second, the need for a future capability for generating a separate, synchronous pulse for target diagnostics required us to leave room for a second preamplifier beam line that would have all the functions of the main beam line.

Figure 2-71 shows the new MOR layout. All of the required diagnostic-pulse hardware is shown, including the synchronized oscillator, the regenerative compressor,³⁶ and the second preamplifier beam line. We have located all the controls at the left end of the room, including those for the pulse synchronization system (PSS).³⁷ This arrangement minimizes traffic flow around the tables and allows convenient interconnection to the main control room. The 50-mm-diam rod amplifiers and their associated Pockels cells and rotators are located in the right half of the room to minimize electrical interference. To accommodate the diagnostic-beam requirement, we have incorporated two beam lines per table. This layout causes some sacrifice in accessibility but provides the most total table space, including room for expansion and room for pulse-shaping hardware, when needed, on the central table.

Two types of oscillators will be used to provide the needed range of pulse widths for the main target pulse (see "Oscillator Development," below). An actively mode-locked, Q-switched oscillator will provide pulses ranging from 0.1 to 1 ns. Longer

pulses, from 1 to 10 ns, will be obtained from the output of a single-axial-mode Q-switched oscillator. We will use fast Pockels cells to generate the desired pulse length from its nominal 50-ns pulse. The two oscillator outputs will be

Fig. 2-71. Layout of the Nova master oscillator room showing diagnostic-pulse hardware and main beam line.

Each letter designator is shown in more detail on a separate drawing used to organize the components into a system. Each of the blocks are assigned to a separate sheet for more detail. If the component level drawing is not reached, this drawing is again divided into blocks titled with this page number plus another number separated with a decimal point. (This allows more than nine subdocuments at any level, such as P7.16.23, and the number of sub-levels to be unlimited.) The detail grows until the component level schematic is reached (see Fig. 2-55). The page reference number created by this process allows one to regress to a higher level drawing at any point by ignoring the last number group of the sheet being used and turning to the page with the remaining number. The higher level drawing will show the block and how it is related to surrounding units.

Another aid for cross referencing is the reference bubble. When a signal path is broken the drawing and zone number at which it continues are shown by a bubble as shown below.

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used for either target or diagnostic pulses. This redundancy will allow maintenance or setup to be performed on one beam line without interfering with the operation of the second beam line.

The ASE energy from the MOR that will arrive at the target from any given amplifier is proportional to:

- The ASE spectral width at the target.
- The time that the target is exposed to the amplifier.
- The apparent cross-sectional area of the amplifier.
- The maximum solid angle subtended by the target.

To control ASE from the MOR, we will restrict the above factors in the following three ways. First, the first two amplifiers in the MOR will use Nd:YLF rods, which, because of the relatively narrow spectral width of Nd:YLF, will result in the amplifiers producing only about one-third the ASE at the end of the chain that would be produced by Nd:glass amplifiers with the same gain.

Second, improvements in Pockels-cell driver technology will allow us to drive the last MOR Pockels cell with a 10-ns gate, which is about 5 times shorter than we had planned on last year.

Third, we will reduce the area and solid angle by locating the apodizing aperture as far downstream as possible. (The apodizer reduces the apparent area of amplifiers behind it.) Before entering the apodizer, the laser beam has a Gaussian profile, which allows much tighter spatial filtering than does an apodized profile and gives a corresponding reduction in transmitted solid angle. However, since a Gaussian profile also gives a very poor fill factor, there is a limit to how far downstream the apodization can be done without sacrificing output energy. For the MOR layout, we have decided to locate the apodizer after the first four amplifiers and immediately after a spatial filter with the smallest possible pinhole. This arrangement will reduce the ASE from these four amplifiers by about a thousandfold, as compared with apodizing immediately after the oscillators.

With the reductions in ASE outlined above, the ASE energy from the MOR will be comparable to that from the remainder of the system, even without the dye cell.

Other aspects of the MOR layout have been retained as before:

- The beam will be relayed completely from the output mirror of the oscillator to the input of the splitter array.

- Space is provided for automatic alignment systems for the two main preamplifier sections, as well as for the alignment laser and the PSS. We will use the same alignment sensors for both preamplifier lines.

- All gain control will be provided with adjustable half-wave plates followed by polarizers. All amplifiers will be operated at the same voltage or will be turned completely off.

- An alternative injection point for the alignment laser will allow bypassing of the preamplifiers and the apodizer, thereby providing a backup for the alignment laser in the main laser bay.

This current MOR layout will provide adequate gain for the most demanding drive requirement of the current Nova design, and it will do so with only a 30% reduction in small-signal gain due to saturation, giving a minimum of temporal pulse distortion in the MOR. In addition, the layout has an excess gain capability that is 12 times the maximum projected requirement, and it has table space for additional expansion.

Author: J. E. Murray

Major Contributor: D. J. Kuizenga

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37. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977), p. 2-94; *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), p. 2-30.

Optical Components

This discussion of Nova optical components will cover fluorophosphate glass; BK-7 borosilicate glass; Faraday rotator material; deuterized KDP (KD*P); epoxy membranes; KDP material for harmonic generation; finishing of optical flats; lens finishing; and optical coatings.

Fluorophosphate Glass. Early in 1979, Hoya Corporation, Owens-Illinois, Inc., and Schott Optical Glass, Inc., embarked on a three-phase

Table 2-16. Laser disk specifications for three phases of development program.

Phase	Quantity	Damage threshold ^a (J/cm ²)	Refractive index homogeneity (Δn)	Loss (cm ⁻¹)	Edge cladding reflectivity
I	4	18	$\pm 3 \times 10^{-6}$	0.004	0.4%
II	4	23	$\pm 2 \times 10^{-6}$	0.002	0.25%
III	4	30	$\pm 1 \times 10^{-6}$	0.001	0.1%

^aMeasured normal to beam with disk at Brewster's angle.

preproduction program to deliver 340-mm aperture disks of fluorophosphate glass, the quality of which would increase with each succeeding phase of the program. The disk specifications for the three program phases are listed in Table 2-16; additional specifications, which are not listed in Table 2-16, are similar to those used for the Shiva components.

As Phase I neared completion, we modified the program to obtain delivery of new Nova-sized disks of 315- and 460-mm clear aperture to conform to the final design of the laser, and Phases II and III were combined into a single phase, called Phase II/III. The 460-mm disks will be split along their minor axes to reduce the ASE loss and to simplify the manufacturing process. Three 315-mm disks and six 460-mm disk halves will be delivered in Phase II/III from each manufacturer.

Significant progress has been made toward improving the optical quality of fluorophosphate glass. The refractive index homogeneity of some of the 340-mm disks is $< \pm 1.7 \times 10^{-6}$, as shown in Fig. 2-72. Measured loss coefficients are between 0.001 and 0.003 cm⁻¹. Both frit and solid edge claddings have been successfully employed to suppress parasitic oscillations.

The only remaining significant problem with the fluorophosphate glass is the laser-beam damage threshold of the bulk material. To date, one manufacturer has melted and cast fluorophosphate glass that meets the Phase II/III damage-threshold specification, while the other two manufacturers have produced disks that meet the Phase I specification. The typical number of damage-causing inclusions has been decreased by three or four orders of magnitude during the past year. In addition, we have strong evidence that the damaging inclusions are metallic platinum particles (see "Damage Studies," below). The manufacturers are working to eliminate these particles by preventing dissolution

Fig. 2-72. An interferogram of a 340-mm diameter by 350-mm thick fluorophosphate disk. The interferogram was made on a 305-mm aperture Fizeau interferometer using He-Ne laser light. The measured variation in refractive index is $< \pm 1.7 \times 10^{-6}$. (Courtesy of Schott Optical Glass, Inc.)

of the platinum crucible and by oxidizing the platinum in the melt to the benign 2+ and 4+ ionic states. Considering the recent progress that has been made toward solving the inclusion problem, we are confident that damage-free fluorophosphate glass meeting the Nova requirements will be in production by mid-1980.

In conjunction with the melting program, we supplied glass to fabrication companies for a surface-finishing program. We inspected the returned parts and found smooth surfaces ($\sim 8 \text{ \AA}$ rms) with an absence of streaks, scratches, and pits. The LLL optical shop has polished fluorophosphate glass surfaces to between 4 and 8 $\text{\AA}$ rms smoothness, as measured by an optical heterodyne technique

(Fig. 2-73). Because the fluorophosphate glass surface is softer and more reactive than commonly used optical material, we initially employed very soft pitches (viscosity of about 10^7 P), but these proved to be too soft for large, continuous-polishing planetary laps. We then found that a beeswax-pitch mixture, which has viscosities ranging from 6 to 9×10^9 P, is adequate for planetary lapping. Surfaces resulting from such lapping have damage thresholds of 13 to 17 J/cm^2 .

BK-7 Borosilicate Glass. The 10 beams of Nova Phase I contain about 8000 litres (20 000 kg) of BK-7 glass, of which about 3000 litres is high-homogeneity material and the remainder is mirror-quality material. The largest high-homogeneity pieces are 940 mm in diameter and 100 mm thick, while the largest mirror-quality pieces are 1.09 m in diameter and 160 mm thick. Most of the BK-7 glass for Nova is being manufactured by Schott Optical Glass, Inc., where the manufacturing and test facilities have been increased to accommodate projects of this magnitude.

Faraday Rotator Material. Hoya Corporation has contracted to manufacture FR-5 Faraday

rotator disks for the 315-mm-diam stage. These disks, which are approximately 330 mm in diameter by 20 mm thick, contain about 1.7 litres of material (70% terbium oxide by weight) and require a Verdet constant of ≥ 0.070 units at $1.05 \mu\text{m}$ and a wave-front homogeneity of $0.08 \mu\text{m}$. These disks represent a considerable achievement in the field of melting and casting of rare-earth glasses.

Phase-Separated Material. Phase-separated material, which is based on original work done by Corning Glass Co., has recently been developed for optical applications. Three glass companies (Corning Glass, Owens-Illinois, and Hoya Corporation) have now developed this technology to the point where we are optimistic that it can be used in Nova spatial-filter lenses up to and including the 460-mm size. (The 740-mm beam-line optics, which will initially be made of BK-7 glass, might eventually be retrofitted with phase-separated material.)

Although it varies in detail from manufacturer to manufacturer, phase-separated material is basically a two-phase silicate glass that is etched after finishing to produce a graded index at the surface. This graded index suppresses the Fresnel reflection and has a higher damage level³⁸ than is currently obtainable with thin-film coatings.

Deuterated KDP (KD*P). In August 1978, an order was placed with Cleveland Crystals, Inc., to grow, on a best-efforts basis, 90% deuterated KDP single crystals suitable for use in Pockels cells having a 100-mm-diam aperture and a z-axis length-to-diameter ratio of 1:1 or more. Several crystals were harvested in the fall of 1979, and one of these appears to meet all critical specifications for homogeneity and birefringence. Figure 2-74 is an interferogram in double pass at $0.633 \mu\text{m}$ over the 100-mm-aperture, 120-mm-long crystal. This crystal will be cut to a length of 100 mm and assembled in a prototype Pockels cell.

As reported in "Large-Aperture Pockels Cells," below, we are developing a technology that should permit the use of crystals with much shorter z-axis lengths. When this technology matures, long crystals like the ones grown for this experiment could provide enough material for several Pockels cells. In addition, Cleveland Crystals is currently using an improved process to grow additional 100-mm-diam KD*P crystals. The apparent success of the improved process, together with the excellent results obtained on the crystal grown last year,

Fig. 2-73. Surface profile of a finished fluorophosphate sample as measured by an optical heterodyne technique. The figure shows the surface elevation around a 0.5-mm-diam circle; the zero value of elevation is that at the center of the circle. The surface has a $4.1 \text{ \AA}$ rms roughness, a $24\text{-}\text{\AA}$ peak-to-valley (p-v) value, and $4 \text{ \AA}$ astigmatism.

Fig. 2-74. Interferogram over the 100-mm diameter of a 120-mm long KD*P (90% deuterated) crystal. Double pass at 0.633 μm . (Courtesy of Cleveland Crystals, Inc.)

$\lambda/6.6$ ($\lambda = 1.064 \mu\text{m}$)

4-in. diam

suggests that massive, heavily deuterated KDP crystals are practical for use in Pockels cells.

Epoxy Membranes. Epoxy membranes have been produced by Acton Research Corporation for use in evaluating transmitted wave fronts and laser-beam damage thresholds. These epoxy sheets, each 0.001-in. thick, may partially or completely replace the more-expensive polished debris shields currently used to protect the optics in our target chambers.

An epoxy membrane supported in a tensioning ring exhibited a transmitted wave front of $\lambda/6$ at 0.6328 μm . The transmitted wave front of the membrane remained essentially the same ($\sim\lambda/6$) after the tensioning ring was loosened and also when the membrane edge was supported only by masking tape at three points 120° apart.

At a 45° incidence angle, the wave front was virtually unchanged, but a significant increase in small-scale roughness appeared on the figures. The reflected wave front at 45° was so irregular that no image was formed.

Based on the above results, we judged that the epoxy membrane is useful in transmission, even

when crudely supported, but is of little use in reflection.

Three commercial plastic wraps were ring supported, and each was evaluated for wave-front transmission; all were found to be of poor quality in transmission.

After the initial wave-front measurements had been made on the ring-supported epoxy membrane, both sides of the membrane were coated with a quarter-wave of cryolite. No difficulties in either vacuum compatibility or sensitivity to the heated vapor source were experienced during the coating cycle.

Damage-threshold measurements were made using the comparative-damage-test (CDT) laser both before and after coating. This epoxy membrane exhibited a high damage threshold (between 15 and 24 J/cm²) when uncoated and a lower damage threshold (between 2.7 and 3.5 J/cm²) after coating. There was no evidence of decomposition of the epoxy, even at high fluence levels.

A second membrane was measured for wave-front transmission in three stages of positioning in the ring support: course position, adjusted or straightened, and tensioned. In all cases, the transmitted wave front for the second membrane was approximately $\lambda/3$. This somewhat lower wave-front quality, as compared with the first membrane, is probably attributable to processing variations in this state-of-the-art effort.

Both membranes tested were of debris-shield quality. Small-scale roughness was more apparent when tensioning was absent.

KDP Material for Harmonic Generation. We are studying the possibility of converting the Nova infrared beam to a green beam, with the harmonic generation, or doubling, occurring in a highly nonlinear material. Of the nonlinear materials that could possibly be used, KDP is the only one that has been grown to a size comparable to the Nova apertures. A recently grown 200-mm KDP crystal is shown in Fig. 2-75.

We have the option of placing the frequency-doubling crystals anywhere after the final 460-mm amplifier and before the 740-mm final-focusing lens. Because it takes 2 years or more to grow KDP crystals greater than 460 mm in diameter, we will have to use crystal arrays to cover apertures of

Fig. 2-75. KDP crystal boules measuring 200 by 200 mm in cross section. (Courtesy of Interactive Radiation, Inc.)

≥ 460 mm; otherwise, the KDP doubling assemblies will not be available in time for the Nova activation date of April 1983.

The array configuration that we now favor is a 460-mm 2×2 array with the crystal elements oriented so that one set of edges is parallel to the direction of the split in the 460-mm amplifiers. This configuration has several advantages over other configurations that use larger apertures on a larger number of elements, including:

- Smaller number of elements.
- Minimum aperture size and crystal volume.
- Faster availability.
- Minimum number of beam obscurations.

The only disadvantage of the selected configuration is a higher risk of surface damage due to the higher

energy fluence at the 460-mm aperture. We will be measuring the susceptibility of KDP surfaces to laser damage and determining the dependence of the damage threshold on surface-polishing techniques. Both conventionally polished and diamond-turned surfaces will be investigated.

KDP crystals are solution-grown from seeds in large tanks over a long period (about 1 year for a 250-mm crystal). Because of the long growth times, we have initiated programs at three crystal producers to grow large crystals and to start new seeds; by the end of 1980, the KDP crystal growers will start growth runs of crystals up to 340 mm in diameter. As a result of this production capability, we will be able to double the Nova frequency (i.e., produce a green beam) by early 1983. We expect Cleveland Crystals, Inc., Lasermetrics, Inc., and In-

teractive Radiation, Inc., to participate in the program.

Finishing of Optical Flats. During the past several years, LLL, working closely with industry, has been instrumental in developing advanced technology for the precision finishing of large, flat optical components.³⁹ LLL owns the largest high-precision planetary lapper in use, a 2.4-m-diam machine currently installed at the Zygo Corporation.

Several of our vendors have studied the flat-lapping requirements for Nova, and two of them, Eastman Kodak Co. and the Zygo Corporation, have proposed extending the annular-ring-lapping technology to machines in the range of 3.7 to 4.6 m in diameter to accommodate the large sizes of the Nova components. In comparison with the more conventional Draper or modified-Draper machines, the annular-lap technology appears to produce parts at about one-third the unit manufacturing cost. For example, the average quoted price to finish a 1.09-m-diam front-surface mirror on an annular-lap machine is about \$6000 ($\$0.64/\text{cm}^2$) vs about \$20 000 ($\$2.14/\text{cm}^2$) on a Draper machine. Thus, the annular-lap technology is remarkably cost effective for flat optical surfaces, of which the 10-beam Phase I Nova contains about 170 m^2 , with sizes ranging up to 1.09 m in diameter.

LLL is having two annular-lap machines built, one at Eastman Kodak and one at Zygo Corporation, together with the required interferometry components. This equipment will be ready to begin work on Nova components late in 1980.

Lens Finishing. The lenses used in Nova are the spatial-filter lenses and the focusing lenses, which are located in the laser beam, and various diagnostic lenses, which are not located in the beam.

The lenses in the laser beam must withstand high fluence densities: the input spatial-filter lenses will see about $20 \text{ J}/\text{cm}^2$ at 3 ns, and the output spatial-filter lenses and the focusing lenses will see about $7 \text{ J}/\text{cm}^2$ at 3 ns. Because of the particularly high fluence level on the input spatial-filter lenses, the baseline design calls for these lenses to be uncoated. In addition, to control the first ghost reflection, these lenses will be meniscus-shaped so that the second surface of each lens will be concentric with the focus, thus producing a collimated ghost reflection. (Actually, the reflection will be slightly decollimated so that the focus of the ghost will not

occur exactly in the focal plane of the previous spatial-filter assembly.) There is a good possibility that we may be able to use lenses made of the more desirable phase-separated material as an alternative to the uncoated meniscus lenses.

The largest lenses in the system are those used in the 740-mm output beam: these large lenses include, for each beam, the output spatial-filter lens, the focusing lens, and the beam-diagnostics objective lens. The overall diameter of these lenses is actually 800 mm, which allows 30 mm of additional clear aperture for alignment and 30 mm for mounting.

The spatial-filter lenses are $f/20$, so that the 740-mm output lenses, which are bent for minimum coma, require about $1 \mu\text{m}$ of asphericity for the correction of spherical aberration. The 460-mm spatial-filter input lenses, which are meniscus-shaped, require about $3 \mu\text{m}$ of asphericity.

The focusing lenses and the diagnostic lenses are significantly more aspheric than the spatial-filter lenses. For the focusing lenses, the aspheric deviation from the best-fit sphere is 0.31 mm at the edge of the clear aperture (770 mm) for a focal ratio of $f/2.88$; for the diagnostic lenses, the aspheric deviation is 1.10 mm for a focal ratio of $f/1.92$.

We expect that Eastman Kodak Co., Perkin-Elmer Corp., and Tinsley Laboratories, Inc., will participate in the manufacturing and finishing of these large aspheric lenses, which represent a significant challenge to the optical industry.

Optical Coatings. The peculiar characteristics of Nova that relate to optical coatings—large substrate size, coating complexity, and high damage threshold—have necessitated a special approach to the procurement of production optics. The magnitude of Nova coating problems is indicated by Fig. 2-76, which compares the largest Shiva mirror with the largest Nova mirror.

Optical coatings contain up to 30 layers, with the thickness of each layer controlled to within as little as $10 \text{ \AA}$. State-of-the-art production coatings have the damage threshold ranges shown in Fig. 2-77, and these thresholds are the limiting factors in the Nova design.

Vendors currently do not have the facilities to produce optical coatings on Nova-sized substrates to the tolerances required for lasers used in fusion

Fig. 2-76. Comparison of the largest Shiva mirror with the largest Nova mirror.

	Shiva	Nova
Diameter	370 mm	1090 mm
Thickness	80 mm	160 mm
Weight	22 kg	375 kg

Fig. 2-77. Ranges of damage thresholds for production optical coatings.

*Includes 100% reflectors, 98% reflectors, and 's' polarizers.

research. During production of the Shiva optics, only two vendors were able to successfully coat the most complex coatings (polarizers) on 240- by 420-mm substrates; the largest Nova polarizer will be almost three times this size. These historical factors, combined with a review of the production capabilities of other potential vendors, determined the current approach to procurement of the large-aperture coated optics listed in Table 2-17.

The two sources of large coated optics for Shiva, Optical Coating Laboratory, Inc. (OCLI),

and Spectra Physics, Inc., were selected as Nova coating vendors because of their proven ability to produce large-aperture, complex, high-damage-threshold coatings. Even these vendors, however, had facilities that were limited to producing the largest Nova optics on a one-at-a-time basis, which is inefficient because hundreds of hours are required to safely cool each massive optical component from the high temperature required by the coating process.

When many substrates can be coated in one coating run, the unit cost and the unit processing time become inversely proportional to the number of parts in each run. Consequently, we are having both vendors design and build very large coating chambers for us at their facilities; OCLI is building a 120-in.-diam chamber, and Spectra Physics is building a 96-in.-diam chamber. OCLI will provide most of the largest coated optics ($>800\text{-mm-diam}$), while Spectra Physics will produce coatings on most of the intermediate-sized optics (130 mm through 610 mm) as well as enough of each type of coating on large optics to qualify as a second source.

In addition to building the 120-in. vacuum coating chamber, OCLI will design a photometer for measuring both transmittance and reflectance and will employ a test laser, supplied by LLL, for evaluating the damage thresholds of production optical coatings on large optics. The OCLI chamber is designed to support at least two 830-lb substrates per run or, alternatively, four substrates weighing up to 460 lbs each. The vacuum coater will include a planetary rotation system and a relatively long source-to-substrate distance to achieve the required uniformity of coating thickness (see Fig. 2-78). The photometer will be an improved, scaled-up version of the instrument used to measure the large Shiva optics and will include a large motorized x-y stage to position the largest optics for measurement of spectral performance.

The test-laser system at OCLI will be similar to the CDT instrument currently in use at LLL (see Fig. 2-79). This system will enable OCLI to confirm the damage-threshold level of production-coated optics by comparing the incipient damage to these optics with damage caused (or not caused) simultaneously on a previously measured reference plate, which will be characterized at LLL.

In addition to these facilities tasks, OCLI will also pursue a modified substrate-cleaning process

Table 2-17. Optical coatings for Nova optical elements.

Coating	Diameter (cm)	Center thickness (cm)	Clear aperture normal to the beam	Quantity
98% Turning mirrors	94	10	79	14
	60.4	7	35.5	14
100% Turning mirrors	109	16	79	16
	94	12	79	32
	82	12	79	12
	60.4	7	35.5	14
Polarizers	70 × 40	2	33.5	52
	42 × 24	1	22	34
AR coatings				
Spatial-filter lenses	24	1.7	22	13
	36.5	2.6	33.5	13
	52	3.7	49	13
	80	5.7	77	16
Focusing lens	80	9.2	77	16
Window	80	6.5	77	16
ABD/IBD lens	80	12.9	77	12
FR-5 rotators	23.6	1.5	22	12
	33.1	1.97	35.5	12
Debris shield	80	1.5	77	12

Fig. 2-78. Sketch of the LLL 120-in. coating chamber being built by OCLL (Courtesy of Optical Coating Laboratory, Inc.)

Fig. 2-79. Comparative damage test facility at OCLI.

for large optics and a yield-improvement study for large-sized Nova polarizers.

The 96-in.-diam chamber to be constructed by Spectra Physics will be used to stage smaller optics on a planetary rotation system; however, it will be able to coat only one of the largest optics at a time. Larger, improved spectral measuring instruments that are currently being developed by Spectra Physics will be used to qualify the transmission and reflection of each optical element. Damage tests on the coated optics from Spectra Physics will be performed at LLL.

Both of the LLL-owned facilities described above (optical coating chambers and designated peripheral and support equipment) will be maintained and staffed by the respective vendors through the period of Nova construction and for at least two years beyond; coating schedules and priorities will be set by LLL. The construction of both facilities is scheduled to be completed by early 1981; delivery of coated optics will begin in mid-1981 and will be completed by late 1982.

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Mechanical Subsystem

Mechanical subsystem responsibilities include the design, fabrication, and assembly of Nova hardware. The major units within this subsystem are spaceframes, rod and disk amplifiers, spatial filters, Pockels cells, Faraday rotator and plasma-shutter isolators, mirrors, gimbals and mounts, beam-line transport tubes, and system utilities.

The mechanical subsystem for the Phase I Nova system will begin in the master oscillator room (MOR) located in the basement of the Nova building. A single laser pulse will be amplified and relayed upwards to the spaceframe, where it will be split into 10 beams. Initially, each beam will be directed away from the target; after several expansions through spatial filters, the beam diameter will reach 315 mm at the end of the spaceframe, where it will be folded and pointed in the opposite direction and returned toward the target on the opposite side

Fig. 2-80. Schematic of turning mirrors in the switchyard and target room.

of the spaceframe. Each beam will reach an ultimate diameter of 740 mm and will then enter a switchyard of turning mirrors that will turn the linear array of beams from two vertical rows of five beams each into a complex target irradiation geometry inside the target room (Fig. 2-80). Beam diagnostics will be located behind the first switchyard mirrors. Forty mirrors will be required to achieve sufficient degrees of freedom to both center and point the 10 beams onto the target; there will be a maximum of six mirrors in a single chain. The final leg of each beam line will lie as a ray on the side of a cone having a nominal included angle of 75° . The final mirrors will be arranged so that this cone angle can be adjusted to as much as 110° . Five beams on each side of the target chamber will form two opposing cones.

Spaceframe. The spaceframe, which will serve as a stable support for all optical components, is shown in plan view (Fig. 2-81), in an elevation view of the end containing the target room and mirror switchyard (Fig. 2-82), and in an elevation view of the end of the laser bay (Fig. 2-83). The spaceframe

will have three major sections: the laser frame, the switchyard frame, and the target-room frame. Thermal and vibrational stability are the dominant requirements for the spaceframe; seismic resistance, accessibility, cleanliness, and strict attention to system requirements are secondary, but still essential, requirements.

The vertical-stacking arrangement of laser chains on the spaceframe was optimized to best suit the turning mirrors and associated diagnostics. The laser frame is designed to accommodate desirable new components or arrangements at minimal cost.

Vibration data were recorded on the Shiva spaceframe using quartz accelerometers and geophones, and the reduced data have been compiled in the form of the acceleration spectrum, integrated displacement spectrum, and rms displacement. With these as input data, Nova calculations using the SAPIV code (Ref. 40) have shown that cross-room stiffeners (used on the Shiva spaceframe) can be eliminated by making the side walls

wider and stiffer. This improvement not only will simplify the structure but also will enhance system access for maintenance.

As on Shiva, 6-in.-square mild-steel tubing will comprise the primary structural members for the Nova spaceframe. Thermal motion of the frame will be kept within tolerable limits by the building environment and the supports for the Nova frame, like those for Shiva, are designed to accommodate thermal expansion caused by air-temperature changes. Roller-bearing supports will allow the frame to expand and return to its original position

without high strain. Each frame will be fixed at a single point, the seismic anchor, and allowed to expand in all directions from this point.

An earthquake of magnitude 5.5 with its epicenter near Livermore showed that the Shiva system is adequately designed; information gained from post-earthquake studies will be used in the Nova spaceframe design. The seismic anchor for Nova will be dynamically analyzed by using the response-spectra approach, and inclusion of shock-recovery mounts and heavy lift jacks at each support point will be considered. These features would

Fig. 2-81. Plan view of Phase I Nova spaceframe.

help expedite realignment of the spaceframe after a seismic occurrence.

Chain Layout. The Nova laser-chain components have been selected as described in "Laser Chain Design and Performance," above. The chain components will be positioned to relay the image of an aperture in the MOR onto an aperture at the input to the disk-amplifier chain. The chain input aperture will then be imaged to the focusing lens of the target chamber. Each component will be separated by approximately 300 mm to allow for the insertion of a calorimeter, cameras, alignment

crosshairs, and other temporary system components.

The total path length from the oscillator to the target must be identical for each chain. This will be accomplished by using movable corner reflectors called the front-end or beam-splitting section located at the input to each chain. A combination of movable and fixed mirrors will also compensate for path-length differences from the MOR to the front end. The total distance from the MOR to the target is 213 m; mirror angles and the optical path length from the beam outputs to the target are given in Table 2-18. The difference in length between each individual path to the target will be adjusted to within ± 3 mm or ± 5 -ps arrival time by the movable corner reflectors and a time-of-flight path-length measuring instrument.

Incidence angles at each turning mirror have been optimized to minimize the included angle, thus greatly reducing the size and cost of each mirror. Studies have shown that the cost of mirrors rises exponentially with size; therefore, a greater number of smaller-diameter mirrors will cost less than fewer large-angle (large-diameter) mirrors. Table 2-18 shows that we have designed the system with no mirror angle exceeding 82° and with an average mirror angle of 60° . This design requires between three and six 750-mm-aperture mirrors per chain, but the total cost is lower than for fewer large-angle mirrors.

A long-term evaluation of disk-amplifier cleanliness has shown that the disks, when mounted on edge, remain measurably cleaner for from 5 to 10 times longer than when mounted facing upwards. For this reason, the 460-mm and 315-mm amplifiers will have their disks mounted on edge. Smaller-aperture amplifiers cannot be edge mounted due to the 45° rotation of polarization, introduced by the Faraday rotators. By maintaining horizontal beam lines from the output amplifiers to the target chamber, it is possible to maintain nearly radial polarization on the target. At the front end, half-wave plates will be used to rotate the beam polarization from the MOR onto the first polarization-sensitive component in the chain.

Fig. 2-82. Elevation view of Phase I Nova switchyard and target room, looking toward the laser bay.

Fig. 2-83. Elevation view of Phase I Nova laser bay, looking toward the mirror switchyard.

Fig. 2-84. Exploded view of a 460-mm box amplifier.

Table 2-18. Mirror angles and optical path lengths (from the last spatial filter to the target) for the 10 beams of the Nova Phase I laser.

Beam No.	Optical path length (m)	Mirror angles (deg)						
1	49.11	45	45	—	66.9	55.6	50.0	
2	44.83	45	45	—	—	72.0	50.0	
3	45.85	45	45	40.5	81.0	40.5	50.0	
4	44.83	45	45	—	—	72.0	50.0	
5	49.11	45	45	—	66.9	55.6	50.0	
10	54.18	45	45	—	81.4	81.4	50.0	
9	59.46	45	45	—	50.5	78.7	50.0	
8	49.16	45	45	—	—	—	50.0	
7	59.46	45	45	—	50.5	73.7	50.0	
6	54.18	45	45	—	81.4	81.4	50.0	

Amplifiers. Ten chains will be arranged on the spaceframe to satisfy all of the operational, geometrical, and constructional constraints of the Phase I Nova system. The total straight-line length of the laser chain exceeds the length of the laser bay; thus, it will be necessary to fold the chains to allow them to fit within the building (see Fig. 2-81). Nova will use six sizes of amplifiers in each chain: a 50-

mm rod amplifier; 94- and 150-mm Shiva round-disk amplifiers; three 208-mm amplifiers, of which one is a Shiva round-disk amplifier and two are box amplifiers; followed by four 315-mm and three 460-mm box-amplifier units (see Fig. 2-84).

Fig. 2-85. Detail of bottom mounting of the 460-mm disk.

The box amplifiers are similar to the earlier disk amplifiers in several ways: the basic elements of disk, lamps, reflectors, and structure, and their close-packed relationship with each other, have not changed; however, the box design allows us to build large disk-containing amplifiers more economically. Figure 2-84 shows an exploded view of a 460-mm box amplifier. In a Shiva disk amplifier, lamps are arranged in a tight circle around the disks; in a box amplifier, fewer lamps are arranged in two opposing planes to pump the disk faces. There are structural differences also. In disk amplifiers, the disks are mounted in a support structure and carefully slipped into a quartz tube; in box amplifiers, disks are supported directly from the box covers, which act as structural supports. Thus, in comparison with the disk amplifier, the box amplifier is more efficient electrically, because there are fewer lamps, and its assembly is easier and less critical. Performance predictions for the new box amplifier are given in "Amplifier Development," below. We

discuss here the mechanical design of this amplifier.

The pump cavity of the box amplifier is a long rectangular box with six reflecting sides that enclose the lamps and disks. Optionally, shield glass can be placed between the lamps and disks (Fig. 2-84) to protect the disks from contamination and to control gas flow. The inner box must offer maximum reflectivity of the pump light and must have no cracks, gaps, or openings that would contribute to energy losses; the box volume must be kept small for maximum pumping efficiency. Because the assembly is simple, it is compatible with cleanliness and with safe handling of the sensitive, expensive glass disks.

The pump cavity of the inner box is supported with electrical insulators that are fastened to the external box; the latter serves both as a structural support and as a hermetic seal. Electrical isolation from ground serves to guard the spaceframe from the high voltage (22 kV) that would be caused by flashlamp failure.

Cooling gas (nitrogen) is circulated through the pump cavity to remove heat from the flashlamps and the disks. This heat, if not controlled, would

Fig. 2-86. Detail of top mounting of the 460-mm disk.

distort the surfaces of the glass disks, which are finished to a one-twentieth wave.

The disks are assembled and operated vertically in mechanical mounts. This vertical positioning has two advantages: the disks can be kept cleaner (a large, horizontal surface collects more contaminants than a vertical surface), and they will not deflect from their own weight. The disks are held in elliptical nickel holders, which are kinematically mounted with two points at the bottom and one at the top (Figs. 2-85 and 2-86), and the disk edges are supported on spring pads to prevent high stress concentrations. Flashlamps, which are mounted to the sidewall covers, serve as the final closure to the box. In the 460-mm amplifier, the lamps are mounted transverse to the beam by placing the bulky lamp connectors at the sides of each

box instead of at the ends. This arrangement allows closer coupling of amplifier units and reduces end losses by allowing pump light from one unit to enter the adjacent unit. Figure 2-87 shows how three amplifiers are coupled, and Fig. 2-88 shows how the intervening gap is closed with reflecting surfaces.

In the 208- and 315-mm box amplifiers, the flashlamps are mounted longitudinally; Fig. 2-89 shows this arrangement and contrasts it with the transverse arrangement of the 460-mm amplifier.

The elliptical disk holders and reflectors will be fabricated by electroforming, a very cost-effective process. This process eliminates 90% of the machining normally required for these complex shapes and produces an extremely good surface finish, which is

Fig. 2-87. View showing close coupling of three 460-mm box amplifiers.

Fig. 2-88. Detail of the joining of two 460-mm amplifiers.

necessary for these parts, while the associated tooling allows replication of many high-quality parts.

Silver-plated nickel will be used as the pump-cavity material, aluminum will be used for components located outside the pump cavity, and aluminum oxide will be used as the insulator material.

Spatial Filters. Spatial filters, which control beam propagation, are vacuum tubes that are sealed at both ends with lenses and that contain an aperture located around the beam waist at the focal points of the lenses. These devices smooth the beam, magnify it between amplifier sections, and relay the image of an input aperture through the amplifier stages to the target chamber.

The spatial-filter vacuum tubes are usually constructed of stainless steel tubing, although rolled taper sections of stainless steel are used for the larger filters, and the diameter of the spatial filter decreases near the pinhole.

The final spatial filter in each chain contains a plasma shutter (Fig. 2-90) that projects a critical density of aluminum plasma across the beam path at the pinhole immediately after the beam pulse passes, thus preventing the pulse from reflecting

Fig. 2-89. Schematic of the three box amplifiers, showing lamp orientation.

Fig. 2-90. Schematic of the final spatial filter in the Nova chain. (Vertical scale exaggerated.)

back into the chain. This shutter is described in detail in "Plasma Shutter," below. Design parameters of each spatial filter in the chain are given in Table 2-19.

Lens Adjustment. The beta-beta and the beta-gamma spatial filters from the Shiva system will be integrated into the Nova chain; the other spatial

filters in the chain will be of a completely new design. Each of the new spatial filters will be fitted with an adjusting mechanism that will allow each lens in the system to be adjusted independently under full vacuum. The range of adjustment will be

Table 2-19. Design parameters for Nova spatial filters.

Beam diameter (mm)		f/No.	Pinhole diameter (mm)	Clear aperture (mm)		Back focal length (mm)		Distance between lenses (mm)
in	out			in	out	in	out	
447	710	20	3.3	460	740	9162	14 766	33 928
302	442	20	1.5	315	460	6273	9 178	15 458
200	302	25.29	1.0	208	315	5448	8 262	13 710
140	200	19.67	0.75	146	208	2615	3 734	6 349
88	140	10.82	0.3	92	146	995.2	1 586.2	2 580
88	88	10.82	0.3	92	92	995.2	995.2	1 990
40	88	17.5	0.76	42	92	700	1 540	2 240
25.6	40	65.7	1.3	27	42	1681	2 628	4 310

± 12 mm in the x and y directions across the beam and ± 50 mm in focus along the beam line. This adjustment capability will allow the long vacuum chambers between the lenses to be rigidly mounted to the spaceframe with only a rough adjustment to the beam line. The input and output lenses of the last spatial filter will be motor driven in the x-y directions; all other lenses will be manually driven.

The recycled Shiva spatial filters will use the Shiva pinhole manipulators; the other filters will use a newly designed z-axis long-travel manipulator. This new manipulator will have motor-driven adjustments of ± 25 mm in both directions across the beam.

All spatial filters with an outlet aperture of less than 140 mm will be vacuum pumped with 28-l/s ion pumps salvaged from the Shiva system; all larger filters will be vacuum pumped with 1000-l/s cryogenic pumps. All vacuum systems will be designed for a base pressure of 10^{-5} Torr.

Authors: C. A. Hurley, I. F. Stowers, C. B. McFann, F. A. Frick, and G. S. Bradley

Reference

- 40 K. Bathe and E. L. Wilson. *SAP IV - A Structural Analysis Program for Static and Dynamic Response of Linear Systems*. College of Engineering, University of California, Berkeley, Calif. EERC 73-11 (Rev.) (1974).

Power Conditioning

The Nova pulse-power engineering group has the following areas of responsibility:

- Flashlamp power system, including the flashlamps and the pulse circuitry to drive them,

capacitor banks, power supplies, switches, and the distribution system.

- Optical isolation system, including the circuits that power the Faraday rotators and the Pockels cells, that minimize ASE, and that prevent oscillation within the chain. This system also includes the plasma shutter that protects laser components from damage caused by target-reflected light and opposing-beam light.

- Pulse distribution, including the system integration of Pockels cells, plasma shutters, and the fast-pulse circuitry in the MOR; and ensuring that pulse timing, synchronization, and abort signals are interfaced properly for reliable operation of the system.

- Pulse-power control system, including shot timing, system status, and data retrieval. This system must operate reliably in the high-noise environment of a 300 000- to 400 000-MW capacitor-bank discharge.

- Electrical design of the building, including incorporation into the building design of requirements for grounding, for various types of power, and for power distribution.

The subject of power conditioning is discussed below under the following headings: staging of Nova pulse-power system; flashlamp power system; summary of capacitor development; capacitor test facility; pulse-forming network; Nova power supply; design rationale; pulse distribution; pulse-power control system; and Nova laboratory building—electrical design.

Staging of Nova Pulse-Power System. During 1979, it was determined that the full Nova system would be able to operate more efficiently as a 20-beam system rather than as a 40-beam system. One result of this determination has been a modification in the staging of the pulse-power system. Newly

Table 2-20. Staging of the 10-arm Nova pulse-power system for the new laser bay. The other half of the Nova system will be identical.

Component	Number		Lamps		No. of circuits per component	Total circuits	No. of cans per circuit	Bank energy/circuit (kJ)	Total bank energy (kJ)
	Per arm	Total	Size (in.)	No.					
25-mm rod	—	7	15	42	1	7	7 ^a	21 ^a	147
50-mm rod	2+								
	Splitters	26	15	390	1	26	10 ^a	30 ^a	780
94-mm disk	3	30	44	480	8	240	6 ^a	18 ^a	4 320
150-mm disk	2	20	44	480	12	240	6 ^a	18 ^a	4 320
200-mm FR ^b	1	10	—	—	5	50	8 ^c	40 ^c	2 000
200-mm box	3	30	44	480	8	240	2	25	6 000
315-mm FR	1	10	—	—	4	40	4	50	2 000
315-mm box	4	40	44	960	12	480	3	37.5	18 000
460-mm box	3	30	19	2400	16	480	4	50	24 000
			15	432		1803		Shiva-3 kJ ^a	9 567
			44	2400				Shiva-5 kJ ^c	2 000
			19	2400				Nova-12.5 kJ	50 000

^aShiva components at 20 kV; the rest are Nova components at 22 kV.

^bFR = Faraday rotator.

^cShiva components at 5 kJ.

developed system components will still be fully utilized, but individual circuits will have higher energy and the overall circuit count will be reduced.

The staging of the Phase I Nova pulse-power system is summarized in Table 2-20. The new Nova circuits are based on 22-kV, 12.5-kJ capacitors placed in 2- to 4-can circuits, depending on the load. The circuit components have been carefully selected to obtain reliable, low-cost parts, and even these carefully selected components have been improved in several ways. The pulse-power system uses large power supplies to charge the majority of the bank, as shown in Table 2-21.

Flashlamp Power System. During 1979, we tested components, optimized the pulse-forming network, designed the power supply, and wrote specifications that will permit reliable procurement of the long-lead-time items.

Summary of Capacitor Development. At the conclusion of the Shiva design, we recognized the need for reducing the size and cost of the capacitor bank to be used for Nova. The Shiva bank has a capacity of 25 MJ and uses about 8000 ft² of floor space; the Nova bank is projected to have a capacity of 130 MJ. Clearly, an improvement in the energy density of the capacitor bank to be used for Nova would reduce costs and would make more effective use of materials and space. However, when the energy density of a capacitor is increased by increasing the dielectric stress, the lifetime of the capacitor

Table 2-21. Power-supply staging for Nova laser bay. The other half of the Nova system will be identical.

Component	Energy (MJ)	No. of power supplies	No. of switches
94-mm disk }	9.6	1	20
150-mm disk }			
200-mm box	6	1	15
315-mm box	18	2	40
460-mm box	24	2	30
Spare	—	1	—
		7	105
100-kVA power supplies^a			
25-mm rod	0.147	2	2
50-mm rod	0.780	2	3
200-mm FR	2	4	4
315-mm FR	2	4	4
LCD ^b	0.07	2	12
Spare	—	1	—
		15	25

^aReused from Shiva.

^bLCD = Lamp and circuit diagnostic.

is decreased. Thus, to take advantage of the lower costs and reduced volume of capacitors having higher energy densities, a realistic trade-off between life and energy density had to be carefully established. Table 2-22 presents the stress levels and

Table 2-22. Stress levels and nominal life spans of capacitors.

	14.5 μ F	25 μ F	52 μ F	52 μ F
Operating voltage (kV)	20	20	22	22
Energy storage (kJ)	2.9	5	12.5	12.5
Number of series sections	4	2	2	2
Voltage per section (kV)	5	10	11	11
Operating stress (kV/mil)	2 083	2 564	5 000	3 333
Dielectric type	Paper/castor oil	Paper/castor oil	Paper/poly/dop	Paper/castor oil
DC life (h)	2 000	1 200	1 000	1 000
Pulsed life ^a (shots)	10 ⁶	500 000	200 000	200 000

^aNonreversal (3 kA)

nominal life spans for several types of capacitors that we investigated.

The full 20-beam Nova system will have about 8000 high-density capacitors, and the system will experience approximately 10 000 total-system shots in its lifetime. The failure rate of capacitors, based on early failure statistics, should be less than 2 to 3 capacitors per year. From these considerations, we have generated a preferred Weibull distribution for life performance of the capacitors (Fig. 2-91). Data taken in 1979 show this distribution to be achievable.

In Fig. 2-91, at the 2% failure level, the 50% confidence life is 10 000 shots. In a 4000-capacitor (50 MJ) Nova Phase I bank, 2% represents 80 failed capacitors. We could, therefore, expect an average of 10 000 $80 = 125$ shots between failures at the 50% confidence level during the entire 10 000 shots, representing 2 to 3 failures per year at the projected shot rate. By extrapolating these data at a typical slope to the 50% failure point for damped (nonoscillatory) shots, we obtain a characteristic 63% life ($1 - e^{-1} = 0.63$) point of 200 000 shots. The next shipment of capacitors from each vendor will be tested to determine if these capacitors will meet this objective.

Direct-current life is an important factor in sizing the charging power supplies for the Nova bank; slow charging creates a higher failure rate. The trade-off study for the Nova bank resulted in a 30-s charge time for the bank. With a dc life of over 1000 h, the failure rate due to time at voltage is reduced below that of pulsed life.

Based on the above considerations, the Nova system will require capacitors with an average life of 200 000 shots in nonoscillatory service and a dc life

Fig. 2-91. Estimated Weibull plot for Nova capacitors. (b = slope of the curve; N_0 = point below which there are no failures; N_a = characteristic life.)

greater than 1000 h. These requirements have been written into the LLL capacitor specification and have resulted in different manufacturing approaches by different vendors. All methods of construction have resulted in costs of approximately \$0.05/J for large quantities of capacitors.

Capacitor Test Facility. To evaluate the projected capacitor lives associated with the various capacitor construction methods, we built a 20-channel capacitor test stand that will provide three major tests: pulse-discharge test, ring test, and dc-life test.

The pulse-discharge test allows up to 20 individual capacitors to be charged and then discharged repeatedly into a resistor load bank, thus testing capacitor life. Each capacitor has its associated fan-out, ignitron, and pulse-forming

network (PFN) board so that each circuit can be selected as desired. The entire system has been automated so that a test sequence of 100 000 discharges can occur without supervision.

The ring test, shown in Fig. 2-92, discharges the capacitor into a low-impedance load of about 20 m Ω . This circuit is very underdamped and rings with an 80% reversal; peak currents of 60 kA stress the solder connections within the capacitors. This test ensures that the capacitors will have an adequate life, even if they are subjected to high current faults.

The de-life test applies full voltage to the capacitors and holds this voltage for a specified time, usually 1000 h. This test ensures that the capacitors accepted for use on Nova will have an adequate de life.

The capacitor test facility will be used to qualify all types of capacitors that will be used on Nova. A batch of 35 capacitors has been ordered from each vendor; when each batch has been completely tested, the performance distribution of each capacitor type will have been established with good accuracy.

Pulse-Forming Network. The Nova capacitors will be placed in circuit modules in groups of two to four, as indicated in Table 2-20. An integral part of each circuit is the PFN board that holds the circuit components. This board, shown in Fig. 2-93, contains a fuse, a charge resistor, a dummy load, and a pulse-shaping inductor.

New components are required for the Nova PFN because the energy per circuit ranges up to 50 kJ for Nova, as compared with 21 kJ for Shiva. The fuse size has been increased from a rating of 3 kA to 5 kA; in addition, the fuse element has been changed from an all-silver element to a silver-coated copper element to reduce the cost of the fuse. The knife switch, which is used to "safe" the capacitors, has been replaced by an inexpensive, but still

Fig. 2-92. Capacitor ring-test stand. A 60-kA, 9-kHz discharge waveform is generated to test capacitors under fault conditions.

reliable, "banana jack" switch. To accommodate the longer Nova pulse width, a 650- μ H inductor has been designed; it is a Brooks-coil type and has approximately the same dimensions as the 450- μ H coil used on Shiva.

A significant improvement over the Shiva PFN board is the addition of a dummy load on the Nova board. This dummy load, which consists of a resistor that approximates the impedance of a flashlamp, will be used when exercising the pulse-power system during the testing and debugging of Nova. Extensive testing has been performed to find a resistor that can absorb the high energy (up to 50 kJ) and the high currents (greater than 4 kA) that

Fig. 2-93. Pulse-forming network for Nova bank circuits.

will be encountered in Nova. Wirewound, ceramic, water, and flat-ribbon type resistors were tested, and an "Ohmweve" flat-ribbon resistor has been chosen as the dummy load. This type of resistor can absorb large amounts of energy and then, because of its large surface area, cool down rapidly during system activation and testing.

The dump resistors have been removed from the PFN board and placed in the dump mechanism. The dump resistor presently being considered for Nova is a copper-sulfate water resistor; this type of resistor can absorb up to 300 kJ without damage.

The components of the PFN board are carefully laid out to provide adequate distances for voltage standoff. A prototype board has been successfully subjected to a high-potential test of 30 kV, and the Nova PFN boards will be further tested in a 1-MJ capacitor bank during 1980.

Nova Power Supply. To charge the Nova bank within 30 s, as required for adequate bank lifetime, 12 to 14 MVA of dc power must be applied to the bank. Large, substation-sized power supplies have been designed to apply this much power at an efficient cost. Smaller, Shiva-type 100-kVA supplies will be used on the front end for charging rod-amplifier circuits and rotators, but most of the bank will be charged with 1.5-MVA power supplies

located in the substation area outside the Nova lab building. The three-phase voltage doubler of this power supply is diagrammed in Fig. 2-94 and has the following salient features:

- Vacuum contactors and resistor step start.
- Transformer.
- Doubler capacitors.
- Diode bridge.
- Transient-suppression networks.
- Cable terminator.
- Monitor and interface chassis (not shown in Fig. 2-94).

in Fig. 2-94).

- Interlocks (not shown in Fig. 2-94).

The power supply is rated as follows:

- Input voltage: 13.8 kV ac.
- Input power: 1.5 MVA.
- Output voltage: 0 to 27 kV dc.
- Design load: 50 000 μ F.
- Charge time to 22 kV: 30 s.

Table 2-21 gives the staging planned for the power supply.

The charge cycle is initiated by closing vacuum contactor C1 (Fig. 2-94). The inrush current is limited to the power supply's nominal full-load value by the step start resistor; after 10 line cycles, this resistor is bypassed by vacuum contactor C2.

Vacuum contactor C1 is the control element of the supply. This contactor opens when the desired charge voltage on the capacitor bank is reached. Testing on a 25-kVA "model" power supply has

Fig. 2-94. Schematic of three-phase voltage doubler.

shown that the desired output voltage is repeatable to a level of $<1\%$.

The transformer will be a three-phase, oil-type transformer configured in a delta-wye. The primary voltage will be 13.8 kV line-to-line, and the secondary voltage will be 9.6 kV line-to-neutral. The nominal peak power rating of this transformer will be 1.5 MVA.

The doubling capacitors will provide current limiting and are chosen to set the charge time of the power supply. This supply should charge 50 000 μF of capacitor bank in about 30 s.

The diode bridge provides rectification. The individual diode stack ratings each have a safety factor of 2.5 for peak inverse voltage rating and an approximate safety factor of 3 above the nominal current rating.

The transient-suppression network limits voltage transients arising when the contactors are opened. The network components are sized to limit peak primary voltage to its nominal rating when opening the full-load current and to limit the secondary line-to-neutral voltage to less than the line-to-line voltage.

The cable terminator limits transient voltages arising from the load. The resistor matches the

surge impedance of the cable and the capacitor holds off dc voltage.

The monitor and interface chassis will provide metering of primary line current, output voltage, and output current. The chassis also connects our standard control modules to the new power supply.

The components of the power supply will be mounted in a weatherproof enclosure located outdoors in a substation next to the Nova building. The transformer and rectifiers will be immersed in oil within this enclosure.

Design Rationale. The design of the Nova power supply was conceived after studying the following possible alternatives:

- Transformer with motor-driven variable-voltage feature.
- Constant-current Graetz bridge.
- Capacitors in primary Graetz bridge.
- Phase-regulated doubler, 480-V input.

These possible alternatives were rejected for the following reasons: the transformer with a motor-driven variable-voltage feature could not respond fast enough to limit short-circuit fault currents; the controls for the constant-current Graetz bridge may

have problems in limiting short-circuit fault currents and may be unreliable in an electrically noisy environment; the capacitors in the primary Graetz bridge offered no advantages; and the phase-regulated doubler with 480-V input would require an additional transformer to step down the voltage from 13.8 kV to 480 V.

The chosen design incorporates the advantages of a voltage doubler:

- Inherent short-circuit protection.
- Approximate constant-current charging.
- Cost effective.

In addition, our extensive experience with doubler power supplies enables us to understand the system-interaction problems of the selected design.

The selected power-supply design should provide significant cost savings as compared with the power supply used on Shiva. Because of economy of scale (the Nova power supply will be 15 times more powerful than that used on Shiva) and because the new design will use vacuum contactors (eliminating the need for costly silicon-controlled rectifiers), the estimated cost of the Nova power supply is \$0.08 VA vs \$0.15 VA for the Shiva power supply (both in constant dollars).

Extensive testing of a full-scale prototype of the Nova power-supply system is scheduled for 1980.

Pulse Distribution. Certain Nova components will require timing-control signals with subnanosecond jitter. These components include fast optical gates (Pockels cells, plasma shutters, and oscillator Q switches) and diagnostics (e.g., streak cameras). Since the master oscillator timing will determine when beam switchout will occur, we are centralizing generation of these high-speed timing signals at the oscillator controls.

The master oscillator will be fired at a rate of approximately 10 Hz in response to computer command. However, switchout of the oscillator pulse will not occur until shot time, when a bank of delay generators, with 1-ns resolution, will delay the oscillator master-timing pulse by preselected amounts. The delayed pulses will be distributed to the controlled devices via high-speed, parallel-fiber optic links, each of which will be driven by a pulsed laser diode that will couple several watts of optical power into the transmission fiber. A high-speed photodiode in each receiving unit, which could be

up to 200 m from the oscillator, will convert the pulse back to electrical form.

As described in "Plasma Shutter," below, the plasma shutters merit special consideration because of the optical damage that could occur if a shutter failed. If a shutter should prefire so near to shot time that the computer could not detect it and respond in time, a high-speed fiber-optic abort link from the shutter to the master oscillator controls would set a latch that would disable all Pockels cells. Thus, the Nova system will be protected from plasma-shutter prefires up to approximately 400 ns before target illumination.

The inclusion of plasma shutters in the laser chain, the tight timing control of Pockels cells to minimize ASE, and the ability to control up to four oscillators make the Nova pulse-distribution system considerably more complex than that required for Shiva. Nevertheless, we have found that the Nova requirements can be met by using essentially the same approach that was used successfully with Shiva. The main difference is in the area of delay programming, which was handled on Shiva by using thumbwheel switches. Nova delay programming will be handled by storing delay values in an electronic memory. At our option, this memory will be loaded either from a local keyboard or remotely from the power-conditioning computer.

Pulse-Power Control System. The pulse-power control system has progressed from a conceptual design phase through a breadboard and test phase to a prototype phase. We concentrated our efforts on ensuring that the control-system elements would function reliably in the high electromagnetic-noise environment anticipated for Nova. The control-system architecture is based on extending the control computer's bus to each controlled device; this concept is illustrated in Fig. 2-95. When a bus of this type is used with pulse-power devices, a significant amount of isolation is required to provide both safety and immunity from noise.

Fiber-optic technology was insufficiently mature to be used for Shiva but has progressed rapidly over the past three years. Inherent features that make fiber-optic communication a natural choice for pulse-power systems include:

- Electrical nonconductivity.
- Immunity to external electromagnetic fields.
- Very wide bandwidths.

● Prices now so low that, in many cases, fiber optic devices are cost-competitive with copper systems.

Figure 2-96 is a block diagram of the control system showing the relationship between the control room and the controlled devices. We plan to use redundant LSI-11 microprocessors as front-end processors, with each Q-bus serialized and extended throughout the laser system. The fiber-optic bus will be operated at 10 Mbps and will be tapped at each major laser-system device that is controlled, monitored, or synchronized. The bus structure design is heavily influenced by the need to operate in a hostile environment of high voltage (25 kV), high current (20 MA), and extreme fields during the 400 000-MW pumping of the laser amplifiers and optical shutters. Operational requirements for redundant bus operation and system synchronization are also incorporated into the bus structure.

The choice of network greatly affects the cost of the large bus system required for Nova, where

Fig. 2-95. Nova pulse-power devices controlled and monitored by extending the bus of the control computer.

Fig. 2-96. Block diagram of the Nova power-conditioning control system.

Fig. 2-97. Block diagram showing one-half of the Nova power-conditioning bus network. The other half will be an identical, redundant network.

140 nodes will service 10 laser arms. (A node comprises a group of devices in the same physical area.) Limitations of available fiber-optic receivers, transmitters, and couplers introduce additional restrictions on the architecture of the bus network. Because improved fiber-optic devices are constantly being developed, the Nova schedule allows for incorporation of new devices through 1980.

Specific limitations that currently exist with fiber optics are

- Transmitter output power.
- Receiver dynamic range.
- Coupler, cable, and connector losses.
- Differential switching times.
- Propagation delay.

The most easily implemented fiber-optics network is the repeater chain. Repeaters efficiently resolve the first four limitations above, but propagation delays add with each repeater in the chain. The first repeater in a chain delays each bus transaction by up to 3.4 μ s; each additional repeater adds a further delay of up to 200 ns. Thus, a chain

Fig. 2-98. Prototype printed-circuit boards for the Nova power-conditioning control system.

of 15 repeaters could delay each bus cycle by $62\ \mu\text{s}$. Repeater chains with more than 33 serial repeaters could delay each bus cycle by $10\ \mu\text{s}$ and cause the processor to timeout.

An average of 10 nodes per repeater chain would require that the Nova network have between 10 and 20 parallel chains; thus, the control-computer bus will first be fanned out into a number of parallel chains and will then be fanned in to a single chain. Figure 2-98 depicts one-half of the envisioned bus network for Nova; the second half is a redundant network that will also interface with all devices of the power-conditioning system.

Control system components will be developed and tested in association with a planned 1-MJ segment of the Nova power-conditioning system. A system prototype was used during 1979 to investigate problems of compatibility between the control system elements and the pulse-power devices controlled by these elements. As outlined in the 1978 Annual Report,⁴¹ the control-system development plan is divided into four 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 segments of the control system.

During 1979, we completed Phase A and half of Phase B. Printed-circuit boards were designed, fabricated, and installed as part of the prototype control system; some of these circuit boards are shown in Fig. 2-98.

Circuit boards are grouped to form unique device interfaces for the 140 controlled devices. Figure 2-99 shows the prototype interface for controlling the ignitron switches. Various interface units were tested with externally generated noise to simulate expected Nova emi conditions. Further

Fig. 2-99. Prototype interface used to control and monitor the operation of Nova ignitron switches.

tests will be conducted as part of the 1-MJ prototype operation.

Nova Laboratory Building—Electrical Design.

We worked with various laser-program groups to establish criteria for power, grounding, interlocks, and other electrical parameters for the Nova laboratory building. The solid-state laser electronics group worked directly with A. C. Martin and Associates in the layouts and details of conduit runs, door and run-safe interlocks, personnel warning boxes, and power distribution systems throughout the Nova laser facility. We reviewed all electrical prints and the specifications for the electrical bid package to ensure that all requests submitted by the Nova team were included in the bid package. We also ran rfi tests on the electronic controllers that the architect had proposed for controlling facility equipment in the Nova building, and we suggested possible ways of improving the system. Finally, we are monitoring construction to ensure that installation is performed as requested.

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41. *Laser Program Annual Report—1978*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-78 (1979), pp. 2-100 to 2-103.

Control System

The Nova control system (Fig. 2-100) has many of the same requirements as Shiva, including the need to control and diagnose the four major subsystems: power conditioning, alignment control, beam diagnostics, and target diagnostics. However, changes in emphasis on these requirements, as well as additional needs, have resulted in modifications of the method and degree of control-system distribution and architecture that will be used for Nova. The evolution of the Nova control system is outlined below and is more fully described in Ref. 42.

Fully Integrated Control System. Integration of the four subsystems into a cohesive, functional control system is a major design goal. Bringing the system on-line from the beginning in an integrated

Fig. 2-100. Nova control-system architecture.

Align

CCD alignment sensors

Target viewing video sources

Security disconnect

Laser diagnostics

MOR pulse shape

M.S. transient

Laser bay

Chain energy

Calibration

Novanet node star

Novabus fan in/out

ns/interlocks c. devices

IOC

IOC

Video digitizer

Array processor

IOC

IOC

IOC

I/O controller LSI-11/23's Multi-port memories

VAX-11/780's

(One-way Novalink to green analysis facility)

Color hardcopy

Conditioning

Central control

Target dia

Operator consoles

Terminal

Fiber optic Novabus connection

Fiber optic Novanet connection

VAX-11/780

Mass storage

Terminal

Dial up access

Printer/plotters/tapes

Development

Laser diag.

Development Analysis

architecture will save time and procurement and maintenance costs during development and operation of the laser. We intend to eliminate redundant software development efforts and, during the early stages, concentrate on developing common software and hardware modules to perform universal subsystem functions, thereby using standardization to ease the integration effort. Early development efforts are also aimed at creating a prototype for the modular programmable control stations that will provide a uniform operator interface to each of the subsystems.

Maintaining flexibility to meet new requirements remains an important goal. As with Shiva, a distributed-processor approach will be used on Nova; however, knowledge gained from the Shiva experience will be used to effect economies in both software and hardware, primarily by combining similar high-level operations into a single processor.

One of the major technical differences in Nova that affects the control-system architecture is the project commitment to use charge-coupled-device (CCD) array technology to produce video images at all alignment-sensor locations. This type of "camera" will replace the position-sensitive quadrant detector used in Shiva as the primary sensor for closed-loop alignment functions.

Cost constraints have forced a careful evaluation of distributed-control processors. Software-intensive remote computers will be eliminated in those instances where they provide functionality that can be more easily implemented in central computers. The resulting emphasis on high-level cooperating software processes is expected not only to reduce the total amount of software development but also to reduce divergence in subsystem hardware and software. A total hardware cost reduction will also be realized by using fewer computer components.

To meet the requirements described above, the architecture for the Nova control system has evolved to the configuration shown in Fig. 2-100.

Control organization is similar in concept to the proven Shiva architecture. It will employ three high-level, on-line control computers (HLCs)—VAX-11/780s or their equivalent—and will centralize and integrate all control-system functions.

An additional VAX-11/780 computer is currently providing the facilities needed to develop the control-system hardware and software; this machine will ultimately provide a multiuser unclassified analysis, development, and maintenance capability when the system is operational.

Control and data-acquisition functions are to be performed at remote locations by a combination of LSI-11 microcomputers and remotely accessible interfaces interconnected via the Novanet and Novabus communications systems. The use of remote microcomputers allows the processor-intensive, low-level functions, such as stepping-motor control and data acquisition, to occur independently of other system activity, while the interconnection of these computers through Novanet allows integration, interlocking, and centralization functions to be incorporated.

The key architectural component that will enable integration of the four control subsystems will be the multiported input-output controller (MPIOC) associated with each subsystem.

Each MPIOC will consist of a multiport memory connected to each of the three high-level computers and an LSI-11/23 microcomputer. The MPIOC computer will continually process commands (functional requests) placed into the multiported memories by the HLCs and will store updated subsystem status information for use by software processes in the HLCs.

Operational interlocks will be implemented through a combination of software in the MPIOCs and HLCs by using system-status information available in the multiported memories.

Novalink. An interconnection link is being designed for the alignment-control and target-diagnostics subsystems to allow computers to communicate at high speeds with remote computers and devices. Operating at an effective transfer rate of one 16-bit word every 25 μ s, this serial link will perform computer-to-device transfers (e.g., computer access to remote CCD camera memories) with the same error checking and recovery protocol that it uses for computer-to-computer communications. Any node (device or computer) can initiate and control transfers to any other node, and there is a failure-mode provision for automatic transfer of bus control to alternative nodes in cases of power failures or processor malfunctions. The Novalink

Table 2-23. Novalink specifications.

- Computer-to-computer, computer-to-device capabilities.
- 10 megabits/s (25 μ s per 16-bit word).
- Fiber-optic or coaxial-cable capabilities.
- Multiple processors and devices on a single network.
- Direct memory access to processors.
- 256 nodes (attachments) allowed.
- Error checking on every word transferred.
- Single-word and block transfers.
- Interrupts from remote devices.

will use both fiber-optic and wire data paths according to individual ground-isolation and emi requirements. Characteristics of the Novalink are summarized in Table 2-23.

Novabus. In the power-conditioning subsystem, a fiber-optic equivalent of the bus structure used on Shiva will be used for controlling very-high-speed devices. The need to operate at a transfer rate higher than 25 μ s per word led to a low-overhead, purely computer-to-device communications system. Designated the Novabus, its characteristics are described in "Power Conditioning," above.

Operator Controls. To reduce the amount of manpower needed to develop and operate Nova, we will eliminate special-purpose switch panels for normal operations and, instead, will use four identical, highly programmable operator consoles, each consisting of three high-performance 19-in. color displays. Each display will be capable of displaying status for any subsystem; in addition, the central display in each console will be overlaid by a transparent touch-sensitive panel forming a "programmable switch panel" that can be configured by software to provide control-function selection capabilities for the operators.

This control-system architecture is considered to be evolutionary rather than revolutionary, in the sense that it is founded upon the concepts of distributed control that have been proven on Shiva. Some changes are being introduced to lower the total software effort (e.g., elimination of software-intensive microprocessors at the intermediate and lower levels, where possible); conversely, we will frequently employ fixed-program processors as highly cost-effective building blocks.

Other changes being made to the control system to reduce costs and improve performance are

- Integration of all high-level diagnostics functions into a single central computer.

- Use of a common logging facility to retain event records that will be synchronized across subsystems.

- Centralization of video-driven, closed-loop control functions in the alignment subsystem's high-level processor.

- Use of very-high-speed communication links designed for both processor-to-device and processor-to-processor communications.

Figure 2-101 illustrates the Nova output-alignment system. Comparing this structure to the equivalent Shiva structure, shown in Fig. 2-24, we see that closed-loop control software for all alignment subsystems, previously resident in separate LSI-11s, will be centralized in the second-level processor. Video signals will be routed through a video switching system, allowing any video sensor to be selected for digitized analysis. Remote-control panels and stepping-motor controllers (SMCs) will communicate with each other and with the HLCs via the same communications link, thereby simplifying software, improving system interconnectivity, and reducing communications costs. High-speed color displays in the operator consoles will be driven by HLC resident software to provide a continuous status of the alignment subsystem.

Integration of the Nova control system is being accomplished by two strategies:

- Less physical distribution of critical control software. (However, general distribution of lower-level slave functions is still planned.)

- Early planning and development of standardized software packages, which will provide subsystem designers with effective tools for commonly performed functions (e.g., data storage and process-to-process communications).

The importance of the latter strategy, particularly in the area of process-to-process communications, cannot be overestimated. By ensuring that the primary method of interprocess communication and coordination will employ well-defined common interfaces, the processes (software functions and tasks) can be either centralized or distributed among computers with little or no program changes. The use of this type of communication structure in some portions of the Shiva alignment subsystem has allowed the operation of the system to be easily tuned by moving processes from

Fig. 2-101. Nova output-alignment system.

saturated computers into other computers having available resources. Such a communication structure also provides an economical approach to system upgrades involving additional computers.

Control systems for large laser-fusion facilities must handle a wide variety of spatially and temporally distributed functions, yet provide integrated, simplified operation. Shiva has shown that

a hierarchically arranged, distributed-computer network is a highly effective approach to meeting such requirements. The Nova control system is designed using a similar approach but with increased emphasis on developing an integrated control facility that will use fewer independent software-intensive control computers.

The Nova control system, therefore, is designed with an underlying philosophy that too much distribution can be as much of a problem as too little distribution. While Shiva's extensive distribution allowed independent development and activation of system functions, it also resulted in difficulties with system integration and in limited high-level processing capabilities. Nova, building from Shiva's base design, will use a more powerful central-control system while maintaining distributed processing.

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Development of the Control-System Implementation Language (Praxis). When we began planning for Nova, our experience with the Shiva control system, comprising 55 processors, clearly indicated that substantial savings in time and effort would result if a powerful controls-oriented programming language were available.

After carefully evaluating the alternatives, including the Ada language currently being developed by the Department of Defense (DOD), we felt that implementation of a specialized controls language was the best alternative. The Ada language would meet our needs but will not be fully developed in time for Nova. Compilers must exist before the mid-1980s to be useful for the Nova controls-programming effort; a compiler for our new control language, which we have named Praxis, now exists and is in use, but a compiler for the more ambitious Ada project is still in the future.

Development of the Praxis language originated from an initial study by Bolt, Beranek and Newman, Inc. (BBN), under the aegis of the Defense Communications Agency (DCA), to determine the needs of a language for communications programming. That study⁴³ concluded that no current

language fulfilled the rigorous needs of communications programming.

BBN was then funded by DCA to design an appropriate programming language; this effort resulted in a preliminary design for a language that was given the name of COL.⁴⁴ A compiler design effort was also funded by DCA.⁴⁵

In January 1979, we funded BBN to redesign the COL language and to develop a compiler for the language on the PDP-11 computer. In November 1979, we expanded BBN's effort to include development of a compiler for the advanced-instruction set of the VAX-11/780 computer, design of additional language features, and provision of a high-level input/output package. The first PDP-11 compiler will become operational by early 1980 on the Shiva PDP-11/70 and on the Nova developmental VAX-11/780. Completion of the compiler development effort, with delivery of documented operational compilers for the language on both the PDP-11/RSX-11 and VAX/VMS systems, written in themselves, is scheduled for the fall of 1980.

In December 1979, we changed the name of the new language from COL to Praxis because the language had evolved significantly from the original COL study and we felt that a new name would better reflect the power of the evolved language.

Praxis is a modern block-structured, fully typed algorithmic programming language in the tradition of Pascal. Its design has been influenced by the languages Simula, BCPL, Jovial, Mesa, and Bliss, as well as by the developmental Ada language. In scope and power, Praxis most closely resembles Ada and Mesa.

The control environment differs in important ways from application to application and from machine to machine; the language must have features to handle these differences. High-level facilities that mask machine dependencies and foster machine independence (portability) usually prevent exactly the capability needed for programming real-time control applications. Praxis is a high-level language with controlled machine-dependent access methods.

Praxis is strongly typed; i.e., the programmer is given a collection of predefined types and has the ability to construct new types. Every variable, constant, parameter, and expression has a type. All types can be deduced at compile-time, and the compiler requires that each value be used in a way

consistent with the rules associated with its type. For instance, it is a *compile-time error* to attempt to pass an integer parameter to a routine that requires a real parameter.

The language is also block structured. A block is a method of packaging statements and declarations so that the scope of each statement or declaration is clearly specified and controlled. Praxis has more than 10 block-structured statements, each of which is delimited by a form "XXX"endXXX" pair where "XXX" represents the particular statement name. For instance: "for...endfor". The block structuring also enforces a particular programming style that has been found to be more readable and maintainable than unstructured programming. The language design, while adhering to modern programming design, has been oriented to the intended application of programming for Nova controls and communications.

Praxis is equally applicable to programming both the large VAX systems and the LSI-11/23 front-end processor (FEP) systems. In addition, system programming applications require the same language facilities, and Praxis will be used for these applications, also.

The intended applications for Praxis impose stringent requirements in such areas as efficiency of object code, direct access to machine facilities, efficient bit manipulation, complex data and control structures, team development of large programs, and maintenance and upgrades. Also, the programmer working with these applications requires detailed control over the code produced by the compiler in such areas as optimization, variable allocation, and implicit run-time support. It is important in these applications that exactly "what is going on" is explicitly represented by the programmer.

The Praxis design goals, which are based on the requirement that the language be a useful tool for programming control applications, may be stated as follows:

- Efficiency of compiled code and, secondarily, of the compiler.
- Readability, which is of greater importance than writability.
- Completeness, in the sense that it must be possible to program all parts of any application in the language without recourse to assembly

language, and it must be possible to write the compiler for the language in the same language.

- Portability, which is the ability to move a program from one machine to another.
- Modularity, so that large projects may be programmed within the language by separate compilation of modules and configuration control.
- Usability, which means that ease of learning is less important than ease of use (experienced programmers will be the primary users of Praxis).

The primary requirements for control applications are efficiency of the compiled code, completeness, and portability. The language must produce programs that make effective use of hardware resources under direct control of the programmer; in addition, the programs should be as portable as possible between machines. In general, the language features are portable, but, where machine-dependent parts are necessary these features are as conspicuous as possible: e.g., the programmer can override the language's type-checking mechanism, but it is easy to see when this is being done.

The requirement for efficiency has had one other impact on the language design: all proposed features and facilities had to be scrutinized as to the run-time efficiency of their implementation. No matter how desirable a particular feature might be, it was rejected if a reasonably efficient implementation could not be designed.

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Alignment and Beam Diagnostics

The basic function of the alignment and beam-diagnostics system is to achieve optimized irradiation of each target while avoiding optical damage to laser components. Optimized irradiation is achieved by making the laser perform consistently and by accurately characterizing each target-irradiating beam. To perform this basic function adequately, the alignment and beam-diagnostic system must perform the following tasks:

- Position the output beam accurately on a variety of targets.
- Direct the beam from the oscillator to the target without violating component apertures.
- Precisely position pinholes in 186 spatial filters.
- Adjust the beam path lengths to obtain simultaneous arrival of all pulses at the target.
- Measure ASE and prepulse energies.
- Time the Pockels-cell and Faraday-rotator gates for optimum isolation.
- Monitor the temporal, spatial, and energy evolutions of the main pulse from the oscillator along each amplifier chain to the target.
- Acquire and process diagnostic data in a time that is short compared to the laser turnaround time so that laser parameters can be adjusted on the basis of data interpretation.

The sections that follow describe alignment and diagnostics subsystems, design details of some representative components, and techniques of diagnostic data acquisition and processing. As in previous years,^{36,47} emphasis in the design and development of these subsystems and techniques has been placed on integrating the alignment and laser-diagnostic components to achieve maximum functionality at minimum cost.

Subsystem Organization. The alignment and diagnostic tasks have been divided into groups that can be performed by independent subsystems. This subsystem organization will facilitate the phased installation of alignment and diagnostic capabilities during construction of the laser and will greatly increase reliability when the whole system is complete: failures will usually be isolated in a single subsystem, and the other subsystems will automatically continue without interruption. Figure 2-102 identifies the alignment and diagnostic subsystems.

In the MOR, major groups of components will be separated by pairs of motorized gimbals. Each

Fig. 2-102. Nova alignment and diagnostic subsystems.

pair of gimbals will respond to an alignment and diagnostic sensor that will measure beam centering and pointing errors, the transverse spatial profile, and the energy of a propagating pulse. The control loops are shown schematically in Fig. 2-103. The sensors are designed to operate with either pulsed or cw oscillators and can therefore coalign a cw alignment beam with the pulsed oscillator output. Other alignment tasks in the system can then be performed, using whichever source is most appropriate.

Additional diagnostics, not shown in Fig. 2-103, will measure the pulse energy at intermediate points and the oscillator characteristics listed in Table 2-24.

The beam-splitter array consists of all components between the last motor-driven gimbal in the MOR and the splitter at the input to each chain. Alignment sensors and motorized gimbals in this section will assure that the beam first reaches the proper starting point in the laser bay and that half of the beam then follows the proper path through each of the two groups of five beam-splitters. The control loops for the two functions described in the previous sentence are shown in orange and blue,

respectively, in Fig. 2-103. A separate diagnostic sensor measures the energy ahead of each five-way split.

The oscillator and signal-processing electronics for pulse synchronization are also part of the splitter-array subsystem. The heterodyne approach to synchronization that is used on Shiva will also be used on Nova.⁴⁸

The alignment and diagnostics functions in the amplifier chain include monitoring and adjusting the path through each chain, positioning the spatial-filter pinholes before each shot, and measuring the pulse energy and transverse profile at selected points in the chain. The two primary sensors in the amplifier subsystem, the chain input sensor and the output sensor, will collect most of the data for performing these functions, but the diagnostic data will be supplemented by several separate energy-monitoring and near-field photography stations. The primary sensors will be described in some detail below.

Remotely insertable crosshairs will provide additional alignment references at eight places in the chain. Although the alignment data provided by

Fig. 2-103. Alignment control loops for a representative path from the oscillator to the target. The sensors, gimbals, and beam-path segments are color coded to identify each sensor with the part of the system that it will monitor.

Table 2-24. Measured oscillator characteristics.

1. Energy in the mode-locked train or single-mode Q-switched pulse.
2. Energy in the switched-out pulse or shaped Q-switched pulse.
3. Prepulse oscillation vs time.
4. Temporal profile of switched-out pulse or Q-switched pulse before and after shaping.
5. Prepulse energy after switchout or shaping.

this combination of sensors and crosshairs will be extensive, the ability to implement automatic alignment corrections will be limited to two pairs of motorized gimbals: one pair at the very front of the chain, and a second pair at the folding point of the

chain. With stable component mounts and good temperature control in the room, these eight axes of automatic control should be sufficient; they are shown as green and yellow control loops in Fig. 2-103.

The output sensor will also collect pinhole-alignment data using the same back-illumination technique employed on Shiva.⁴⁹ Each pinhole will then be accurately positioned by a motorized manipulator.

Target-related alignment and diagnostics functions are grouped in the output subsystem. The output sensor is designed to characterize the chain output in a plane optically equivalent to the target plane and to collect alignment and diagnostic data from the direction of the target chamber by use of an auxiliary mirror, as shown in Fig. 2-104. Dis-

Fig. 2-104. The output sensor will collect light from both the laser and target directions by use of an auxiliary mirror. Discrimination between light from the two directions will be achieved by introducing a small angular difference with the auxiliary mirror, by sensing the difference in arrival time, or by closing a shutter in front of the auxiliary mirror.

crimination between light from the laser and light reflected from the target or from a reflector inserted ahead of the focusing lens will be achieved by introducing a small angular difference with the auxiliary mirror, by sensing the difference in arrival time, or by closing a shutter in front of the auxiliary mirror.

Other components that will be used to correctly place a target in the target chamber and to align each beam on the target are orthogonally mounted target viewers on the target chamber, a target positioner, a three-axis motor-driven lens drive, and two motorized output gimbals. The control loop driving these gimbals will use the same sensor as the second amplifier chain loop; consequently, the former loop is also shown in yellow in Fig. 2-103. As described previously,⁵⁰ we are also working on ways to place a charge-coupled-device (CCD) array in the target chamber during alignment to directly sense the position of beams in the target plane.

Chain Input Sensor. The chain input sensor, located between the rod amplifiers and the 42- to 92-mm spatial filter, will measure beam position and direction near the input to the amplifier chain, will record the spatial profile and pulse energy of the beam, will collect data for Pockels-cell alignment and timing, and will insert lenses for spatial-filter pinhole backlighting. The basic performance characteristics of the sensor are shown in Table 2-25; a number of additional design features are listed in Table 2-26.

Table 2-25. Performance characteristics of the chain input sensor.

Characteristic	Required performance	Design goal
Pointing measurement accuracy	15 μ rad	10 μ rad
Centering measurement accuracy	0.5 mm	0.1 mm
Energy measurement accuracy	5%	1%
Pockels-cell timing resolution	5 ns	2 ns
Near-field photography	(10 mJ/cm ² on film)	

Table 2-26. Design features of the chain input sensor.

1. The sensor incorporates internal signal-level adjustments for both alignment and diagnostics.
2. No part affecting the measurement of beam direction is a moving part.
3. Installation of the sensor causes no offset of the main beam.
4. Interference fringes resulting from the sensor's beam splitters cause negligible intensity modulation on the main beam because the uncoated second surfaces of the beam splitters are at Brewster's angle.
5. Provision is made for calibrating the energy-measuring diode.
6. Readout of the detector, a CCD array, is synchronized with the pulsed oscillator, so the sensor can perform its alignment functions on either a pulsed or a cw beam.
7. All actuators are compatible with the standard Nova motor-driver module.

Figure 2-105 is a schematic of the current design of the input sensor. Detection of 10- μ rad pointing errors will be achieved by using lenses L1 and L2, which will focus the beam on the CCD array detector. Lens L1 will bring the beam to a virtual focus just past L2, and L2 will relay the focus onto the CCD array. Given the 10- μ rad resolution goal, the required effective focal length of this lens system is determined by the CCD's resolution of 16 lines/mm and vertical dimension of 7.7 mm. The resulting acceptance angle for pointing measurement is $\pm 616 \mu$ rad.

The insertable crosshair, shown in Fig. 2-105 at the input to the sensor, is the centering reference. To verify that the beam is aligned to this crosshair, the plane of the crosshair will be imaged onto the CCD array. This imaging function will be performed by lenses L1 and L3 and by lenses L1 and L4 for 60-mm and 12-mm fields of view, respectively. The two fields of view will provide a choice between an image of the entire beam, with a resolution of 0.5 mm, and a view of the central portion only, with a resolu-

Fig. 2-105. The chain input sensor will monitor beam position, direction, energy, and transverse profile. All adjustments required for normal operation will be controlled through the alignment and diagnostics parts of the system control network.

tion of 0.1 mm. The latter view will be used primarily to compare the crosshair pattern on the beam with the reference crosshair.

To avoid moving any of the optics used in the pointing measurement, the beam will be deflected along alternative paths for the centering measurement. The adjustable beam dump, W1, and filter wheel, W2, provide a convenient way to redirect the beam through either lens L3 or lens L4 and back to the CCD. Although these adjustment mechanisms are intended primarily to control the signal level in the pointing mode by inserting reflectors and filters having a range of transmissions, the mechanisms have enough extra detect positions to hold mirrors for the centering mode.

Pulse energy will be measured by a calibrated photodiode located behind beam splitter S3. To calibrate the photodiode, a calorimeter will be inserted in the main beam at the output of the sen-

sor and held there by the same fixture that would normally hold a beam tube.

An insertable mirror will divert the beam into a photomultiplier tube for checking the Pockels-cell timing. (These components are not shown in Fig. 2-105.) A wave plate placed in the oscillator switchout will send an entire mode-locked train into the chain with only the normally selected pulse missing. An oscilloscope display of the photomultiplier output will then provide timing data such as that shown in Fig. 2-106.

An energy density of approximately 10 mJ/cm^2 is required to produce an acceptable image on film. The Brewster's-angle beam splitter, S1, will divert approximately 3% of the beam energy to the film. This arrangement will work for all but sub-nanosecond-pulse operation, in which case there will be insufficient energy to expose the film. Therefore, for short pulses, the near field will be photographed by mounting a camera in the calorimeter/beam-tube fixture at the output of the

Fig. 2-106. Oscilloscope display for Pockels-cell timing. When a wave plate is inserted in the oscillator switchout, the photomultiplier tube in the chain input sensor will detect the portion of the mode-locked train that gets through the Pockels-cell gates. From the envelope of the transmitted pulses and the position of the missing pulse, an operator can determine the relative timing of the gate and pulse.

sensor; a choice must be made between recording a near-field image or allowing the beam to propagate past the sensor.

The chain input sensor contains a mechanism, W3, for inserting lenses to backlight the subsequent spatial-filter pinholes. This insertion capability is unrelated to the sensor's basic functions, but incorporation of this capability will reduce the number of separate motor-driver interfaces.

The chain input sensor will be controlled through the Nova digital-control network, and the normal operator interface will be through the control consoles in the control room. By specifying the desired mode of operation at the console, the operator can cause all of the sensor's stepper motors to drive automatically to the proper position, alignment loops to close, and diagnostics to be appropriately configured for a shot.

When necessary, it will also be possible to control the sensor and associated gimbals on a more local basis. Besides being sent to the central control system's video processor, the CCD output from any sensor can be displayed in standard TV format on local monitors, and an operator can address any stepper motor from local motor-driver switches.

Output Sensor. The output sensor will be located behind the first turning mirror in the optical switchyard, as shown in Fig. 2-104. It will sample light from the chain to provide near-field alignment data and spatial-filter pinhole alignment data before the laser is fired and will collect near- and far-field data at shot time for characterization of the output pulse. A portion of the light reflected from the

target will also be collected. The major functions of the sensor are listed in Table 2-27, along with some preliminary performance requirements. Figure 2-107 shows the current conceptual design of the output sensor; provision will also be made for extending the laser operation to the second harmonic.

Lenses L1 and L2 will reduce the beam diameter to approximately 200 mm. Before the beam diameter can be reduced further, provision must be made for dumping most of the several hundred joules of energy that enter the sensor during a full-system shot. Beam splitter S1 will provide this beam-dump operation and, at the same time, will provide light for a near-field photograph of the beam in a plane equivalent to the target-chamber focusing lens. During alignment before a shot, the signal level is very low, so mechanism W1 will provide a way to exchange S1 for an optically equivalent, but highly transmissive, beam splitter.

Beam splitter S2 will reflect most of the 1.053- μm light and will transmit 0.526- μm (2ω) light. With this dichroic splitter, the output-sensor functions will be performed at the two wavelengths by addition of a 2ω module. Lenses L3 and L4 will reduce the diameter of the attenuated 1.053- μm beam to approximately 60 mm.

Beam splitter S3 will split off a portion of the remaining energy for calorimetry. A small difference in propagation direction between light from the laser and light from the target will be provided by the auxiliary mirror identified in Fig. 2-104. This angular difference will cause light from the two sources to be recorded on different calorimeters. Just ahead of lens L5, which will focus the beams on the calorimeters, is a splitter to further reduce the fraction of energy being sampled. The light reflected from this splitter will be directed to a port on top of the package, where it may be used for interferometry, streak-camera input, or other diagnostic purposes.

The fraction of the signal transmitted by S3 can be varied by using motorized wheel W2 to insert S3 splitters having different reflectivities. Lens L7 is actually a set of lenses that will have no optical power when set at nominal spacings but will be adjustable to either positive or negative power by motorized spacing changes; L7 will serve as a focus adjustment for the viewing optics that follow. Beam splitter S4

Table 2-27. Functions of the Nova output sensor.

Function	Required performance	Use	Pulse or cw
Near-field imaging	Full-beam field of view	Chain alignment	cw
Near-field imaging	Full-beam field of view	Align to focus lens	cw
Near-field imaging	2-mm resolution	Crosshair viewing	cw
Near-field imaging	Focus lens equivalent plane	Beam photograph	Pulse
Far-field imaging	350- μ rad field of view	Pinhole viewing	cw
Target-plane imaging	1200- μ rad field of view	Viewing targets ≤ 2.7 mm	cw
Target-plane imaging	1200- μ rad field of view	Equivalent-plane photo	Pulse
Target-plane imaging	1200- μ rad field of view	Reflected-light photo	Pulse
Target-plane imaging	4000- μ rad field of view	Surrogate viewing	cw
Energy measurement	50- μ J sensitivity	ASE and prepulse	Pulse
Energy measurement	5% accuracy	Total chain output	Pulse
Energy measurement	5% accuracy	Focusable energy	Pulse
Energy measurement	5% accuracy	Reflected energy	Pulse
Streak-camera interface	Illuminate fiber optic	Temporal pulse shape	Pulse
Interferometer interface	Provide port	Monitor chain aberrations	cw

will direct a fraction of the energy to a multiple-exposure-level far-field camera, which is not shown in Fig. 2-104; the rest of the beam will continue toward the CCD camera and a focusable fraction calorimeter.

Motorized wheel W3 will hold a set of mirrors, each of which can be inserted into the beam by rotation of W3. Each mirror will be oriented to direct the beam into one of four near-field or far-field viewing paths. Wheel W4 will hold a corresponding set of mirrors to direct the beam toward the CCD. In one of the positions of W3 and W4, the beam will just pass through clearance holes and lens L7. The paths FFM1, FFM2, FFM3, NFM1, and NFM2 (Fig. 2-107) will each contain appropriate optics (mostly not shown) to provide three fields of view for far-field or target-plane imaging and two fields of view for near-field imaging.

In fields of view FFM2 and FFM3, the plane of interest will be imaged ahead of the CCD array and relayed to the array by lens L9. At the time of a shot, the mirror and pinhole located ahead of L9 will be inserted in the beam with the pinhole positioned in the image plane. The pinhole diameter will be chosen to match the target diameter, so the light transmitted through the pinhole and reflected into the calorimeter will be a measure of the energy that actually hits the target.

Motorized wheel W5 will hold the final optics for field of view FFM1, but the wheel's primary function will be to position an appropriate neutral-

density filter in front of the CCD array. For this purpose, W5 can hold up to nine different filters to cover a signal-level range of several orders of magnitude.

Data Acquisition and Processing. Requirements for diagnostic-data acquisition and processing include rapid turnaround, effective interfacing with the alignment and power-conditioning controls, preservation of data under failure conditions, options for local or control-room modes of operation, and portability of the hardware required for off-line troubleshooting and calibration. Figure 2-108 shows the major elements of a digital system designed to meet these requirements.

Signals will be generated by streak cameras, photodiodes, and calorimeters and collected in one of two ways. In the first instance, single detectors that produce large blocks of data, such as CCD readouts for streak cameras (160K words), will interface directly to the fiber-optic communications bus (Novanet) and the data will be transferred directly to the top-level diagnostic computer, a VAX 11/780, that will be located in the control room. This computer has enough memory and speed to process large volumes of data. In the second instance, for a diagnostic task that produces a small quantity of data per detector (e.g., calorimetry) but that requires many such detectors, groups of detectors will be connected to a microprocessor located near the detectors. This front-end processor (FEP) will collect the data and will supply control signals for the detector electronics. Similar FEPs located off-line will provide

Fig. 2-107. The output sensor will perform a number of output-alignment and diagnostic tasks. Component functions are described in the text. The optomechanical design specifically allows for eventual operation with frequency-doubled (second-harmonic) light by addition of a second, similar, module.

for maintenance and calibration of sensors. Operator interface at this level will be through a control panel on each microprocessor chassis.

All FEPs will be interlaced to each other and to the top-level diagnostic computer in the control room via the Novanet fiber-optic bus and a multiported shared memory. The shared memory will also provide interconnection to the alignment and power-conditioning top-level computers. With this network configuration (see "Control System," above), the mechanical functions shared by alignment and diagnostics can be readily controlled

through either the laser diagnostics or the laser-alignment computers.

Figure 2-109 illustrates how data will be collected from calorimeters and photodiodes. The low-level signal will input to an amplifier package that will reside as close as possible to the detector to provide a short transmission path. The signal—charge-amplified in the case of photodiode signals, voltage-amplified in the case of calorimeters—will

Fig. 2-108. Major elements of the diagnostics data-acquisition and processing system. This system will control the status of diagnostic electronics, collect raw data from individual detectors, and perform all the analyses necessary to provide useful diagnostic information for laser operation.

be converted to a digital signal and then transmitted serially over no more than 200 ft of cable to an FEP.

Data from the detectors and control signals to the detector electronics will be multiplexed to and from each remote electronics package by an interface within the processor. This interface will provide options for direct-memory-access storage of the data or single-sensor data transfer and control.

Each detector amplifier package will have built-in self-test signals so that its operation can be quantitatively verified on line. This feature will help

operators distinguish between laser malfunctions and diagnostic errors, since the state of any sensor can be verified in a few seconds from the operator's control console.

The FEPs will convert voltages to energies by applying the appropriate calibration factors for each detector. Each calibration factor will be identified by the ID number of the corresponding detector amplifier package, and each amplifier package will communicate its ID number, along with the calorimetric data, to the FEP over the serial transmission line. At the local control panel of the FEP, an operator will be able to read the energy, voltage, gain, and calibration factor for any sensor.

Fig. 2-109. Block diagram of diagnostic signal-conditioning elements and an FEP interface for control of detector electronics. This system will be used for collecting data from calorimeters and photodiodes.

The same data display and control functions will be available in the control room, along with a variety of additional display, graphic, and analysis capabilities.

Temporal pulse shapes will be recorded by streak cameras, each of which will be equipped with a 512×320 -element CCD array. The CCD electronics unit will provide both a standard TV-format video output for continuous operation and a digitized output for pulsed operation. The digitized data will be written into a local memory of 160K words and either replayed continuously on a TV monitor or transmitted to the control room. The CCD array and its memory will be linked to the control room for both control and data transmission by interfacing the Q-bus protocol output of the camera/memory combination to Novanet.

As shown in Fig. 2-108, the data from other time-resolved signal recording devices (e.g., transient digitizers) will also be handled by direct interfaces to Novanet without using an FEP. In these cases, the quantity of data generated or the complexity of the display required will exceed the capability of a standard FEP. By contrast, the top-level diagnostics computer is fast, has a large memory, and is capable of displaying these data on a number of graphics, TV, and hard-copy displays.

There will be three types of triggers for laser diagnostics on Nova: high-speed triggers, with less than 1-ns jitter and resolution; medium-speed triggers, with less than 100-ns jitter and resolution; and low-speed triggers, with approximately 1- μ s resolution and 200-ns jitter. These triggers will form an interlaced network, as shown in Fig. 2-110, to control the operation of all laser diagnostic devices.

The high-speed triggers will originate directly from the countdown circuitry for the Q-switch of the oscillator. During a period that extends for several milliseconds before Q-switch time, a time can be selected with 1-ns precision relative to the actual Q-switch time. This time selection allows detectors to be triggered at precise times with respect to the arrival of the optical pulse. The high-speed trigger will be used with streak cameras and transient digitizers to start the sweep before the optical signal arrives. Approximately 10 such triggers are

required, and each trigger will use a separate channel from the oscillator.

The medium-speed triggers, which will also originate at the oscillator, are required throughout the laser bay, oscillator room, and switchyard to control the gate circuit of the photodiode charge amplifiers. A gate of approximately 1 μ s will be used to discriminate the laser pulse from flashlamp light. As shown in Fig. 2-110, these triggers will originate from a few oscillator timing channels; each pulse will then be regenerated and fanned out in parallel to all the amplifiers at a particular diagnostic location on all the arms.

The low-speed triggers will be generated by the power-conditioning system through programmed timing channels on the power-conditioning bus, Novabus. These signals will be used to trigger the FEPs to notify them of a shot.

All triggers will be transmitted over fiber-optic cables. This mode of transmission will provide complete electrical isolation between source and destination. In the case of triggers originating from the oscillator, this isolation is essential so that noise is not transmitted back to the oscillator timing circuitry. Noise picked up along wire cables might also disrupt the gate timing of the charge amplifiers.

For all but the low-speed triggers, an electrical pulse from the oscillator countdown circuitry will fire an avalanche transistor to generate a fast current pulse that will switch a laser diode. The laser diode will be coupled to a fiber-optic cable that will go directly either to the device being triggered or to an optical fan-out with two input diodes and six outputs. To ensure against the loss of diagnostic data that would result from trigger failure, the triggers are designed so that either of the input diodes is sufficient to trigger all six outputs. Five of the outputs will go to devices as triggers and one output will be used to monitor the optical-signal level of the trigger.

Optical receivers typically are highly subject to false triggers induced by emi. We will avoid this problem by using very high optical-signal levels from the laser diodes to switch a photo silicon-controlled rectifier (SCR), causing the discharge of a capacitor. This will provide a stable trigger voltage, and the SCR will be driven far enough into saturation that it will switch even if one of the laser diodes fails to function.

Authors: E. S. Bliss, R. G. Ozarski, J. Parker
Major Contributor: R. O. Hutchinson

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Nova Target System

This subsection on the Nova target system encompasses scope and layout, target chamber, target handling, target alignment, beam focusing, handling equipment, target diagnostics, data acquisition and communications, and neutron and photon dosimetry for effective radiation protection.

Scope and Layout. The Nova target system includes the target chamber; equipment for handling, positioning, and aligning the target; beam-focusing equipment; equipment for handling, installing, and maintaining the components; and controls and instrumentation for the entire system.

The target chamber will be located in a concrete-shielded room north of the laser bay, as shown schematically in Fig. 2-111. Laser beams will be routed from the mirror switchyard to the target chamber through a series of turning mirrors mounted on a steel spaceframe, as described in "Mechanical Subsystem," above.

During operation of Phase I Nova, we will irradiate the target with 10 beams; these beams will be divided into two 5-beam open cones, one on the east end and one on the west end of the target chamber. To provide flexibility in target irradiation geometries, the included angle of the cones can be set from 80° to 100°.

Target Chamber. The target chamber, depicted in Fig. 2-112, will be supported on the steel spaceframe in the center of the target room, 10 m

Fig. 2-110. Data acquisition will be synchronized by in the oscillator countdown circuitry; low-speed triggers will be converted to optical signals. All timing signals will be converted to optical signals.

optic trigger network. High-speed and low-speed signals will be transmitted over fiber-optic cables.

10. Data acquisition will be synchronized by a fiber-optic trigger network. High-speed oscillator countdown circuits; low-speed triggers will come from crystal timing channels in ng signals will be converted to optical signals and transmitted over fiber-optic cable

or Time

Medium-speed triggers will originate from a power-conditioning control system.

ger network. High-speed and medium-speed triggers will originate in crystal timing channels in the power-conditioning control system. ed over fiber-optic cables.

Fig. 2-111. Nova target room and switchyard arrangement.

above the floor. The main body of the chamber will be a central ring, 1 m wide by 2.3 m outside radius, that will provide structural support for the target positioner, target-alignment optics, vacuum system, and target-diagnostics instruments.

Two removable hemispherical heads, which will be attached to the center ring, will have ports for the laser beams, effects experiments, and target diagnostics.

Phase I requirements call for an experiment yielding 1×10^{17} neutrons from a 100-kJ, 1-ns laser pulse. The neutron, x-ray, and debris fluences generated by this neutron yield are not serious enough to require local shielding or protection of the chamber by a first-wall absorber; thus, the minimum radius of the hemispheres is dictated by mechanical considerations, primarily the mounting of the focusing lenses. The baseline lens for Phase I is $f/3$, with a 740-mm clear aperture, but we are making provision for a future change to a lens of

about $f/1.6$. The faster lenses will necessarily be inside the target chamber, so the ports in the hemispheres must be large enough to admit the full laser beam plus some mechanical hardware. These considerations dictate a minimum chamber radius of 1.5 m for Phase I. Since neutron activation is not a large problem, the structural material can be stainless steel.

For Phase II, the target chamber is being designed for an increase in laser energy to 250 kJ and an increase in neutron yield to 5×10^{18} neutrons, with as much as 3.2 MJ of cold x rays and 4.0 MJ of target debris. As described in detail in the 1977 annual report,⁵¹ these conditions will require a first wall to absorb the x rays and debris, an aluminum vessel to allow decay of neutron activation to the level of personnel-exposure limitations, and a water shield around the chamber to reduce activation of the steel spaceframe and the concrete building. To accommodate 10 lenses per side instead of 5, and to reduce the x-ray fluence on the first wall, the Phase II chamber radius must be at least 2.3 m.

Fig. 2-112. Target chamber of Nova Phase I. Ten laser beams, each 740-mm diameter, will be focused on the target in two cones of five beams each. The cone angle shown is 100°, but any angle down to 80° can be accommodated. Some target diagnostics packages, such as the filter-fluorescer, are located behind concrete shielding walls to reduce radiation-induced damage and spurious signals.

We have evaluated several plans to meet the requirements of both Phase I and Phase II. In the long run, the most economical plan obviously is to build a single chamber to satisfy Phase II, except that the first wall and water shield will not be needed for Phase I. There are short-term economies that could be realized by building a 1.5-m radius hemisphere of stainless steel to satisfy Phase I only; however, since the center ring is integral with the spaceframe, with the vacuum system, and with the principal target diagnostics, the long-term costs of replacing this ring for Phase II would be extremely high. Therefore, except for the first wall and water

shielding, we will build the Phase I center ring to Phase II requirements (2.3-m radius).

The vacuum system will incorporate mechanical pumps and Roots blowers for rough pumping and turbomolecular pumps and cryogenic pumps for high-vacuum pumping. We will attain a pressure of 10^{-5} Torr in 30 min and ultimately reach a base pressure of 10^{-7} Torr. Backfilling will be done with dry air to keep the system clean and dry for faster pumpdown. The chamber size requires at least two of each type of pump for capacity, which will also

give us an emergency operating unit in case of a breakdown.

Vacuum-system controls will be micro-processor controlled and will be integrated via Novalink into the overall Nova control, alignment, and diagnostics system. Programmed interlocks will prevent inadvertent operation of any valves that could cause damage to either the equipment or the target diagnostics. Many of the target-diagnostics experiments will have their own satellite vacuum systems, which will be integrated into the central control and interlock system.

Target Handling. Targets will be supported in the center of the chamber by a remotely controlled positioner that will position the target to within $5\text{ }\mu\text{m}$ of the theoretical true position with four degrees of freedom. Controls for the target positioner will be integrated into the overall Novalink control system.

Provision will also be made for handling cryogenic targets in all phases from receipt from the factory through installation and alignment to exposure.

Target Alignment. Because of the high fluences of cold x rays expected in Phase II, all equipment must be at least 1 m from the target to prevent blowoff and shock damage to the equipment. At this distance, an $f/4$ lens, which is required to form an image with a resolution of $5\text{ }\mu\text{m}$ with $0.5\text{ }\mu\text{m}$ green light, will have a lens diameter of 250 mm. A shield will protect the lens from x rays and debris during the shot.

The image of the target will be relayed to coincide with a reticle; the combined image will then be magnified, projected onto a CCD array, and transmitted to the control room. The target-alignment optics package will define the center of the chamber, the reference point to which all beams will be aligned.

Beam Focusing. Each focusing lens will be supported in a remotely controlled positioner that will have a lateral (x-y) range of 40 mm and a focusing (z) range of 150 mm. Stepper motors will move the lenses a distance of $2\text{ }\mu\text{m}$ per step with a position-readout accuracy of $5\text{ }\mu\text{m}$. Lens tilting and rough centering will be done manually during setup.

The initial configuration provides for 2220-mm, $f/3$ lenses located outside of the target chamber. If more uniform target irradiation is desired, we

will substitute $f/1.6$ lenses that will be supported inside the chamber with the same lens positioners.

Lenses will be protected from cold x rays and target debris by inexpensive debris shields, which may have to be replaced on a regular basis. We are developing replicated epoxy shields for this use, as described in "Optical Components," above.

Handling Equipment. All parts of the beam-focusing system will be massive. A lens will weigh 56 kg, and the vacuum window will weigh over 80 kg. Handling equipment is necessary to install and service these large elements. Each optical element is designed to be supported in a removable cell that will provide an attachment for powered handling tools. All Nova component designs provide for convenient servicing during operations.

Target Diagnostics. The Nova target chamber will have a number of ports for laser beams, target diagnostics, and other functions. The adopted target-coordinate system has Cartesian axes directed as shown in Fig. 2-113, where X = up (toward the target positioner), Y = south, and Z = east. The corresponding spherical coordinate system has $\theta = 0^\circ$ at the +Z axis and $\phi = 0^\circ$ at the +X axis.

Each lens will have its own Cartesian coordinate system (X_i , Y_i , Z_i). The Z_i direction is positive radially outwards along the beam axis. The

Fig. 2-113. Nova target coordinate system. This is a right-handed spherical coordinate system in which θ is measured from the Z axis and ϕ is measured from the X-Z plane. The range of θ is from 0° to 180° , of ϕ is from 0° to 360° .

Fig. 2-114. Principal target-diagnostics lines of sight and work platforms in the mirror switchyard and diagnostics loft.

Y_i direction, in a plane defined by the beam axis and the target Z axis, is positive when pointing towards the nearest Z axis: for the east hemisphere, this is $\theta = 0^\circ$; for the west hemisphere, this is $\theta = 180^\circ$. The X_i axis forms a right-handed system with Y_i and Z_i .

Each lens will have an axis defined by the angles θ and ϕ . Spherical coordinates for each lens are shown in Table 2-28 for an assumed 100° open cone. Opposing beams are 1 and 6, 2 and 7, etc. (difference of 5). Target/lens coordinate transformations are calculated by the target alignment codes, described earlier.

Beam numbers have been assigned for Nova Phase I; their locations in the laser bay, the wall penetrations into the target room, and the positions on the target chamber are shown in Fig. 2-111.

All target-diagnostics lines of sight are expressed in terms of their θ and ϕ coordinates. Wall penetrations and clear paths through the space-frame are calculated from these vectors.

Table 2-28. Nova beam axis spherical coordinates.

Beam No.	θ	ϕ
1	50	306
2	50	18
3	50	90
4	50	162
5	50	234
6	130	126
7	130	198
8	130	270
9	130	342
10	130	54

Figure 2-114 is a section through the equatorial plane of the target chamber and target room and schematically shows beam-penetration and work-platform locations in the mirror switchyard and diagnostics loft.

Data Acquisition and Communications.

Novalink is a high-speed, serial, fiber-optic-distributed communications link designed by us for use on the Nova laser-alignment and diagnostic computer-control system. This link will provide error detection on each transfer and a multidrop capability between computers and remote interface devices.

The Nova laser-control system, based on a hierarchical network of distributed minicomputers and microcomputers, will effect closed-loop control, data acquisition, and operator-interface functions as discussed in "Control System," above. Experience gained from implementation of the predecessor Shiva laser system has shown that inter-processor communications is a critical constraining factor with respect to system integration, operating speed, and processor overhead. The Nova system will require the transfer of relatively large amounts of data because of heavy reliance on CCD array cameras for alignment, beam characterization, and target diagnostics, and a hardware and software package, termed Novanet, has been designed to meet the control needs associated with these large-volume transfers.

The Novanet system will use the logical equivalent of a bus structure (Fig. 2-115), which will allow any node to communicate directly with any other node. Unfortunately, presently available fiber-optic components restrict the maximum number of nodes to approximately 20. This limitation is based on the power output of available solid-state fiber-optic emitters and the inherent optical losses

of fiber-optic power splitters and connectors that will be required at each tap point on the bus.

Our implementation of Novanet, shown in Fig. 2-116, will accomplish the logical equivalent of the bus structure in Fig. 2-115 but without the limitations of insufficient power at the optical receiver due to multiple optical power divisions. Note in Fig. 2-116 that the individual nodes will not repeat the incoming message; all optical transmitters will feed a common node star, and all optical receivers will listen to the node-star output. Thus, a transmission will be received by all other nodes, just as in a bused system. The node star need have very little logic except for the "OR" gate and the fiber-optic receivers and transmitters. With the addition of a limited amount of logic, the node star can offer maintenance capabilities (e.g., detection of bad nodes) that will allow automatic fault isolation.

Note that, to minimize costs, local coaxial-cable connections are allowed in place of fiber-optic components if multiple nodes are physically close enough to guarantee that differential ground potentials among these nodes will not disturb TTL (0- to 5-V) signal levels.

Neutron and Photon Dosimetry for Effective Radiation Protection. In previous annual reports,^{51,52} we examined pulsed-radiation effects on instruments, shielding against prompt and residual radiations, dose levels inside and outside the target room, kerma factors for silicon and tissue, radiation flux densities along beam penetrations, and induced radioactivity in materials that are exposed to neutron fields.⁵² We have now ex-

Fig. 2-115. Novanet direct communication system (computer-to-computer, computer-to-device). Any node can address any other node (256 nodes maximum).

Fig. 2-116. Physical connections that will be used in implementing Novanet.

amined the applicability of LLL thermo-luminescence dosimeters (TLDs) for measuring biological doses in the Nova radiation environments.

A detailed understanding of energy transfer from neutron and photon fields to various TLD materials with respect to tissue, water, and air is exceedingly important in certain energy regions if these materials are to be properly used for radiation dosimetry. We have computed the mean local energy transferred per unit path length and the total energy imparted, within equivalent masses, to TLDs, tissue, water, and air. The ratio of these values are plotted in Figs. 2-117 and 2-118 for neutron energies from 10^{-9} to 20 MeV and for photon energies from 10^{-3} to 20 MeV, respectively. In Fig. 2-118, the measured response is compared with the computed response at photon energies above 1.5 keV. All calculations were carried out using the Livermore Evaluated Nuclear Data Libraries (ENDL).

The mean local energy transfer in each energy group (E_g) per neutron collision is defined as

$$\bar{F}_L^n(E_g) = \frac{\sum_L f_L \sum_J \sum_I \sigma_{LJ}(E_g) E_{LJI}(E_g)}{\sum_L f_L \sum_J \sigma_{LJ}(E_g)}, \quad (1)$$

where f_L is the atom fraction of the L th element in the material, $\sigma_{LJ}(E_g)$ is the cross section for the J th reaction at neutron energy (E_g) for the L th element, and $E_{LJI}(E_g)$ is the energy transferred to the kinetic energy of the J th charged particle in the I th collision. In ENDL evaluations, the average energy of the final-state neutrons is taken either from the kinematics of a two-body reaction with a defined Q -value or from tabular representations. The average energy of the final-state charged particles is either taken from the experimentally tabulated data or is estimated to equal X times the square root of the energy that is available after the average neutron energy has been removed, where X is 0.5 for Z (atomic number) ≥ 29 , 0.25 for $7 < Z < 29$, and 1 for $Z \leq 7$.

Similarly, the mean local energy transfer per photon collision is defined as

Fig. 2-117. (a) Ratios of neutron energy transferred per unit path length to various materials, with respect to tissue; (b) ratios of total neutron energy imparted to materials, with respect to tissue.

$$\bar{E}_t^P(E) = \frac{\sum_L f_L \sum_J \sigma_{LJ}(E) E_{LJ}(E)}{\sum_L f_L \sum_J \sigma_{LJ}(E)}, \quad (2)$$

where $E_{LJ}(E)$ is the average energy transfer for the J th reaction of the L th element. All relevant atomic reactions were included.

The ratio of energy transferred per unit path length of material N to material M is defined as

$$R_t^n(E)_M^N = \frac{\bar{E}_t^n(E)_N / (\rho_N dl)}{\bar{E}_t^n(E)_M / (\rho_M dl)} \quad (3)$$

and

$$R_t^P(E)_M^N = \frac{\bar{E}_t^P(E)_N / (\rho_N dl)}{\bar{E}_t^P(E)_M / (\rho_M dl)}, \quad (4)$$

for neutrons and photons, respectively, where ρ_N and ρ_M are the densities of materials N and M , respectively.

The responses of TLDs (ribbon 3.18 mm $\times$ 3.18 mm $\times$ 0.89 mm) were experimentally determined for photon energies above 1.5 keV. Monoenergetic photon beams were obtained by using appropriate anode and filter materials. The TLDs were exposed under vacuum at photon energies below 10 keV. Photon fluence densities were monitored by using liquid-nitrogen-cooled windowless Si(Li) and NaI(Tl) detectors. The gamma spectra were unfolded by using computer codes that we have developed.

The results obtained using Eqs. (3) and (4) for $R_t^n(E)_M^N$ and $R_t^P(E)_M^N$ are shown in Figs. 2-117(a) and 2-118(a). The $R_t^n(E)_M^N$ for fast neutrons ($E > 1$ MeV) is less than one, as previously reported.⁵³

Since the penetrating ranges of neutrons and photons at certain energy regions are less than the thickness of the TLD materials used in this study (0.89 mm), the energy imparted within TLD masses becomes quite important. Ratios of energy imparted to equivalent masses of TLDs, water, and air are shown with respect to tissue in Fig. 2-117(b); ratios of energy imparted to equivalent masses of TLDs, water, and tissue are shown with respect to air in Fig. 2-118(b).

A knowledge of local energy transfer by neutrons and photons in TLDs, water, air, and tissue allows us to define the overall problem of radiation dosimetry for Nova. We can determine neutron biological doses on the basis of the TLD-to-tissue energy transfer ratio for each TLD; however, the neutron biological dose should also be evaluated by other methods. We will measure the neutron energy spectra and fluences using Ag and "long" counters and then calibrate the TLDs to relate the thermoluminescent yield to the neutron biological dose. Because the neutron spectra and fluences will change with locality, this calibration will be done at all occupied locations.

When the photon biological dose is determined, the use of $\text{CaF}_2:\text{Mn}$ (TLD 200) should be limited to energies above 200 keV unless supplemented by other methods of dosimetry. The

Fig. 2-118. Ratios of photon energy transferred per unit path length to various materials: (a) with respect to tissue and (b) with respect to air. The experimental data are based on local energy transfer values.

response of LiF dosimeters (TLD 700) is quite good at photon energies above 20 keV; TLD 100 and 600 are also LiF and respond to neutrons in addition to photons. The prompt gamma radiation outside the target room and the residual gamma radiation inside the target room will have energies appreciably higher than 20 keV; therefore, LiF dosimeters will be quite appropriate for monitoring gamma exposures.

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52. *Laser Program Annual Report—1978*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-78 (1979), pp. 2-109 to 2-118.
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Conventional Facilities

The Nova project has special technical requirements for housing the experimental apparatus within an ultraclean and environmentally controlled atmosphere. To achieve these requirements, we designed a 115 000-ft² addition to the existing high-energy-laser facility that houses Shiva; this addition is shown in Fig. 2-119. In addition to the laboratory building, we designed an office building to provide close communication between the Nova project team and the other members and groups within the overall laser-fusion program.

Fig. 2-119. The Nova laboratory addition is shown in the foreground of this architectural rendering; the attached target and laser bays in the background presently house the Shiva laser system.

Fig. 2-120. Construction of the Nova laboratory is shown. The laser bay basement is in the foreground, the target room is at the upper center, and the optical switchyard is to the left of the target room.

Albert C. Martin Associates is designing the conventional facilities described above, and Kaiser Engineers is providing construction-management services. The San Francisco Operations Office of

DOE is administering the major-facilities contracts.

Significant progress in the design and construction of these facilities was achieved during 1979, as described below (see Figs. 2-120 to 2-123).

Laboratory Building. Physical construction of the Nova laboratory was started in May 1979; by

Fig. 2-121. Plan views of the proposed addition to the existing laser facility: (a) first floor; (b) lower floor.

Fig. 2-122. Proposed Nova office building.

the end of the year, major portions of the site and building underground utilities had been completed, and the massive concrete wall and floor structures were approximately 50% completed. This progress is illustrated in Fig. 2-120. Since the laboratory is being constructed by the fast-track method, construction began while some building components and subsystems were still in the Title II design stage. At year end, major contracts had been placed for the earthwork and site excavation, structural concrete, shielding doors in the target room and adjacent areas, underground mechanical and electrical systems, structural steel, and the bridge cranes for the high-bay areas of the target room, optical switchyard, and laser bay. The remainder of the laboratory contracts are to be awarded in early 1980.

The 1978 Luser Program Annual Report contained a detailed discussion of this 115 000 ft² Nova laboratory⁵⁴; therefore, only a brief summary of the

laboratory requirements will be presented in this report.

The major requirements for this facility are: the attainment of a controlled environment in which the laser, optics, and diagnostics can perform effectively; and high safety standards, particularly for the target room. Figure 2-121 illustrates the facility floor plan and shows the integration of the laser and the target facility. To achieve the environmental conditions, the facility air-handling systems have been designed to maintain the target room, laser bay, optical switchyard, and the master oscillator room as Class 10 000 clean rooms with a controlled temperature of 74 ± 0.5 °F.

The vibrational stability of the facility is maintained by coupling the sensitive optical components directly to the massive concrete structure of the building. To meet the safety requirements for the planned high-fluence target experiments, the target room is constructed entirely of reinforced concrete with 6-ft-thick walls between the target chamber and any area occupied during experiments.

Fig. 2-123. Architectural rendering of the Nova office building, to the right, and the existing laser fusion offices, to the left. A connecting bridge at the second floor will provide effective communications between the two buildings.

Office Building. The Nova office building has been designed to provide a strong functional and architectural link with the existing facilities within the laser-program complex. The conceptual design and major building elements were presented in the 1978 report⁵⁵; the proposed design is shown in Figs. 2-122 and 2-123. By the end of 1979, the architect-engineers had completed the Title I design and had completed 90% of the Title II designs. The building designs were continually reviewed to obtain an effective and energy-efficient building. In keeping with the energy-efficiency goal, some modifications to the basic design and building operating equipment were made. The building mechanical equipment was connected to the Nova laboratory cooling-water system so that the office building can make use of the waste heat from the laboratory's air handlers. The two-story courtyard, which was previously open, has been enclosed with a skylight, and the resulting area will be used for a library and for the stairwell. An energy analysis of the building showed both that the enclosed atrium is energy efficient in the Livermore climate and that the atrium approach is functionally effective for the program.

Since this office building is also being constructed by the fast-track method, the earthwork and concrete footing were completed by the end of 1979.

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54. *Laser Program Annual Report—1978*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-78 (1979), pp. 2-123 to 2-126.

55. *Laser Program Annual Report—1978*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-78 (1979), pp. 2-126 and 2-128.

Project Management Systems

The Nova project has formally instituted three major systems to ensure proper project management:

- Financial planning and tracking system.
- Quality and safety assurance system.
- Scheduling system.

These systems provide for the development of accurate and optimum cost and schedule baseline plans, for integrated quality assurance controls, and for tracking reports that highlight cost and schedule deviations.

Each of the three project management systems has been designed to be consistent with the Nova work-breakdown structure (WBS), shown in Fig. 2-124, which provides for planning and control at the appropriate level of detail.

Financial Planning and Tracking System. The Nova financial planning and tracking system has these objectives:

- Ensure the development of accurate and optimum baseline plans showing time-phased costs.
- Provide tracking reports that highlight cost deviations from planned dollar amounts and from planned times of expenditure.
- Provide a consistent accounting system that satisfies the requirements of the project office, LLL, and DOE.
- Have a consistent and uniform set of graphic tracking reports at all levels of the WBS.

● Provide computerized methods that allow the rapid and accurate revision of baseline cost schedules.

This system, which is consistent with the LLL accounting system, is designed within the

framework of the Nova WBS, shown in Fig. 2-124. 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

Fig. 2-124. Nova work-breakdown structure (WBS) shown down to level 3. The financial planning and tracking system, quality assurance system, and scheduling system all use this structure.

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 es-

timated amounts and estimated times of procurement.

The system has a financial-planning phase and a financial-tracking phase. Figure 2-125 presents a schematic showing the basic financial processing system and the relationship between these two phases. The financial-planning phase occurs each time new cost baselines are prepared, which is done whenever any of the following occurs:

- A significant change in technical scope of the project is authorized.
- A significant change occurs in the funding schedule.
- An expenditure of contingency funds is authorized.

The financial-tracking phase involves monthly updates of commitments, costs, and obligations against the baseline plans. Performance-measurement graphs are prepared down to level 3, and detailed cost and variance reports are prepared down to level 5 for procurements.

The planning phase has formal procedures to ensure that baseline cost estimates are accurate. The *Nova Project Cost Estimating Manual*⁵⁶ was prepared by a consultant for use by the level-2 lead engineers and by the project-office administrative staff. The consultant also 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.

Each time that replanning occurs, computer codes are used to price the revised labor and procurement estimates. All planned expenditures are priced at the time of expected occurrence using appropriate inflation-related escalation factors.

After each estimating and pricing cycle, the Nova project manager conducts budget-review sessions 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 generation of a time-phased obligation plan that is consistent with the schedule of expected funding and probable contingency expenditures. Time-phased performance-measurement baselines are

Fig. 2-125. Schematic of the Nova financial processing system showing the financial-planning and financial-tracking phases. This system enables collection of data by use of standard estimate forms, performance of budget analyses, and establishment of approved plans and baselines against which cost- and schedule-performance measurements are made.

generated automatically from the budget plan for both financial commitments and costs.

The financial-tracking phase was made fully operational during 1979, with performance-measurement graphic displays generated each month down to level 3 of the WBS. To ensure accuracy and consistency between the graphs produced, plotting data bases are computer updated each month with new actual and budgeted work-performed values.

To measure performance, the Nova financial planning and tracking system displays, both

numerically and graphically, deviations from the baseline values. 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 for commitments are given in Figs. 2-126 and 2-127. These figures show how the financial performance of the project is monitored graphically at level 0. Graphs similar to Fig. 2-127 are generated each month for levels 1, 2, and 3. Those graphs that encompass the major contributions to total project deviations are

Fig. 2-126. Scheduled commitment of project funds. This schedule serves as a baseline, and performance is measured against it. The estimated commitment of funds for Nova Phase I is \$121 million without contingency expenditures. Comparative data are shown for budgeted commitments for work scheduled (BCWS), budgeted commitments for work performed (BCWP), and actual commitments for work performed (ACWP).

Commitments
Level 0 Total project

November 1979

Planned complete: 18.61%

Actual complete: 15.75%

9/24/79 Baseline	121.000
Estimate at completion	120.310
Variance over (-) under (+)	+0.690
Contingency	16.000
Total est at completion	137.000

reviewed to determine the causes of the deviations. The level-2 and level-3 graphs are distributed monthly to each of the lead engineers responsible for a level-2 cost center. Each lead engineer also receives both a detailed listing of costs that have been charged to his or her center that month and a financial status report that shows where any cost deviations are occurring.

Quality Assurance System. DOE mandated that we develop, as a major line-item project, a series of three assurance plans aimed at successfully

completing the Nova project. The three plans, typically used for all of LLL's major projects over the last few years, are

- A quality assurance plan.
- A safety plan.
- A configuration-management plan.

The interrelationships among these plans caused us to search for an approach that would provide a consistent plan for Nova that would avoid

Fig. 2-127. Scheduled commitment of project funds for FY 1980. BCWS values are displayed for FY 1980 along with the latest monthly values for ACWP and the corresponding BCWP. The schedule variance (BCWP minus BCWS) shows whether funds are being committed at the rate planned. The cost variance (BCWP minus ACWP) shows the difference between actual and planned costs for the work actually done.

Commitments
Level 0 Total project
November 1979
Planned complete: 18.61%
Actual complete: 15.75%

Optical design freeze
(Baseline change)

9/24/79 Baseline	121.000
Estimate at completion	120.310
Variance over (-) under (+)	+0.690
Contingency	16.000
Total est at completion	137.000

the redundancies found when separate plans are prepared. Our solution was to prepare an integrated Nova master assurance program plan,⁵⁷ which includes the techniques and controls by which we will ensure:

- Technical performance of Nova parts, components, software, and systems.
- Elimination or control of hazards that jeopardize the health and safety of people or the environment.
- Engineering documentation that describes Nova requirements and the completed facility.

Nova is the first project at LLL to use an integrated plan for implementing quality assurance, safety, and configuration-management activities.

Our approach is consistent with LLL's Quality Assurance Manual⁵⁸ and Health and Safety Manual.⁵⁹ DOE has not yet developed a policy on quality assurance and configuration management; their primary thrust has been directed toward health, safety, and the environment, with emphasis on facility operations rather than on the design and construction of new facilities. The Nova assurance plan provides both us and DOE with an auditable technique for improving our confidence in satisfying the objectives for Nova.

This quality assurance approach has been reviewed by the DOE Environmental Office and has been accepted for Nova.

In addition to the Nova master assurance program plan, we will prepare five subordinate plans for implementing the requirements of the

Table 2-29. Nova subordinate assurance program plans status.

Subsystem	Plan number	Responsibility	Status
Mechanical and target systems	M-078-10-20,30	C. A. Hurley, F. Reinecker	Approved Nov. 26, 1979; in printing.
Power conditioning	M-078-10-40	K. Whitham	Draft in review.
Optics	M-078-10-50	E. P. Wallerstein	Draft in review.
Alignment, control, and diagnostics	M-078-10-60	E. S. Bliss, F. W. Holloway	To be started in 1980.
Laboratory building	M-078-10-70,90	C. P. Benedix	Released April 23, 1979.

master plan for the major Nova subsystems. A list of plans being prepared, and their status at the end of 1979, is shown in Table 2-29. We used an interview process to develop the content of the subordinate plans; discussions with each of the project engineers revealed how they intended to assure themselves and the project manager that their efforts would be completed successfully. The successful engineering practices used during the design and construction of Shiva provided the foundation for the Nova plans. Where Shiva experiences indicated a need, additional controls and communication links were included in the Nova plans. Since the Nova team consists of essentially the same members as the Shiva team, all that was needed to implement the Nova plans was to:

- Formalize Shiva practices in written plans.
- Assign individual responsibilities in the plans.
- Provide for documenting the results of assurance actions.
- Provide for conducting periodic and independent audits to verify the adequacy and effectiveness of the assurance program.

We are implementing the assurance plan requirements during the design and construction of the Nova laboratory building and the design, procurement, and integration of the Nova laser. Our first audit of the program will occur in mid-1980, at which time we will be able to assess how well our integrated approach satisfies both the Nova project and DOE.

Scheduling System. The objectives of the scheduling system are to provide:

- A plan for performing the tasks to design, procure, and integrate the laser system and to design and construct the laboratory and office buildings.
- A means for tracking progress against the plan.
- A means for developing work-around plans based on schedule-variance projections.

The Nova project uses a schedule tracking and control system that is based on the one used effectively on Shiva. During the design and procurement phase of Nova, this system primarily consists of bar charts to the Nova WBS level 2 (Fig. 2-124), the procurement plan (discussed above), and schedules prepared and maintained by each of the project engineers at WBS level 3 and below as required. During the system-integration phase, a critical-path network/performance-measurement schedule system will also be used.

We evaluated MISTER⁶⁰ and EZPERT,⁶¹ computer programs recently purchased by LLL, for use during this integration phase. Using our best estimates, we tested these programs to determine how the integration will be conducted. It appears that a system using these computer codes will provide us with a schedule system that will meet our objectives. MISTER provides the critical path and resource analysis; EZPERT provides the graphics.

The Nova conventional-facility construction manager, Kaiser Engineers, is providing monthly schedule-comparison charts for laboratory and office-building construction contracts and Gantt charts that show planned and actual progress summarized to the construction-contract level.

In 1980, we will prepare plans for integrating the laser system into the laboratory building and will begin using the system to track the procurement activities as they become needed for integration. Reporting graphics will be prepared and distributed as needed.

Authors: F. J. Holcomb, A. J. Levy, C. W. Mickel, and L. C. Lewis

Major Contributor: R. O. Godwin

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Research and Development

Overview

Theoretical and experimental studies in 1979 led to completion of the Nova design and to development of new or improved laser materials and components. Accomplishments in the latter areas will lead to enhanced performances and reduced costs of the Argus, Shiva, and Nova lasers.

The following discussion presents an overview of the research and development programs conducted in 1979. More detailed discussions of these programs appear in succeeding articles.

For Nova, we determined that the optimum number of beams was 20 by calculating uniformity of target illumination and laser-system costs as functions of the number of beams. We also modified the MALAPROP beam-propagation code to ensure a realistic simulation of Nova's performance. The major modifications to the code were

- Doubling the array size to accommodate the larger-output amplifiers.
- Incorporating split disks.
- Including time-dependent changes in pulse shape caused by gain saturation.

We also calculated the expected ASE output from Nova to determine the amount of suppression that would be needed to protect the target. To verify MALAPROP predictions, we measured ASE from a rod amplifier; although the calculated emission fell 30% below the measured emission, the agreement was adequate for design purposes.

One of the most important developments for Nova in 1979 was the reduction of platinum inclusions in fluorophosphate laser glass. This accom-

plishment enabled the production of large amplifier disks having an adequate bulk-damage threshold.

Predictions of laser performance rely on knowledge of gain saturation in the amplifiers. Our initial measurements of saturation fluence gave unexpected results; consequently, we followed these measurements with the most comprehensive experiments on saturation to date. From these experiments, we learned that the value measured for the saturation fluence increases when pulses of higher fluence are used to make the measurement.

The power output and performance reliability of large laser systems are limited by the laser-damage thresholds of the optical surfaces in the laser chain. In 1979, we continued development of new materials and processes that showed promise of increased damage thresholds. In particular, phase-separated glass was rapidly advanced from small research samples of marginal optical quality to 300-mm-diam pieces suitable for spatial-filter lenses. In the field of antireflection (AR) coatings, significant improvements were observed in the damage thresholds of $\text{Ta}_2\text{O}_5/\text{SiO}_2$ and $\text{TiO}_2/\text{SiO}_2$ coatings that had been deposited at lower-than-normal temperatures. Also, we completed an initial survey of damage thresholds of various materials subjected to 266-nm pulses; these measurements suggest that fused silica and LiF have high damage resistances when used as UV-transparent materials.

We decided that the three largest Nova amplifiers would use a rectangular pumping geometry (box amplifiers) because this design, which was developed at LLL, offers improved efficiency over the earlier cylindrical pumping geometry. The largest amplifier, with a 460-mm clear aperture, will feature a split disk and a transverse flashlamp arrangement. Simulation of amplifier performances by the GAINPK code permitted efficient optimization of the box-amplifier design with regard to reflector materials, geometry, and number and arrangement of flashlamps. The good agreement of code predictions with experimental values gives us confidence in this modeling.

We extended our earlier studies of multipass amplifiers to include a 40-mm-diam rod amplifier and found that maximum multipass gain was limited only by the onset of superfluorescence depumping. We achieved a net saturated gain of 100 in the experiment; however, application of a multipass rod amplifier is limited by problems of pump-

induced thermal distortions of the beam and by high ASE. On disk amplifiers, we found that the potential advantages of an off-axis multipass disk amplifier would be further enhanced by development of a large-aperture switch that would permit a much larger net gain.

We redesigned the basic AMQ oscillator to improve ease of assembly and maintenance and to increase its reliability and flexibility, and we decided that Nd:YLF will be used for the Nova oscillator. A prototype planar-triode pulse selector was built and tested successfully. This device will replace the older avalanche-transistor pulse selector, which has proven difficult to repair; maintenance of this selector has been complicated by manufacturers' variations in transistor characteristic...

In 1979, we began a very active program to efficiently convert large-aperture Nd-glass lasers to higher harmonic frequencies. Practical limitations on the sizes of nonlinear crystals led us to the development of crystal arrays, and we have achieved uniform second-harmonic conversion with good beam quality in a prototype 2×2 array of deuterated KDP (KD*P) crystals with a 100-mm clear aperture. There are no fundamental difficulties in extending the crystal-array technique to the aperture sizes required for converting Nova to higher harmonic frequencies.

Large-aperture Pockels cells have important applications in suppressing ASE and in gain-switching multipass amplifiers. We studied the advantages of both conventional and liquid electrodes for a 100-mm clear-aperture cell. Other, more advanced, designs using transparent conductive coatings, grid electrodes, a high-field dielectric pusher geometry, and new materials were considered for future applications to Pockels cells with much larger clear apertures.

A prototype compensated pulsed alternator was built at the University of Texas Center for Electromagnetics, and the machine was successfully operated at 90% of design speed. At full speed, a short circuit occurred between the high-voltage rotor and the grounded stator; the insulation has since been increased to prevent further such faults. We have modeled the alternator's performance with a computer code that will be used to optimize the designs and costs of future, larger machines.

In target irradiation, some of the laser pulse is reflected back into the amplifier chain where, unless stopped, it will be amplified and cause damage. We

currently use Faraday rotators on both Argus and Shiva to stop the reflected pulse. The Faraday rotator is reliable, but its cost increases rapidly with increasing aperture size. In 1979, we developed and built a prototype plasma shutter that propels a high-density plasma across the beam path at precisely the right instant, thereby preventing reflected light from reentering the amplifier chain. The success of the plasma shutter will reduce the cost of each Nova chain by \$1 million.

Lasers generate strong electrical noise that can interfere with the transmission of control and data signals. To eliminate such problems with Nova, we have developed three types of fiber-optic signal lines that will greatly reduce the noise problem and increase operating reliability.

We completed a design study of a high-speed rotating-wheel shutter to block ASE, and we then built prototypes of some components. However, because current estimates of ASE are within acceptable limits, we do not plan to install this type of shutter in Nova at the present time.

Our confidence in the performance and reliability of Nova has been increased by the substantial progress made in 1979 on a broad spectrum of developmental materials and components. Some developments, notably in damage-resistant materials, have already been successfully translated into production and are currently being used to improve the performances and reduce the operating costs of Argus and Shiva.

Author: W. H. Lowdermilk

Theory and Design Analysis

Nova Target-Illumination Studies. The Phase I Nova laser must use an illumination scheme that will uniformly irradiate spherical targets and will also be compatible with the Argus- and Shiva-style two-sided irradiation scheme. To find the best such illumination scheme, we undertook a study in which various 8-, 10-, and 12-beam geometries were investigated.

As in previous investigations of illumination uniformity,⁶² we used variations of the absorbed-energy profile from each beam to find the optimum illumination conditions. The incident-energy profile is easily found from the absorbed-energy profile,

and the time-consuming calculations needed to directly compute the incident-energy profile are thereby avoided.

The energy profiles used were the filleted power shapes previously used, with an added step at the edge to remove the restriction of zero intensity that would otherwise occur at the edge. The profile function is then

$$I(r) = \frac{I(1-r) - I(R)/R)^P + S}{1+S} \quad 0 \leq r \leq R$$

$$I(r) = \frac{I \left(\frac{1-r}{1-R} \right)^B + S}{1+S} \quad R < r \leq 1, \quad (5)$$

where the shape is specified by the intensity match ratio, I (the fraction of the central intensity at which the edge fillet is matched to the central-power function), the radius match ratio, R , the step, S , and the power, P (usually $P = 2$). The radial coordinate, r , is

Fig. 2-128. Geometry of one laser spot on a target sphere. The spot is formed when the converging laser beam (arrows) strikes the sphere and is symmetric about its central point, P . [Note: this P is not the same P as that used in Eq. (5).] The size of the spot is specified by the angle θ from P to the spot edge, as seen from the sphere center, C . The absorbed energy is assumed to be a function only of ϕ , the angle from P to a point in the spot.

the ratio of radial position to spot size, θ , (see Fig. 2-128)

$$r = \frac{\rho}{\theta} \quad (6)$$

and the fillet power is

$$B = P \frac{(1-R)(1-I)}{RI} \quad (7)$$

Any spot is completely specified by its center location on the target sphere, by its size, and by the shape parameters, R , I , S , and P .

A number of spot geometries were considered. Although complete freedom of spot positions was not allowed (because of the excessive time required for such calculations), a single geometrical parameter was often varied to improve uniformity.

For eight beams, the spots were bunched into two groups of four each (Fig. 2-129), and the spots in each group were placed at 90° intervals around a cone of variable angle. The two cones (of equal angle) were then positioned so that the spots either came in opposing pairs (octahedral positioning) or were interleaved.

For 10 beams, two cones of 5 beams each were used (Fig. 2-130), as was a geometry in which there was one spot each at the "north pole" and "south pole" of the target and there were two cones of four spots each (Fig. 2-131). Again, both opposed and interleaved versions were tried.

The 12-beam geometries were either dodecahedral in form, with two polar spots and two rings of five spots each (Fig. 2-132), or an alternative geometry, comprising two cones of four spots each with an equatorial ring of four spots.

The Nelder-Mead simplex minimization method⁶³ was used to maximize the ratio of minimum-to-maximum intensity on a discrete, roughly rectangular, grid on the target sphere. The intensity at each point was the sum of the intensities contributed by the individual beams. The spot-shape parameters (R , I , S , and P) and the cone angle were varied. Since the coverage gets better as spot sizes increase, calculations were carried out for a variety of sizes. As spots become larger, the angle of incidence of the incoming beams increases and losses due to reflection also increase, so the spots cannot become arbitrarily large.

Results of the illumination optimization are shown in Fig. 2-133. Because of inherent irregularities ($\pm 25\%$) on the laser beams themselves,

Fig. 2-129. Geometry for 8 spots on the target sphere. The centers of the dots lie at equal 90° intervals on two opposing cones of angle ψ . The spots may be positioned so that each beam is opposed to another on the opposite side of the sphere (as shown), or the lower cone can be twisted 45° around its axis so that spots alternate from top to bottom. The angle ψ is varied for best illumination uniformity.

Fig. 2-130. Geometry for 10 spots on two cones of 5 spots each. The lower cone can be twisted 36° to make spots oppose each other.

Fig. 2-131. Ten-spot geometry, with two polar spots and two cones of four spots each.

Fig. 2-132. Dodecahedral arrangement of 12 spots on a target sphere. Each cone angle is 63.4° for a perfect dodecahedron.

Fig. 2-133. Some results of the optimization studies made on illumination uniformity. Best opposing-beam results are shown for 8-, 10-, and 12-beam geometries. Although dodecahedral 12-beam illumination is better than 10-beam illumination, the greater cost-effectiveness of the latter scheme led to the choice of 10 beams for Nova. Nonopposed geometries were not used because they make diagnosis of laser-beam properties more difficult.

the min. max uniformity cannot rise above 0.6, even for perfect illumination. Thus, the most important measure of the quality of a given geometry is the spot size at which the uniformity, calculated assuming perfect beams, rises above 0.6. We see that this

Fig. 2-134. Profile of the absorbed energy of a typical spot. Ten of these spots, properly placed on a target sphere, give uniformity as good as the quality of the laser beams themselves. The half-angle at the spot edge is 55° and the cone angle is 52.9° .

Fig. 2-135. Contours of constant intensity on a target sphere when 10 spots, each with the absorbed-energy shape shown in Fig. 2-134, are arrayed in two opposing cones, each with 5 spots at a cone angle of 55° .

North polar view

Equatorial view

spot size is 40° for the 12-spot dodecahedron, 56° for the 10-spot opposed 5 + 5 geometry, and about 60° for the 8-spot 4 + 4 interleaved geometry. All other things being equal, the dodecahedral scheme would have been chosen; however, cost-benefit analyses of the laser chains showed that 10 beams are noticeably more cost-effective because of the use of larger amplifiers, a better match to the existing (Shiva) driver components, and lowered system complexity. Overall, after balancing relative laser capabilities available within the budget envelope against the relative losses due to incident angles at the spot edges, we found that the 10-beam option was slightly preferable to the 12-beam option, consequently, we chose the 10-beam option for Phase I Nova.

A typical spot size that approaches 0.6 mm max uniformity with two five-beam opposed cones has a 55° half-angle; the spot-shape parameters are $R = 0.6718$, $I = 0.4756$, $S = 0.2581$, and $P = 2$, and the angles of the cones are 52.9° (i.e., the spots just overlap at the poles). The absorbed-energy spot profile for these conditions is shown in Fig. 2-134, and contours of intensity on the sphere are shown in Fig. 2-135. The min max uniformity is 0.593.

Authors: J. B. Trenholme and E. J. Goodwin

ASE Considerations. An effect associated with high-energy lasers that may have deleterious consequences on their ability to initiate fusion is the problem of prepulse amplified spontaneous emission (PASE). As a working definition, we can consider PASE as that fraction of the total light bathing the fusion target that arises due to spontaneous emission prior to the onset of the laser pulse. (The balance of the total light comes from flash lamps and after-pulse spontaneous emissions.)

Consider a laser chain consisting of rod and disk amplifiers (active gain elements) interspersed by spatial filters and other passive optical elements. Prepulse fluorescence (small-signal noise) is created in the amplifier gain media and is continuously emitted in all directions and in all polarizations with the full fluorescence line width. Some of the radiation from preceding amplifiers enters the acceptance solid angle of succeeding amplifiers and sees gain. Thus, the resultant PASE on target is the sum of source (nonamplified) and amplified PASE con-

tributions. For laser systems the size of Nova, the PASE intensity and cumulative energy may be substantial enough to damage some targets.

Because of this potential target damage, we developed a code⁶⁴ to calculate the accumulation of single-pass ASE (including PASE) throughout an arbitrary laser chain. Input parameters for this code include the experimentally measured fluorescence line shape, $g(\nu)$, and a lumped-parameter description of the laser chain. The peak of the frequency-dependent gain coefficient, $\gamma(\nu)$, is determined by linear interpolation of the measured small-signal gain at the oscillator pulse wavelength.

The code is designed to separate ASE contributions from the asymmetric polarization of disk amplifiers and polarizers. Polarization-dependent transmittances are fixed either to vendor specification or to experimental measurement. Output from this code is presented in four ways:

- Instantaneous ASE radiance at any element along the laser chain.
- An intensity vs target spot size (image of the spatial filter pinholes in the target-chamber focal plane) histogram.
- Cumulative power and energy distribution as a function of target spot size.
- An option for examining the cumulative distribution, described immediately above, out of the target-chamber focal plane and for evaluating the instantaneous volume distribution of ASE around the focus to simulate the effects of vignetting and image blur.

The basic formula describing ASE⁶⁵ is

$$dP = \frac{h\nu N_2 g(\nu) d\Omega d\Omega' dV}{\tau(4\pi)} \quad (8)$$

Keeping Fig. 2-136 in mind for the ensuing discussion, we define dP as the amount of noise spontaneously emitted by a volume element, dV , of an amplifying medium of length, l , and cross-sectional area, A , at frequencies between ν and $\nu + d\nu$ into a solid angle, $d\Omega$. We assume that the laser medium has an inversion density, $N_2 - N_1(g_2/g_1)$, uniformly distributed between the planes $z = 0$ and $z = l$. N_i and g_i are, respectively, the atom density (atoms/cm³) and level degeneracy of the i th level; τ is the spontaneous lifetime of level 2; and n is the

Fig. 2-136. Amplifier model, with uniform gain medium delimited by the color zone between the planes $z = 0$ and $z = l$.

refractive index of the medium. As light of frequency ν passes through this medium at an angle θ to the optic z -axis, the light is amplified as

$$e^{\gamma(\nu)l/\cos\theta} \quad (9)$$

with the frequency-dependent gain coefficient, $\gamma(\nu)$, given by

$$\gamma(\nu) = \frac{[N_2 - N_1(g_2/g_1)]c^2 g(\nu)}{8\pi n^2 \tau_{sp}^2} \quad (10)$$

Note that $\gamma(\nu)$ in Eq. (10) theoretically models homogeneously broadened systems operating in the unsaturated power regime. This condition is representative of Nd-doped glasses, since the fluorescence and small-signal gain merely measure an integrated contribution from the various local sites. For gain saturation in systems homogeneously

or inhomogeneously broadened, appropriate modifications to Eq. (10) need to be considered.

Assuming that all propagation can be described by geometrical optics, integrating Eq. (8) times the amplification factor, $\exp \{ \gamma [(l - z) / \cos \theta] \}$ along dz yields

$$\begin{aligned} d\hat{P} &= \frac{h\nu N_2 g(\nu) d\nu d\Omega}{\tau(4\pi)} \int_0^l dz e^{\gamma(l-z)/\cos\theta} dA \\ &= \frac{2h\nu^3 n^2 N_2 \{G(\nu) - 1\} d\nu \cos\theta d\Omega dA}{c^2 [N_2 - N_1 (g_2/g_1)]} \end{aligned} \quad (11)$$

where the cross section, dA , is given by dV/dz , and the gain, $G(\nu)$, is given by

$$G(\nu) = e^{\gamma l / \cos\theta} \quad (12)$$

The quantity computed by the code is the frequency-integrated prefactor ($N_1 = 0$ for a four-level laser), $I(\nu)$

$$B = \frac{2h}{c^2} \int_{\nu_{\min}}^{\nu_{\max}} \nu^3 [G(\nu) - 1] d\nu = \int_{\nu_{\min}}^{\nu_{\max}} I(\nu) d\nu \quad (13)$$

B has the units of radiance ($\text{Wem}^{-2}\text{sr}^{-1}$) in free space. As light is staged through successive passive and active elements, the output radiance, B_j , at element j , separated into P and S polarizations, is,

$$B_j^{\text{out}} = \int T_j \{ G_j(\nu) f_j^{\text{in}}(\nu) + f_j(\nu) \} d\nu \quad (14)$$

where $f_j^{\text{in}} d\nu$ and $f_j d\nu$ are, respectively, the input and self-generated radiance at element j ; G_j and T_j are the j th gain and lumped transmission generators, respectively. If j is a passive element, $f_j = 0$ and $G_j = 1$.

In Table 2-30 and Fig. 2-137, we present an example of code output that reflects a subset of a Shiva laser chain. The code was normalized to Shiva experimental ASE energy measurements and is in reasonable agreement with these measurements. The first column in Table 2-30 lists the consecutive components responsible for ASE amplification and attenuation; the second and third columns exhibit,

Table 2-30. Code description of ASE in Shiva laser chain.

Shiva element	Class type: ED-2		Gain	Pockels cells off	
	P-polar (W/cm ² -sr)	S-polar (W/cm ² -sr)		Omega (sr)	Area $\times$ omega (cm ² -sr)
Rod	5.74E+02	5.74E+02	12.900	-	-
Polarizer	5.51E+02	5.74E+00	0.960	-	-
Rotator	5.40E+02	5.62E+00	0.980	-	-
Polarizer	5.18E+02	5.62E-02	0.960	-	-
Rotator	5.13E+02	5.57E-02	0.990	-	-
Telescope	5.03E+02	5.46E-02	0.980	-	-
Apodizer	4.98E+02	5.40E-02	0.990	-	-
Splitter	4.15E+02	4.50E-02	0.833	-	-
Splitter	3.32E+02	3.60E-02	0.800	-	-
Splitter	2.49E+02	2.70E-02	0.750	-	-
Splitter	1.67E+02	1.81E-02	0.670	-	-
Splitter	8.34E+01	9.05E-03	0.500	-	-
Mirror	8.17E+01	8.86E-03	0.980	-	-
Rod	2.27E+03	2.47E-01	45.000	-	-
Pockels cell	2.01E+03	5.43E-05	0.885	-	-
Filter	1.97E+03	5.32E-05	0.980	2.09E-06	8.67E-06
Rod	2.26E+04	6.10E-04	12.900	-	-
Pockels cell	1.96E+04	1.28E-07	0.866	-	-
Filter	1.92E+04	1.25E-07	0.980	3.34E-07	5.55E-06
Disk	6.69E+04	4.36E-08	3.600	-	-
Disk	2.36E+05	1.53E-08	3.600	-	-
Polarizer	2.26E+05	1.53E-10	0.960	-	-
Rotator	2.22E+05	1.50E-10	0.980	-	-
Polarizer	2.13E+05	1.50E-12	0.960	-	-
Filter	2.09E+05	1.47E-12	0.980	8.00E-08	5.55E-06
Disk	7.43E+05	5.21E-13	3.600	-	-
Filter	7.28E+05	5.11E-13	0.980	8.00E-08	5.55E-06
Disk	1.89E+06	2.84E-13	2.600	-	-
Filter	1.85E+06	2.79E-13	0.980	5.59E-08	9.87E-06
Rotator	1.81E+06	2.73E-13	0.980	-	-
Polarizer	1.76E+06	5.46E-15	0.970	-	-
Polarizer	1.70E+06	1.09E-16	0.970	-	-
Disk	3.07E+06	6.20E-17	1.800	-	-
Lens	2.82E+06	5.70E-17	0.920	-	-

respectively, the P- and S-polarized cumulative values for axis-in-the-focal-plane radiance. The values in the table are for single-pass ASE only; multiple reflections and parasitic modes are not included. The fourth column lists the small-signal gain/loss ratio for the optical components. The sparse set of numbers in the two columns at the far right refer to the solid angles from the input spatial-filter lenses, as subtended by their pinholes, and to the product of these solid angles times their preceding-amplifier clear-aperture areas. The product $A\Omega$ determines the choke points of the system; in most cases, these are the limiting-acceptance solid angles for the optical systems that we studied. The gain-narrowed $f(\nu)$ functions at the final focusing lens (the last element in the laser chain) are for both polarizations (P and S) depicted in Fig. 2-137.

To check the validity of our modeling, we performed a series of measurements of ASE. A 40-mm diameter, flashlamp-pumped ED-2 rod amplifier, set up in the simplest possible experimental arrangement, as shown in Fig. 2-138(a), was used to minimize uncertainties due to geometry. The spacing between the rod output face and the detector was typically 1200 mm. A black cloth over the back of the amplifier prevented feedback from external reflections. We purposely misaligned the detector from the rod axis to avoid reflections from the AR-coated surfaces of the rod. A band-pass filter, also misaligned with the rod axis, was used to eliminate flashlamp light.

For comparison with code prediction, we determined the peak ASE radiance as a function of

Fig. 2-137. Typical ASE code output at each component of a laser system.

Fig. 2-138. Determination of ASE radiance. (a) Experimental setup for measuring ASE radiance. (b) A comparison of data with theory. The theory curve includes the transmission of the band-pass filter; the indicated gain is at 1.064 μm , the wavelength at which amplifier gain was measured.

amplifier gain from the relation

$$B = \frac{E}{A \Delta \Omega t}, \quad (15)$$

where E is the total ASE energy measured with a calorimeter, A is the rod area seen from the calorimeter, $\Delta \Omega$ is the solid angle subtended by the rod at the calorimeter, and t is the effective FWHM of the ASE pulse in time. The ASE pulse shape was measured with a photodiode at the same location as the calorimeter; integration of the pulse shape nor-

malized it to its peak value, t . The single-pass amplifier gain was measured by using a cw Nd:YAG probe beam.

Figure 2-138(b) shows measured radiance vs gain data and the prediction of the ASE code. The horizontal axis is small-signal gain at $1.064 \mu\text{m}$; the theory includes a correction for the increased gain at line center and also includes the transmission of the band-pass filter used to reject flashlamp light in the experiment. We measured the spectral transmission of the filter and integrated it against the gain-narrowed ASE spectrum calculated by the code to obtain the total predicted ASE energy at the calorimeter.

Figure 2-138(b) shows that the code predicts about 30% low for the high-gain data. Radiance also appears to increase more quickly with gain than the theoretical prediction, although measurement uncertainties for the low-gain data make this inconclusive. Several sets of measurements were done with different aperture sizes at the rod (20 and 40 mm) and detector (12.5 and 25 mm) and with three different shield-glass/cooling-liquid combinations in the amplifier. These measurements were designed to determine if parasitic oscillations in the rod amplifier were contributing to the high values of measured radiance. All data from these different measurements are shown in Fig. 2-138(b) and are consistent within measurement accuracy. We conclude, therefore, that parasitic oscillations are not responsible for the discrepancy between theory and experiment. Although this discrepancy is not large enough to impact ASE suppression strategy for Nova (see "Laser Chain Design and Performance," above), we plan to investigate it further with higher-gain rod amplifiers and disk amplifiers.

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MALAPROP Code. During 1979, we used the MALAPROP propagation code⁶⁶ primarily for modeling Nova amplifier chains. Design changes, chiefly larger apertures, required expansion of code capabilities to ensure realistic simulations. Consequently, we completed three major programming changes: doubling the array size to a 512×512 transverse mesh; incorporating a capability for modeling split disks; and incorporating multiple

time slices for estimates of local saturation and fluence. These changes are described below. In addition, we used MALAPROP for several off-line modeling tasks, and two of these are briefly described below: computed gain-saturation effects are compared with experimental results obtained with the Argus laser system; and beam uniformity is examined in an equivalent plane upstream from the plane of best focus.

With the addition of a 460-mm final amplification stage in the Nova design, we required additional spatial resolution to retain accurate modeling of nonlinear propagation phenomena. To obtain this additional resolution, we converted to a computer with more memory (CRAY) in the spring of 1979, thus avoiding time-consuming disk staging; by expanding to a 512×512 grid size, we retained the capability for modeling important spatial fluctuations on a millimeter scale during the final-amplification stages of Nova. This expansion also provided far-field bandwidth capacity more than four times our modeled pinhole diameters; this feature is essential for realistic modeling.

To facilitate computer modeling, we added two new components to MALAPROP: DISK and LENS. Both components calculate the phase change generated in the glass but neither includes diffraction. DISK allows a multiplicative gain, $(g) \geq 1$, distributed throughout the glass. For ψ , the complex beam array, γ , the nonlinear index, and ΔZ , the glass thickness, DISK calculates

$$\psi_{\Delta Z} = \psi_0 \sqrt{g} e^{i|\psi_0|^2 2\pi \gamma (\Delta Z)(g-1)/\lambda \ln(g)} \quad (16)$$

LENS includes entrance (L_{en}) and exit (L_{ex}) loss terms with no change in intensity within the glass and calculates

$$\psi_{\Delta Z} = \psi_0 \sqrt{L_{\text{en}}^* L_{\text{ex}}} e^{i L_{\text{en}} |\psi_0|^2 (2\pi/\lambda) \gamma \Delta Z} \quad (17)$$

Modeling of 460-mm amplifiers required bisecting the beam to represent the split disks. We added MASK, which has the capability of representing a zero transmission line or circle with or without an apodized edge region.

As we model longer temporal pulses in spatially filtered systems, gain saturation effects

become more significant. The basic equations used in MALAPROP are

$$g_s(x, y; \tau) = \left\{ 1 - \left(1 - \frac{1}{g} \right) / \phi(x, y; \tau) \right\}^{-1}, \quad (18)$$

where g_s is the saturated gain and g is the unsaturated gain, and

$$\phi(x, y; \tau) = \exp \left\{ \frac{1}{I_s} \int_{-\infty}^{\tau} I(x, y; t) dt \right\} \quad (19)$$

for I_s , a saturation fluence associated with the gain medium, and $I(x, y; t)$, the intensity of the pulse at the entrance to the amplifier.

Introduction of a MATHSY⁶⁷ program, GAINN, to determine saturation effects, greatly facilitated the use of MALAPROP. GAINN determines net amplifier gains in essentially the same way as the one-dimensional MALAPROP program⁶⁶ but graphically displays a range of input vs output curves. This display readily allows selection of the input energy necessary to generate a particular output power or energy. Given the input condition, another segment of GAINN generates a table of net amplifier gains for peak power loads on filter entrance lenses.

In the fall of 1979, we added a new saturation model involving partition of the gain. (See "Gain Saturation Properties of Laser Materials," below.) For small gains, each portion can be applied sequentially with little error by using the equations above. For larger gains, the amplifier is best treated as a series of short pieces, each with a multiplicative gain ≤ 2 .

Both the GAINN and the one-dimensional MALAPROP saturation provide a single global net gain [$g(x, y) \equiv g_s$] for each amplifier in two-dimensional MALAPROP. For relatively smooth profiles, or when saturation is minimal, global gains are sufficient. Since saturation reduces fluence levels at local peaks, global saturation is a conservative assumption in damage studies that are dependent on peak fluence levels.

Until the end of 1979, MALAPROP was only able to process multiple times during the pulse independently, using global gains that were changed

as a function of temporal position in the pulse. Peak fluence levels were estimated by assuming that the temporal shape was independent of intensity variations. GAINN provides conversion coefficients for converting intensity to fluence for the mean intensity used to calculate global gains. At the end of 1979, we added a temporal dimension to MALAPROP with the ability to calculate

$$F(x, y, \tau) = \int_{-\infty}^{\tau} I(x, y; t) dt \quad (20)$$

and to determine the saturated gain (using the partition-gain model), as well as to estimate fluence levels directly. As expected, peak fluence values decrease under saturated conditions. This is illustrated in the MALAPROP-generated curves of Fig. 2-67. The upper estimate of peak fluence was made by using assumptions of global gain and constant temporal shape; the lower estimate of peak fluence was made by using assumptions of local saturation and directly integrated fluence values.

Figure 2-139 illustrates the time evolution of one Nova beam in the plane of the target lens and in the plane of best focus; nominally, the beam has a 3-nm FWHM temporal Gaussian entrance pulse with an integrated energy of 12.8 kJ. Several features of the calculation displayed in Fig. 2-139 have significantly improved our understanding of the complex behavior of real high-power pulses. Notice that the peak of the pulse has advanced in time by about 3 ns; this is the gross characteristic of laser systems operated in a regime of significant energy extraction. The outer ring of the beam saturates later in time than does the central part, thus producing "horns" on the trailing edge of the pulse. Diffraction from the sharp "slot" edges imposed by the 460-mm θ -disk amplifiers is responsible for the highest peak local intensity in the near field; this situation can be ameliorated by suitably apodizing the slot profile. Notice that the spatial-noise peaks also exhibit saturation effects; they have nearly vanished on the far trailing edge.

The far-field pattern also exhibits distinctive features. The prominent side-lobe pattern is characteristic of the 10-mm wide slot running through the center of the beam. Note the sharp cutoff of the side lobes at $\pm 250 \mu\text{m}$; this is the image of the final spatial-filter pinhole in the focal plane of the final focusing lens. Near the temporal pulse peaks, this

Fig. 2-139. Time-dependent near-field and far-field intensity profiles. The near-field profile (at left) shows the MALAPROP simulation of a 3-ns pulse as it appears immediately preceding the final focusing lens. The X-axis intensity is plotted at 16 time slices (the initial peak was at $T = 0$). The steep leading edge is obscured by the more gradual fall following the peak. The log intensity of the far field (at right) shows the same 3-ns pulse at the focus following the target lens (focal length = 2.2 m). The final pinhole shadow, visible at the low-intensity trailing edge (time = 2.5 ns), has been obscured at high intensities by the nonlinearity of the lenses following the final pinhole.

image is significantly blurred as a result of the intensity-dependent, nonlinear glass through which the beam has traveled (B-integral effect). This broadening is, of course, much more severe for shorter pulses of higher intensity.

With the addition of local saturation to MALAPROP, we are able to model propagation of a slotted beam through the Argus system. Experiments⁶⁸ showed that, at high energy levels (0.8 kJ), saturation effects reduce beam modulation even though the B-integral is more than doubled. Figure 2-140 presents a summary of these results, and Fig. 2-141 shows our modeling results. Figure 2-141(a) shows an unslotted intensity profile with minimal saturation (global saturation reduced laser-system gain by 15% at the temporal peak), and Fig. 2-141(b) shows the results obtained with a 0.75-mm slot; peak power is 1 TW with a B-integral of 2.1 rad and a pulse length of 150 ps. The modulation induced by the slot appears as a prominent set of parallel bands. These bands are reduced in am-

plitude by the effects of saturation, as seen in Fig. 2-141(c) for a 1-TW peak power, 800-ps pulse with a B-integral of 2.6 rad; global saturation reduced gain by 50% at the temporal peak. Figure 2-141(d) shows the effect of increasing the B-integral to 4.5 rad by shortening the pulse to 470 ps but holding constant the total energy at 0.8 kJ, thus maintaining the same level of saturation. Peaks are sharpened, but only the central bands have significantly increased intensities.

MALAPROP does not predict the smoothed profile exhibited in Fig. 2-140; furthermore, the experimental scans at long pulses are somewhat obscured by Fizeau fringes arising from the diagnostic beam splitter. Nevertheless, both the filling of the slot and the edge effects appear to be very satisfactorily modeled. It is worth mentioning that

Fig. 2-140. Argus split-beam experimental results. In 1979, Argus experiments indicated that, with significant amplifier saturation, Nova beam quality will not be degraded by split disks. The four experimental results pictured with a profile scan are, from left to right: (a) low saturation with low B-integral and no split; (b) low saturation with low B-integral and with split-induced parallel bands; (c) high saturation with low B-integral and with bands diminished by saturation; and (d) high saturation with high B-integral and with split-induced bands still diminished.

code parameters were not varied to fit the observed data.

In MALAPROP, far-field profiles of intensity and phase are calculated by fast Fourier transforms (FFT). This method provides no information concerning intermediate positions, but we can partially compensate for this lack of information in two ways. One way is to add a curvature to the phase and then propagate forward; however, this method fails if the curvature is too large, because the neighboring computational grid points do not accurately represent the curvature. This method also fails when resolution is lost by beam concentration on fewer grid locations. The second way is to add curvature and then transform. This results in a focal spot that is equivalent to the original beam displaced from the focal plane.

We used the latter method to study beam-intensity profiles at planes that might be equivalent to the front surface of a target. We exercised

MALAPROP to estimate the appearance of a typical beam (a clean beam from a solid-state laser) in such a plane; the results are shown in Figs. 2-142 and 2-143 and are representative of the geometry shown in Fig. 2-144.

The beam entering the final focusing lens was formed by band-limiting a 40-power super-Gaussian profile with a spatial filter; the resulting near-field beam exhibits five ring maxima and minima with a peak-to-average intensity ratio of 1.15. Judging from extremely clean Argus near-field photographs, these conditions may be representative of the very best we can do in modulating laser output beams.

In Fig. 2-142, we plot on a radial-beam section the peak-to-average intensity contours in the plane E (of Fig. 2-144) for four separate cases:

- Diffraction-limited entrance beam, shown on the left. It is apparent that a geometrical projection of rays works very well; unfortunately, real beams have propagated through nonlinear material

Fig. 2-141. MALAPROP simulation of Argus split-beam experiment. Figures 2-141(a) and 2-141(b) show the MALAPROP models of effects of a 150-ps pulse without a split and with a split, respectively, propagating through the Argus system. Both beams have a peak power of 1 TW. Figure 2-141(c) shows the effect of saturation on an 800-ps pulse, also with a peak power of 1 TW. Figure 2-141(d) represents a 470-ps pulse with an increased *B*-integral but with a total energy of 1 TW, as in Fig. 2-141(c).

and suffer from phase distortion, characterized by *B*-integrals in radians.

- Long-pulse beam, typical of 3-ns Nova design performance at 10 kJ/beam; the *B*-integral is 3.3 rad. Note that the scale length of modulation is unchanged (100 μm peak-to-peak) but that the scale height (peak-to-valley) is significantly increased.

- Intermediate-pulse beam, typical of 1-ns Nova design performance at 8 TW/beam; the *B*-integral is 6.5 rad. The scale length of modulation appears mixed, 100 μm near the center, 50 μm toward the perimeter of the beam. (Scale height has doubled relative to the second case.)

- Short-pulse beam, typical of 100-ps Nova design performance at 16 TW/beam; the *B*-integral

is approximately 10 rad. The scale length of modulation is further scrambled as enhanced self-focusing shovels energy toward the beam center; the general trend is toward smaller scale lengths. (Scale height has tripled relative to the second case.)

In a related calculation, we inquire about modulation depth and scale, in the same equivalent plane, when a slotted beam (characteristic of split disks in the final amplifier stages of Nova) is incident on the final focusing lens. The four cases equivalent to those in Fig. 2-142 are shown in Fig. 2-143.

For the geometrical case where the *B*-integral = 0, notice that the slot (15-mm wide in the near

Fig. 2-142. Radial peak/mean intensities near far-field focus. MALAPROP indicates a major degradation of beam quality in the far field as a result of system nonlinearities. Four cases (left to right) depict B-integrals of 0, 3.3, 6.6, and 9.9 rad added to a relatively smooth 740-mm beam, which is then propagated to a plane 7 mm in front of the focal point of an f/7 lens system. For each case, a mean intensity is calculated, and the ratio of the peak intensity within a ring to the mean intensity is plotted as a function of the ring radius.

Fig. 2-144. Target and focal-plane geometries for uniformity calculations. The plane, E, 7 mm from the focal plane of the f/7 lens system, shows the position of the eight beams depicted in Figs. 2-142 and 2-143. The beam enters from the left, has the appropriate B-integral added, and propagates to E.

field) has partially filled in; this is, of course, a manifestation of diffraction. For the case where the B-integral = 3.3 rad, the pattern is dominated by the scale height near the outside of the beam as

before, although the slot "shadow" is still visible. For B-integrals greater than 3.3 rad, the slot shadow has little influence and is essentially unnoticeable in the patterns.

Figures 2-142 and 2-143 plot the maximum intensity as a function of radius (i.e., maxima in a series of concentric rings) divided by the mean intensity of the beam calculated by assuming a geometrical radius of 0.452 mm. The minimum intensity is not plotted; however, the significant variation in ring maxima indicate an even greater variation in local maxima and local minima.

At present, MALAPROP provides accurate answers only to a subset of combinations of lens f/Nos., target diameters, and equivalent planes. For target dimensions of 1 mm, and for lenses faster than f/7, we are encountering algorithmic difficulties. Nevertheless, the calculated curves are remarkably similar to equivalent plane photographs⁶⁹ obtained from both Shiva and Argus.

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Fig. 2-143. Split-beam uniformity near far-field focus. This figure shows the effect on beam uniformity of the split amplifiers. Beams identical to those depicted in Fig. 2-142, except for an on-axis split, are propagated with B-integrals of 0, 3.3, 6.6, and 9.9 rad. Peak intensities are modestly increased.

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Laser Glass

This article covers two topics: laser damage in fluorophosphate glass, and new silicate and phosphate glasses.

Laser Damage in Fluorophosphate Glass. Early in 1978, we discovered that typical inclusion den-

sities (10^6 to 10^7 inclusions cm^{-3}) in fluorophosphate glass were causing damage when the glass was irradiated by 1-ns pulses with energies less than 4 J cm^{-2} . During that year, we tested and examined a large number of fluorophosphate glass samples in an attempt to identify and eliminate the damage source. By the end of 1978, we had not yet identified the nature of the damaging inclusions, but we had obtained fluorophosphate glasses with high damage thresholds (i.e., damage thresholds higher than the Nova damage-threshold specification of 23 J cm^{-2}) (Ref. 70). However, those high-damage-threshold samples could only be obtained from small melts at that time.

In 1979, we were able to obtain high-damage-threshold fluorophosphate glass from large melts (>30 litres), and we reached the conclusion, based on our studies, that the damaging inclusions are platinum particles.

In 1979, the three major glass companies developing fluorophosphate (FP) glass have made significant strides toward decreasing the susceptibility of this glass to laser damage. One company

is consistently producing high-damage-threshold glass in large melts; another company has melted and cast 340-mm disks that contain less than 10 damage centers per cubed centimeter at fluences of 27 J/cm²; and the third company has solved the damage problem in small test melts (<2 litres).

Compared with our observations in 1978, the typical density of damage-causing inclusions in FP glass samples has decreased by more than five or six orders of magnitude; however, the damage problem has not been completely eliminated. In this subsection, we review the known facts about damage in FP glass, our hypothesis as to the damage source, and methods by which we can characterize and quantify the damage susceptibility of a sample.

We have made the following observations about damage in fluorophosphate glasses:

- Before damage tests are made, some of the damage-causing inclusions can be seen under a microscope with 200 $\times$ magnification and dark-field illumination. In some cases, however, the particles are too small (probably less than 0.1 μ m in diameter) to be detected.

- The damage-causing inclusions are less than 1 μ m in diameter and have a high backscattering cross section.

- The inclusions vary in diameter. This is evidenced by intensity variations in backscattered light from different centers and by variations in the volume of damaged glass after laser irradiation.

- Exposure of the inclusions to multiple laser shots increases the damaged volume, as shown in Table 2-31

- Adding Pt to the melt increases the density of damage-susceptible inclusions. Conversely, when fluorophosphate melts are done in non-Pt crucibles, no bulk damage can be observed at beam energies up to 30 J/cm².

Table 2-31. Size of damaged volumes in fluorophosphate glass vs number of laser shots.

Energy fluence (J/cm ²)	No. of shots	Diameters of damaged volumes (μ m)
10 to 12	2	10, 10, 15, 25
10 to 12	4	10, 10, 30, 50
10 to 12	8	30, 30, 40, 40, 120, 140
6 to 8	No damage observed after 8 shots.	

- Traces of Pt in fluorophosphate glasses have been observed by x-ray analysis in a scanning electron microscope (SEM); however, the presence of Pt cannot be assigned to any consistently observed feature under the SEM.

Considering the small size of the inclusions, and the approximate energy required to fracture glass, one can conclude that only metallic inclusions can provide sufficient absorption over small distances to damage glass. Because high-quality optical glass must be melted in platinum crucibles, metallic platinum is the likely culprit. The last two observations, above, give strong support to the platinum-inclusion hypothesis.

A very small amount of Pt in the glass can result in a high density of inclusions; e.g., 1 ppm of metallic Pt can produce 4×10^7 particles/cm³ with an approximate average particle diameter of 0.1 μ m. This small amount of Pt can be introduced by corrosion of the crucible, by Pt impurities in the raw material, or both.

If Pt is in solution in the glass melt, it must be prevented from being reduced to its damage-causing metallic form. Possible techniques to control the oxidation state of Pt include variation of the atmosphere over the melt, the use of electrodes to set the electrochemical potential in the melt, and codoping with other impurity ions, such as Ce. The optical glass companies are investigating the effects of these various techniques on densities of metallic Pt inclusions.

New Silicate and Phosphate Glasses. Several silicate and phosphate glass compositions were melted and studied for possible use as alternatives to fluorophosphate glass for large disk amplifiers in Nova. Our criteria for the glass are that it have the lowest possible nonlinear index (n_2), have a cross section between 1.5 and 3.0×10^{-20} cm², have the highest possible effective saturation fluence, and be producible in large sizes. We concentrated our efforts on the following three glass types:

- Silicates. These have the advantage of a low cross section and, thus, a high saturation fluence. However, the n_2 of present silicate laser glasses is too high, so we searched for low- n_2 silicate compositions.

- Phosphates. These glasses have an n_2 that is about 30% lower than silicates, but the high cross sections and low saturation fluences of phosphate

glasses place them at a disadvantage for use in large disk amplifiers.

● Fluorosilicates. The nonlinear indices of these mixed glasses are 10 to 15% lower than silicates, and their cross sections are approximately $1.5 \times 10^{-20} \text{ cm}^2$.

We investigated silicate glasses with compositions lying within the cross-hatched region of Fig. 2-145. We are restricted to silica contents below 72 mole %, because of manufacturing requirements, and above 60%, to keep n_2 as low as possible. Added borate will give a lower n_2 but at the cost of an increased nonradiative decay rate from the $\text{Nd}^{3+} {}^4\text{F}_{3/2}$ state. The calculated emission cross sections of the silicates ranged from 1.18 to $2.47 \times 10^{-20} \text{ cm}^2$. The lowest calculated n_2 value is 1.15×10^{-13} esu for a borosilicate glass. Nonlinear indices of about 1.2×10^{-13} esu can be obtained in borate-free glasses containing large amounts of MgO , but these compositions are not stable enough for production melting. Glass compositions capable of being produced have n_2 values of about 1.3×10^{-13} esu.

Fig. 2-145. Cross-hatched region depicts compositions of silicate glasses melted in the Nova alternative glass program. R = Mg, Ca, Sr, or Ba; M = Li, Na, or K. Dots represent previously investigated compositions.

We studied Nd concentration quenching in silicates and found that concentrations of from 4.3 to $6.6 \times 10^{20} \text{ atoms/cm}^3$ will cause the first e-folding decay time to drop to 50% of its value for Nd concentrations of less than $10^{20} \text{ atoms/cm}^3$.

We obtained silicate rods (25 mm in diameter $\times$ 250 mm long) from Hoya Corporation, Owens-Illinois, Inc., and Schott Optical Glass, Inc., for saturation fluence measurements and three amplifier disks (each $48 \times 84 \times 12 \text{ mm}$) for gain measurements. The properties of these glasses are listed in Table 2-32. The measured saturation fluence of Owens-Illinois silicate sample No. 1193 was 7.0 J/cm^2 at an output fluence of 5.0 J/cm^2 and a 9-ns pulse length. (See "Gain Saturation Properties of Laser Materials," below.)

In silicate glasses, fluorine can be added in quantities up to a few mole % to lower n_2 . We obtained four fluorosilicates from Hoya that have n_2 values of approximately 1.15×10^{-13} esu. Of particular interest is FSL295-3 (5151), which has the following properties:

- Refractive index (589 nm), $n_D = 1.508$.
- Nonlinear index (106 nm), $n_2 = 1.20 \times 10^{-13}$ esu.
- ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{11/2}$ cross section, $\sigma = 1.52 \times 10^{-20} \text{ cm}^2$.
- Effective line width, $\Delta\lambda_{\text{eff}} = 33.9 \text{ nm}$.
- Fluorescence peak, $\lambda_p = 1056 \text{ nm}$.

Hoya indicates that this glass can be melted in production quantities but that some development work in melting techniques is necessary. In addition to producibility, another advantage of fluorosilicates is that the Nd excited-state lifetime is long ($> 500 \mu\text{s}$), even at Nd concentrations of $4 \times 10^{20} \text{ atoms/cm}^3$.

Owens-Illinois, Schott, Hoya, and Kigre, Inc., supplied us with phosphate glass samples. We investigated the compositional region indicated by the cross hatching in Fig. 2-146; present phosphate laser-glass compositions are indicated by the dots.

Table 2-32. Properties of silicate glass received in rod form.

LLL No.	Company designation	n_D	$n_2(10^{-13} \text{ esu})$	$\sigma(10^{-20} \text{ cm}^2)$	$\Delta\lambda_{\text{eff}}(\text{nm})$	$\lambda_p(\text{nm})$
1193	O-I, 66106E	1.509	1.30	1.5	37.8	1061
6618	Schott, S-7607	1.520	1.34	2.0	33.3	1057
5158	Hoya, A-3	1.546	1.47	1.35	37.1	1060

To lower the cross section, glasses were melted with more than 60 mole % P_2O_5 and a low alkali content.

There are two methods of decreasing the emission cross section: lowering the transition strength, or increasing the effective line width. We prefer to do the former, because increasing the inhomogeneous line width may decrease the saturation fluence due to increased "hole-burning." (See "Gain Saturation Properties of Laser Materials," below.) Thus, we do not add Mg or Al to a phosphate composition because these ions may lower the cross section by increasing the effective line widths. The effect of composition on the homogeneous line width is not known at present but is under investigation. The properties of phosphate glasses that represent a good compromise between low cross section and narrow line width are listed in Table 2-33.

Owens-Illinois supplied two borophosphate glasses, 1209 and 1210. (The four-digit numbers are LLL sample designations.) There does not appear

to be any significant fluorescence quenching due to the borate, as evidenced by the closeness of the calculated radiative lifetime and the measured decay times for low Nd concentrations. The spectroscopic properties of 1210 glass are listed in Table 2-33.

Codoping laser glass with a sensitizing ion—i.e., an ion that absorbs flashlamp energy not absorbed by Nd and then transfers the energy to the Nd—can raise the amplifier efficiency. We have considered the rare-earth ion Ce^{3+} and the transition-metal ion Cr^{3+} as possible candidates for sensitizing Nd laser glass. Preliminary experiments with Ce^{3+} in silicate glasses were described in the 1975 Laser Fusion Annual Report⁷¹; Cr^{3+} sensitization measurements were discussed in the 1976 and 1978 Laser Fusion Annual Reports⁷² and are not discussed further in this report.

The energy levels and absorption spectra of Nd^{3+} and Ce^{3+} are compared in Fig. 2-147. The cerium ion is an excellent absorber of UV light, in contrast to the neodymium ion, which has only very weak UV bands. Energy transfer from Ce^{3+} to Nd^{3+} can occur both nonradiatively, via coupling between the Ce^{3+} 5d bands and the upper Nd^{3+} states, and radiatively, via absorption of Ce^{3+} fluorescence light by Nd^{3+} .

The nonradiative transfer rate from Ce to Nd is obtained by measuring the Ce fluorescence decay rate as a function of Nd concentration, ρ_{Nd} (Ref. 73). The decay rates of Ce^{3+} in different glass types is shown in Fig. 2-148 as a function of ρ_{Nd} ; we measured these rates by observing the Ce^{3+} fluorescence decay after excitation by a pulsed nitrogen laser. Experimentally, the nonradiative transfer rate is approximately linearly proportional to ρ_{Nd} . We define the transfer efficiency (η) as the fraction of excited Ce ions that transfer their energy to Nd. Plots of η vs ρ_{Nd} are shown in Fig. 2-149. Because of the faster radiative decay rate of Ce^{3+} in phosphate glass, the nonradiative transfer efficiency

Fig. 2-146. Cross-hatched region depicts compositions of phosphate glasses melted in the Nova alternative glass program. R = Mg, Ca, Sr, or Ba; M = Li, Na, or K. (Note: compositions high in Al_2O_3 are not covered by this diagram.) Dots represent previously investigated compositions.

Table 2-33. Properties of low-cross-section phosphates.

LLL No.	Company designation	n_D	$n_2(10^{-13} \text{ esu})$	$\sigma(10^{-20} \text{ cm}^2)$	$\Delta\lambda_{\text{eff}}(\text{nm})$	$\lambda_p(\text{nm})$
1210	O-I, 5745-51-4	1.530	1.1	3.2	28.9	1055
3168	Kigre, P-633	1.515	1.1	3.2	26.8	1054
5219	Hoya, P101	1.518	1.05	3.0	29.0	1053
6633	Schott, KU-5074	1.512	1.00	3.0	28.1	1053.5

Fig. 2-147. Energy levels and absorption spectra of Nd^{3+} and Ce^{3+} in a phosphate glass.

in that glass is significantly lower than in other glass types.

Radiative transfer from Ce to Nd will also occur because the Ce emission overlaps some of the Nd absorption bands, as shown in Fig. 2-150 for the different glass types. The amount of radiative transfer is very sensitive to the geometry of the Nd:glass sample and thus is not easily calculated. We can, however, obtain a lower limit to the radiative transfer by measuring the excitation spectra of small samples ($\sim 1 \text{ mm}$ thick). Larger samples and laser disks will have greater radiative transfer because of the longer path lengths involved.

Excitation spectra of Nd^{3+} were analyzed to obtain the total transfer efficiency. The measured total Ce-Nd transfer efficiencies in small ($20 \times 20 \times 5 \text{ mm}$) samples are 62% for $\rho_{\text{Nd}} = 5 \times 10^{20} \text{ atoms/cm}^3$ and 48% for $\rho_{\text{Nd}} = 3 \times 10^{20} \text{ atoms/cm}^3$ in a phosphate glass. The difference between the total transfer efficiency and the nonradiative efficiency obtained from the decay measurements (Fig. 2-148) is ascribed to radiative transfer. Our

Fig. 2-148. Fluorescence decay rates of Ce^{3+} in various glass types at 300 K.

Fig. 2-149. Nonradiative transfer efficiency from Ce^{3+} to Nd^{3+} in different glass types at 300 K.

Fig. 2-150. Ce^{3+} fluorescence spectra in various glass types at 300 K.

results indicate that a significant amount of radiation transfer is occurring.

We can calculate the expected improvement in gain coefficient when Nd:glass is codoped with Ce

by employing the TRANS 4 computer code described in the 1978 Laser Annual.⁷⁴ Using the measured total-transfer rate, we find that codoping with Ce^{3+} may result in an increase of 4 to 7% in

Table 2-34. Gain coefficients vs bank energy for Q-88 liquid-clad amplifier disks.

Bank energy (kJ)	Q-88			Q-88 + Ce ³⁺		
	Ce-quartz lamp	CFQ lamp	Ratio	Ce-quartz lamp	CFQ lamp	Ratio
87	13.45 ± 0.13	—	—	11.83 ± 0.12	—	—
114	15.27 ± 0.11	16.52 ± 0.28	1.08	13.69 ± 0.08	14.05 ± 0.23	1.03
144	16.89 ± 0.17	18.44 ± 0.38	1.09	14.95 ± 0.11	15.96 ± 0.16	1.05
178	18.12 ± 0.20	19.58 ± 0.15	1.08	16.18 ± 0.09	17.14 ± 0.17	1.06
215	19.20 ± 0.14	20.79 ± 0.41	1.08	17.06 ± 0.16	18.24 ± 0.10	1.06
256	19.75 ± 0.14	21.71 ± 0.42	1.10	17.66 ± 0.20	19.12 ± 0.27	1.08

gain coefficient if the pump-lamp envelope transmits to wavelengths below 250 nm.

We have measured gains of liquid-clad disks of Q-88 phosphate, both with and without Ce, in an amplifier using either standard Ce-doped lamps or clear fused-quartz (CFQ) lamps. Experimentally measured gain coefficients vs bank energies are shown in Table 2-34 for the four cases of Q-88: with and without Ce, pumped by either Ce-doped or CFQ flash lamps. Using CFQ lamps with standard Q-88 results in an 8 to 10% increase in gain over that obtained with Ce-doped lamps. The calculated increase in gain is 7%, using our present flashlamp model and Q-88 transmission to 340 nm. On the other hand, we calculated that the Ce-doped Q-88 would have about a 16% increase in gain with CFQ lamps, but the observed gain increase is lower than that of standard Q-88. However, as the pump energy increases, the increased lamp output in the UV results in a larger improvement in the gain of Ce-doped Q-88 with CFQ lamps, thus indicating that additional UV pumping occurs via Ce-to-Nd energy transfer.

Possible explanations for the discrepancy between our predicted and experimental results include:

- Systematic errors in the experimental measurements.
- Differences in the spectroscopic properties of the two glasses.
- Incorrect modeling of the flashlamp spectra, of Ce sensitization, or both.
- Transient absorption.

As to the first possibility, we measured gain on Ce-doped Q-88 first, then on standard Q-88 immediately afterward, employing Ce-doped lamps. Approximately 2 months later, after refitting the amplifier with CFQ lamps, we tested standard Q-88 and then Ce-doped Q-88. A decrease in the cavity

efficiency with time could explain our results, but the decrease required is improbably large.

The only difference in the spectroscopic properties of the disks appears in their UV absorption spectra. The Ce-doped Q-88 shows the first Ce absorption peak at 290 nm; however, the glass becomes opaque by 275 nm, indicating that there is a background absorption. Standard Q-88 contains an anti-solarant ion and absorbs pump light below 300 nm. The Ce-doped Q-88 contained no anti-solarant ion; therefore, the UV absorption below 275 nm is most likely due to Ce⁴⁺. We made our original predictions on the basis that the lamps and glass transmitted to 200 nm. Redoing our calculations with a 290-nm cutoff, we found that Ce-doped Q-88 should have shown an improvement of at least 10% with CFQ lamps.

Finally, transient color centers produced by UV light can have either visible or infrared absorption bands, so that these centers would reduce the gain coefficient. However, these transient absorptive centers would have to be associated with Ce doping, not with the anti-solarant ion present in standard Q-88.

We conclude that, although Ce⁴⁺ theoretically can sensitize Nd in laser glass, its presence actually results in lower gain from UV pumping than would be obtained from glass without this ion. Our best explanation for this result is that Ce⁴⁺ absorption decreases the pumping efficiency of phosphate in the ultraviolet.

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Gain Saturation Properties of Laser Materials

In 1979, we intensively explored the gain-saturation properties of neodymium-doped laser materials in the form of rod amplifiers. We made input- and output-fluence measurements and time-resolved gain measurements at two wavelengths—1.064 and 1.053 μm —and three pulse durations—1, 9, and 50 ns—on silicate, phosphate, and fluorophosphate glasses and on crystalline materials. In the following paragraphs, we briefly describe the results of our experimental measurements.

Gain and Fluence Measurements. Figure 2-151 shows the arrangement used to measure input and output fluences of a test amplifier. Saturating pulses with durations of 1, 9, or 50 ns were sliced by a Pockels-cell shutter from the 70-ns pulses produced by a single-axial-mode oscillator. These pulses were then amplified by a series of rod amplifiers to fluence levels of a few joules per square centimeter. For 1.064- μm operations, we used a Nd:YAG oscillator and YAG and silicate-glass amplifiers; for 1.053- μm operations, we used a Nd:YLF oscillator and phosphate-glass amplifiers. The spatial profile of the saturating beam was shaped by image relaying a hard aperture. The beam diameter was 14 mm at the test amplifier, and the beam was approximately rectangular in intensity profile. This configuration produced input fluences to the test amplifier of up to 10 J/cm² at 50 ns and up to 3 J/cm²

at 1 ns. When higher fluences were required, we used a telescope to reduce the beam diameter at the amplifier; however, the telescope altered the image relaying and produced a beam of lesser quality. Fluence in the saturating beam was measured by using diagnostic pick-off beams at the entrance and exit of the amplifier. The fluence in a diagnostic beam was defined by measuring the energy (J/cm²) transmitted through a 5-mm-diam aperture placed on the beam center. Both input and output calorimeters were electrically calibrated, with an uncertainty of less than 1%, and the ratio of sensitivities was confirmed by optical measurements. Fresnel reflection coefficients of the bare BK-7 splitters, which provided the diagnostic beams, were calculated by measuring incidence angles and indices of refractions; these coefficients were then used to calculate the fluence in the main beam from measurements of fluences in the diagnostic beams. Except for saturation measurements, independent measurements of primary-beam fluence by the two calorimeters agreed within 1.2%.

The passive transmission of each test amplifier was measured in a separate experiment by using a four-pass, 1.064- μm cw beam arrangement. When an amplifier was installed in the saturation experiment, we measured the beam incidence angle at the rod face, which was cut at Brewster's angle, so that internal fluence could be computed; we then calorimetrically remeasured the rod transmission as a test for proper installation of the calorimeters.

We defined calorimetric small-signal gain to be the output/input fluence ratio with input pulses that caused less than 2% gain saturation. We used two other monitors of small-signal gain: a cw 1.064- μm beam, and a fraction of the 70-ns oscillator pulse. The experimental arrangement for the small-signal gain measurement is shown in Fig. 2-152. Both gain probes were contained within the path of the main beam, which was 14 mm in diameter.

An oscillogram of cw gain during a saturation measurement is shown in Fig. 2-153. The intensity of the cw monitor laser was observed throughout the firing of the test amplifier and was displayed at two sensitivities so that the pregain cw level and the amplified signals could be measured. The small-signal gain was found by taking the ratio of the pregain cw level to the amplified cw level; recording at two sensitivities allowed a more accurate measurement of the pregain level. Gain was com-

Fig. 2-151. Saturation-experiment configuration for input- and output-fluence measurements.

Fig. 2-152. Small-signal-gain measurement configuration with a cw 1.064- μm laser.

puted immediately before the passage of the saturating pulse, which is indicated in Fig. 2-153 by the gain reduction.

For 1.064- μm experiments, the calorimetrically measured small-signal gain was experimentally correlated with gain observed with the cw 1.064- μm

beam. The measured gain with the cw beam was usually slightly larger because the cw beam followed a diagonal path through the amplifier. Once the correlation was measured, the cw beam served as a shot-by-shot gain monitor.

Fig. 2-153. Oscillogram of small-signal-gain diode signals. The central pulse shows the amplifier gain following the flashlamp pump pulse in the amplifier and the gain reduction caused by the saturating pulse.

Fig. 2-154. Input and output fluences for ED-2 silicate glass. The small-signal gain of this amplifier was approximately 6.2; the gain for each point was individually measured.

Fig. 2-155. Saturation fluence vs output fluence for ED-2 glass. E_s is calculated point-by-point using measurements of E_{in} , E_{out} , G_0 , and rod transmission. Error bars show the effects of 1% variations in fluence or small-signal gain at low and high fluences.

The cw 1.064- μm beam was also used as a gain monitor in 1.053- μm experiments, since all glasses exhibited gain at both wavelengths. We measured 1.053- μm gain using the quasi-cw prelas beam from the YLF oscillator. Correlation between cw and 1.053- μm gain, G_0 , produced a measured factor, β :

$$\beta = \frac{\ln G_0(1.053)}{\ln G_0(1.064)} \quad (21)$$

This factor accounts for the gain spectrum of the amplifier and gain differences due to geometric effects. On each shot during a 1.053- μm saturation experiment, we measured $G_0(1.064)$ and computed $G_0(1.053)$ as

$$G_0(1.053) = \exp\{\beta \ln G_0(1.064)\} \quad (22)$$

We obtained values from each shot for input fluence, E_{in} , output fluence, E_{out} , and the small-signal gain, G_0 . We used the Frantz-Nodvik equation,

$$\frac{E_{out}}{E_{in}} = \frac{E_s}{E_{in}} \ln \left[1 + G_0 \exp \left(\frac{E_{in}}{E_s} \right) - 1 \right] \quad (23)$$

corrected numerically to account for rod transmission, to compute a value for saturation fluence, E_s .

Input- and output-fluence data for the Nd:silicate glass ED-2 are shown in Fig. 2-154; the saturation fluences computed from those data are shown as a function of fluence in Fig. 2-155. The extremely low scatter in the input output data indicates that our measurement precision was good. Due to the nonlinear nature of the Frantz-Nodvik relation, very small differences in measured fluence and gain data cause large excursions in the calculated value of the saturation fluence at small fluences. The error bars in Fig. 2-155 show the effects of 2% variations in fluence or small-signal gain at low and high fluences. Figures 2-156 and 2-157 show saturation fluence vs E_{out} for a phosphate glass (LHG-8) and a fluorophosphate glass (E-309), respectively. Two factors common to the figures and to the rest of our data are clear: saturation fluence increases with output fluence; and there is no significant dependence of E_s on pulse length. Table 2-35 shows a summary of our fluence data. Where the quality of the data permits, we have in-

Fig. 2-156. Saturation fluence vs output fluence for LHG-8 phosphate glass.

Fig. 2-157. Saturation fluence vs output fluence for E-309 fluorophosphate glass.

Table 2-35. Saturation-fluence calorimeter data.

Material ^a	Wavelength (μm)	E _s (J/cm ²)
ED-2 (S)	1.0642	3.43 ± 0.21 E _{out}
LSG-91H (S)	1.0642	4.12 ± 0.16 E _{out}
LG-56 (S)	1.0642	8.48 ± 0.11 E _{out}
OIH-9 (S)	1.0642	5.68 ± 0.21 E _{out}
Q-88 (P)	1.0642	4.5 ± 1 @ 2 J/cm ²
YAG (C)	1.0642	0.44 ± 0.07 @ 0.5 J/cm ²
Q-88 (P)	1.0530	2.05 ± 0.32 E _{out}
LHG-8 (P)	1.0530	3.75 ± 0.12 E _{out}
E-309 (FP)	1.0530	4.23 ± 0.16 E _{out}
LG-810 (FP)	1.0530	5.1 ± 0.3 @ 5 J/cm ²
LHG-10 (FP)	1.0530	4.9 ± 0.3 @ 5 J/cm ²
LG-800 (FP)	1.0530	4.0 ± 0.5 @ 4 J/cm ²
YLF (σ) (C)	1.0530	0.8 ± 0.2 @ 0.5 J/cm ²

^aS = silicate glass; P = phosphate glass; FP = fluorophosphate glass; C = crystal.

cluded a linear least-squares fit to the experimental points of the form

$$I_s = a_0 + a_1 E_{out} \quad (24)$$

Time-Resolved Temporal Measurements. We previously reported time-resolved measurements of "gain recovery" in ED-2 glass.⁷⁵ Since then, we have measured the gain of a probe beam (a portion of the 70-ns pulse from the oscillator) through the test amplifiers with 0.5-ns resolution; Fig. 2-158 shows the experiment. As in our original experiment, the diode signals were recorded simultaneously on transient digitizers; we also recorded zero-signal levels for baseline subtraction, and we digitally corrected for slight differences in sweep speed among the three digitizers. Figure 2-159 shows data typical of Nd:YAG and all of the glasses that we tested using 1-ns saturating pulses. The gain dip and recovery that are evident in the parallel-polarization channel was first thought by us⁷⁵ to be lower-level recovery with a drain (decay) time, τ_{10} , of about 1 ns. Figure 2-160 shows the calculated variation in E_s that would occur in a silicate glass for values of τ_{10} at the three pulse durations that we used.

We assume that E_s varies between $h\nu/\sigma$ (7.18 J/cm²) and $h\nu/2\sigma$ (3.59 J/cm²). At values of τ_{10} around 1 ns, we would expect to see extreme variations in E_s with pulse length. Since we see no such variation in the measured data, we must conclude that a lower-level recovery of ≈ 1 ns does not take

place either in the glasses or in Nd:YAG. What we took to be a pulse-width dependence of measured saturation fluence has been found to be a fluence dependence. We do not have an adequate explanation for the dip that occurs at all pulse lengths or for the difference between parallel and perpendicular probe polarizations.

Figure 2-161 shows the result of calculating the depth of the transient dip in the parallel channel, with respect to the recovered gain, a short time after the transient; we obtained these data by dividing the parallel-diode (P) signal by the reference-diode signal. We then have three levels,

$$\begin{aligned} a &= \frac{P}{R} \text{ prepulse (II)} & \text{or } a' &= S/R \text{ prepulse (I)} \\ b &= P/R \text{ dip (II)} \\ c &= P/R \text{ postpulse (II)} & \text{or } c' &= S/R \text{ postpulse (I)} \end{aligned} \quad (25)$$

in which a gives the amplifier gain before the saturating pulse arrives, b gives the gain during the passage of the saturating pulse, and c gives the postpulse gain. Figure 2-161 plots the quantity b/c , the ratio of the depth of the transient to the postpulse gain as a function of output fluence, using 1-ns saturating pulses. Silicate, phosphate, and fluorophosphate glasses are similar. Data for 9-ns pulses, plotted in the same fashion, are indistinguishable from the 1-ns data. We believe that n_2 effects cannot account for the transient since silicate glasses at 1 ns look the same as fluorophosphate glasses at 9 ns. There is a factor of 30 difference between these two tests, so that both beam steering and self-focusing due to n_2 effects must be ruled out as explanations for the transient dip.

Figure 2-162 shows the result of performing a similar calculation on the perpendicular data. We show in this figure the ratios of the perpendicular (S) postpulse gain to the parallel (P) postpulse gain, c'/c , vs output fluence. We see that the perpendicular postpulse gain is larger than the parallel postpulse gain for all glasses, wavelengths, and pulse durations. This result may be caused by a distribution of stimulated emission cross sections at different sites in the glass. Studies of polarized fluorescence⁷⁶ also show this polarization-dependent behavior.

Finally, we show the postpulse gain measurements at the 1.064- and 1.053-μm wavelengths. Figure 2-163 shows phosphate and fluorophosphate

Fig. 2-158. Fast-response gain-measurement configuration. Signals from the three vacuum photodiodes were recorded on transient digitizers.

Fig. 2-159. Fast-response diode signals for Nd:YAG. Similar traces were recorded for all tested glasses.

Fig. 2-160. Rate equation calculation of the equivalent saturation fluence from the Frantz-Nodvik equation when a lower-level drain time, τ_{10} , is present. The two limits for this Ed-2 silicate glass are $h\nu/\sigma$ (7.18 J/cm^2) and $h\nu/\sigma$ (3.59 J/cm^2). The saturating pulse width is denoted by w .

glasses for which we have calculated the ratio of two ratios: the ratio of postpulse-to-pprepulse gain coefficients at $1.053 \mu\text{m}$ to postpulse-to-pprepulse gain coefficients at $1.064 \mu\text{m}$. The $1.053\text{-}\mu\text{m}$ ratios were obtained from transient digitizer data (Fig. 2-159), while the $1.064\text{-}\mu\text{m}$ data were obtained from the cw monitor traces (Fig. 2-153). We believe these data are evidence for spectral hole burning in the tested glasses, a belief that is supported by fluorescence line-narrowing experiments.⁷⁷

Analysis and Summary. We know from the calorimetric fluence data that saturation fluence is a function of the output pulse fluence and that there is no observable difference in saturation fluence with pulse length. The $1.053\text{-}\mu\text{m}/1.064\text{-}\mu\text{m}$ gain ratios (Fig. 2-163) and the increase of saturation fluence with the fluence of the saturating pulse indicate that hole-burning occurs. Because of site-to-site differences in glass, the cross section is expected to be different for each ion; therefore, we fitted the

Fig. 2-161. Transient depth vs output fluence for 1-ns saturating pulses. These data are generated by dividing the parallel-diode signal, P , by the reference-diode signal, R .

Fig. 2-162. Perpendicular postpulse gain divided by parallel postpulse gain. These data are found from the ratio of S/R to P/R.

saturation data with the simplest model that has a variety of cross sections—a model with just two kinds of ions. This simple model is very successful in fitting the observations; perhaps it is too successful, since a wide variety of assumptions lead to equally good fits.

The model assumes that there are two kinds of ions that vary in their cross-section values, σ_1 and σ_2 . A fraction, F , of the ions has a cross section of σ_1 , and the remaining fraction, $1 - F$, has a cross section of σ_2 . We require that the population-weighted average cross section be equal to the Judd-Ofelt cross section so that the small-signal gain per unit of stored energy will remain constant.

If the inversion density is n , then the gain coefficient for one cross section is

$$\alpha = n\sigma,$$

where σ is the Judd-Ofelt cross section. For two ions, we have an inversion density, n_1 , for the first ion type, where

$$n_1 = Fn.$$

Similarly,

$$n_2 = (1 - F)n,$$

so the gain coefficient is

$$\begin{aligned}\alpha &= n_1\sigma_1 + n_2\sigma_2 \\ &= nF\sigma_1 + n(1 - F)\sigma_2 \\ &= nF\sigma_1 + (1 - F)\sigma_2,\end{aligned}$$

and we must have

$$\sigma(J = 0) = F\sigma_1 + (1 - F)\sigma_2 \quad (26)$$

to keep the small-signal gain equal to the Judd-Ofelt value. This means that there are only two independent parameters among σ_1 , σ_2 , and F . The third parameter is determined from the other two and σ . For example, we may fix σ_1 and F and find σ_2 from

$$\sigma_2 = \frac{\sigma - F\sigma_1}{1 - F}.$$

We then have a two-parameter model, and we want to vary the parameters to fit the saturation data.

How does the two-ion model saturate? In any small slice, the inversion obeys

$$n = n_0 \exp(-E/E_s),$$

where n_0 is the initial inversion, E is the beam fluence through the slice, and E_s is the saturation fluence for the ion. The saturation fluence is given by

$$E_s = \frac{hc}{\sigma(1 + K)\lambda},$$

where h is Planck's constant, c is the speed of light, σ is the cross section, K is a degeneracy factor, and λ is the wavelength at which σ is taken. If we presume that K is the same for our two ion types, then

$$E_{s1} = \frac{hc}{\sigma_1(1 + K)\lambda} = E_s \frac{\sigma}{\sigma_1},$$

and

$$E_{s2} = \frac{hc}{\sigma_2(1 + K)\lambda} = E_s \frac{\sigma}{\sigma_2}.$$

This two-ion system was modeled by slicing a sample into pieces of gain ≤ 1.1 , doing the gain calculation for each slice by taking losses at the input and output corresponding to any fixed losses, and then

Fig. 2-163. Postpulse gain ratios at two wavelengths. The 1.053- μm data are from the fast-response diodes, while the 1.064- μm data are from the cw gain-monitor diode.

doing the amplification by the two ions one after another. If there are N slices, then a transmission

$$T_1 = T^{(1/2 N)}$$

is applied, the beam is run through the first ion using the Frantz-Nodvik equation

$$E_{\text{out}} = E_{s1} \ln 1 + G_1 \left(e^{E_{\text{in}}/I_s} - 1 \right);$$

the beam then passes through the second ion using the same equation with E_{s2} , and T_1 is again applied. The initial gain of one slice is, of course,

$$G_1 = G^{1/N}.$$

Given the known values of G and T for a sample, we vary σ_1 , F , and K to fit the input-output data from the samples. Table 2-36 shows one such data set that has been fitted to the measured variation of

Table 2-36. Two-ion model for saturation.

Glass	$\sigma(\lambda)$	F	σ_1	σ_2
ED-2	2.61	0.044	15	2.04
LSG-91H	2.32	0.033	15	1.87
E-309	2.44	0.031	15	2.04
LG-810	2.54	0.035	15	2.08
LG-8	4.0	0.025	15	3.70
Q-88	3.9	0.078	15	2.95

saturation fluence with output fluence for the listed glasses. Note that this set is not unique and that the saturation data can easily be fitted by other choices for the fraction F and for the high and low cross sections. What is important here is that this model can be used to predict laser-system performance more

accurately than a single saturation-fluence parameter because the model accounts for the variation of saturation fluence with beam fluence.

We have raised many physics questions about the nature of the gain-saturation process. The saturation data at several pulse lengths indicates that the lower-level drain time is either less than 0.2 ns or greater than 50 ns; furthermore, we do not observe slow gain recovery in the interval between 50 ns and 100 μ s. We do not have an adequate explanation of the transient and polarization behavior of the fast probe beam; however, for systems design, the calorimetric fluence data are the most important parameters. The parameters listed in Table 2-35 are used for the Nova laser-system design.

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Damage Studies

We performed a variety of experiments in 1979 to study damage mechanisms and to improve laser-damage thresholds of bare glass surfaces and optical thin films. The experiments reviewed here were coordinated by LLL and were designed and conducted in collaboration with Optical Coating Laboratory, Inc. (electron-beam-deposited films); with the Naval Weapons Center (CO₂-annealed surfaces); with the Chemistry and Material Science Department (purity of glass surfaces) and the Optical Fabrication Shop (optical polishing) of LLL; and with three companies that developed optical-quality phase-separable glasses: Corning Glass Works (internally funded), Hoya Corporation, and Owens-Illinois, Inc. Damage thresholds were measured at LLL using apparatus⁷⁸ and procedures described elsewhere.⁷⁹

Because damage thresholds of anti-reflection (AR) films are, on the average, lower than the

damage thresholds of thin-film polarizers and reflectors,⁸⁰ a study of AR films constituted a major fraction of our work. We were encouraged by previous observations of high thresholds⁸⁰ for Ta₂O₅/SiO₂ films, and we conducted a deposition-matrix study of these films. We also vigorously pursued an alternative technique for making AR films, that of acid etching phase-separable glass. Median damage thresholds of these etched films, and thresholds of Ta₂O₅/SiO₂ films deposited under optimum conditions, are more than twice the median thresholds of commercially available TiO₂/SiO₂ AR films.

The damage thresholds of thin-film high-reflection (HR) coatings are also of interest to us. We continued a study of overcoats⁸⁰ on these HR coatings; we measured damage thresholds of HR films as a function of film absorption; we tested reflectors with alternative materials in the outer layers; and we also tested modified coating designs.

Bare, polished-glass surfaces are also susceptible to laser damage. Numerous techniques for improving or removing the polishing zone (Beilby layer) were evaluated as potential means of increasing the damage thresholds of the bare-glass surfaces; one of these techniques, CO₂ laser annealing, did provide a significant increase in damage thresholds.

Finally, we surveyed 30 samples of various materials to help establish a broader optical-data base for materials that could be useful at wavelengths near 0.266 μ m. We established damage thresholds for these materials at 0.266 μ m for pulse durations of 0.1 and 0.7 ns.

Electron-Beam-Deposited AR Films. During the previous report period,⁸⁰ we measured damage thresholds of 11 J/cm² and 13 J/cm² (with 1-ns pulses at 1.064 μ m) for two Ta₂O₅/SiO₂ AR films; however, an attempt to reproduce these coatings produced films that damaged at only 4 to 5 J/cm². Nevertheless, believing that high damage thresholds were a possibility for Ta₂O₅/SiO₂ films, we, in collaboration with Optical Coating Laboratories, Inc. (OCLI), designed a deposition-matrix study to evaluate the effects of changes in deposition process parameters on the resultant coatings. The deposition parameters in use today for Ta₂O₅/SiO₂ films were largely optimized for such physical properties of the coatings as adhesion, abrasion resistance, and cosmetic appearance; the intent of the matrix study is to determine optimum coating conditions for

Table 2-37. Damage thresholds of Ta₂O₅/SiO₂ films deposited at three oxygen partial pressures, and two deposition rates, as determined with 1-ns, 1.064-μm laser pulses.

Deposition rate (Å/s)	O ₂ pressure (Torr)	Substrate temperature of 175°C		Substrate temperature of 250°C		Substrate temperature of 325°C	
		Sample ^a	Threshold (J/cm ²)	Sample	Threshold (J/cm ²)	Sample	Threshold (J/cm ²)
1.5	0.5 × 10 ⁻⁴	A-1a	10-16	A-4a	7.1 ± 0.7	A-7a	6.6 ± 0.7
		A-1b	9.6 ± 1.0				
		B-1	9.0 ± 1.4	B-4	5.7 ± 1.3		
1.5	1.0 × 10 ⁻⁴	A-2a	18.7 ± 1.9	A-5a	6.9 ± 0.7	A-8a	4.7 ± 0.5
		A-2b	14.9 ± 1.5				
		B-2	10.3 ± 1.0	B-5	6.1 ± 1.4		
1.5	2.0 × 10 ⁻⁴	A-3a	12.9 ± 1.4	A-6a	5.7 ± 0.7	A-9a	6.6 ± 0.7
		A-3b	9.5 ± 1.5				
		B-3	11.1 ± 1.2	B-6	7.3 ± 0.9		
2.0	0.5 × 10 ⁻⁴	A-10a	7.1 ± 0.8	A-13a	2.2 ± 0.3	A-16a	1.8 ± 0.6
		A-10b	6.8 ± 0.9				
		B-10	4.9 ± 1.3				
2.0	1.0 × 10 ⁻⁴	A-11a	6.7 ± 1.0	A-14a	5.3 ± 0.5	A-17a	5.4 ± 0.7
		A-11b	6.9 ± 0.7				
		B-11	9.0 ± 1.0				
2.0	2.0 × 10 ⁻⁴	A-12a	11.3 ± 1.1	A-15a	9.5 ± 1.4	A-18a	6.5 ± 0.6
		A-12b	9.3 ± 1.2				
		B-12	5.5 ± 1.0	B-15	5.1 ± 0.5		

^aSamples are designated by coating matrix (A is the initial 18-run matrix, B is the repeat matrix) and run number (1 through 18). Each run in matrix A contained two samples (a and b).

producing AR films with high laser-damage thresholds.

OCLI deposited Ta₂O₅/SiO₂ AR films with λ/2 SiO₂ barrier layers on superpolished fused-silica substrates in 18 coating runs at three substrate temperatures (325, 250, and 175°C), three oxygen partial pressures (2.0 × 10⁻⁴ Torr, 1.0 × 10⁻⁴ Torr, and 0.5 × 10⁻⁴ Torr) and two deposition rates (1.5 and 5.0 Å/s). Each run contained two samples for laser damage-tests and samples for measurement of net stress and coating absorption. The index of refraction and reflectivity were also measured for each film. The set of 18 runs was then repeated to test reproducibility of the results.

The 1-ns, 1.064-μm damage thresholds for the Ta₂O₅/SiO₂ AR films are shown in Table 2-37. We first tested one sample at each matrix point from the first 18 runs. Thresholds were greatest for films deposited on substrates at 175°C and least for films deposited at 350°C. To verify reproducibility, we then tested the three duplicate 175°C films from the first matrix and the 175°C films and 250°C films from the repeat matrix.

The results are encouraging: thresholds for nine films from six coating runs (175°C and 1.5 Å/s) ranged from 9 to 18 J/cm², with an average of 11.7 J/cm². There was little correlation between damage thresholds and other film parameters. Damage threshold vs film absorption data for Ta₂O₅/SiO₂ films are shown in Fig. 2-164. The damage threshold was found to be independent of absorption when the film absorbed less than 1% of the incident beam. We rather expected this result because we believe that damage thresholds depend on the actual absorption, linear or nonlinear, at small defects, whereas calorimetry measures the average absorption in the volume of coating material through which the laser beam passes.

Net stresses in the Ta₂O₅/SiO₂ films also showed little correlation with damage thresholds (Fig. 2-165). There was a general tendency toward higher thresholds with increasing compressive stress in the films; however, postdeposition baking in air usually increases damage thresholds of the films

certain alkali-borosilicate glass compositions to separate on a microscopic scale into silica-rich and silica-poor phases.⁸⁵ The regions of different phases are interconnected in a manner such that acid etching of the silica-poor phase, which is more soluble, forms a microporous, graded-index surface layer about 1 μm thick. The pore dimensions, which can range from 10 to 1000 $\text{\AA}$, depend on the glass composition, the phase-separation treatment, and the etching procedure. Because the pore dimensions are small compared to the wavelengths of visible light, scattering is negligible. Surface reflectivity can be as low as 0.1 to 0.2% (comparable to thin-film AR coatings) over a very broad bandwidth ($<0.5\%$ for 0.35- to 2.5- μm light) and range of incidence angles.⁸⁶ These properties are characteristic of a graded-index surface rather than a homogeneous low-index surface.

Minot successfully developed graded-index surfaces on Corning Glass Works Code 7740 (Pyrex) glass. The optical quality of Pyrex, however, does not permit it to be used for laser-transmitting optical elements. Consequently, LLL encouraged and sponsored development of optical-quality phase-separable glass. Suitable glass compositions have now been produced by Corning Glass Works (internally funded), by Owens-Illinois, and by Hoya Corporation.

Transmission spectra of the glasses produced by these companies are shown in Fig. 2-166. The samples were 5 mm thick and were etched on both sides. All three glasses exhibit high transmission throughout the visible and near-IR spectra: the Corning and Hoya glasses are colorless, while the Owens-Illinois glass scatters the shorter wavelengths, giving it a blue opalescence. The composition of the latter glass and the etching procedure can be adjusted to minimize reflectance at other wavelengths.⁸⁷

We believe that the index profile, $n(z)$, of the graded-index layer varies smoothly, as shown by Fig. 2-167(a). The magnitude of the discontinuities at the boundaries ($z = 0, d$) depends on the size and shape of the pores. To calculate reflectivity for an arbitrary profile, we approximated the graded-index layer by a large number of thin, homogeneous layers. The total reflectivity of the multilayer stack can then be calculated by Rouard's method,⁸⁸ in which successive layers are replaced, beginning at the bottom, by equivalent surfaces: the reflected intensity is obtained by squaring the final amplitude.

Fig. 2-166. Transmission spectra of 5-mm-thick phase-separated glass after etching. Glass samples from (a) Corning Glass Works, (b) Owens-Illinois, and (c) Hoya Corporation.

Fig. 2-167. (a) Refractive-index profile for etched surface layer of graded-index glass. The index profile is shown in air, in the etched layer, and in the unetched glass. (b) Reflectivity vs depth of etched layer for the index profile in the inset.

The example in Fig. 2-167(b) shows reflectivity vs the ratio, d/λ , of the etch depth to the wavelength of the light for the index profile in the inset. The reflectivity decreases from 4% for $d/\lambda = 0$, which corresponds to the bulk unetched glass with an index of 1.5, to 0.1% for $d/\lambda = 0.4$. With increasing etch depth, the reflectivity varies periodically, due to interference of the reflections from the index discontinuities at the layer boundaries, but remains below 0.1%.

The measured damage thresholds of more than 60 graded-index samples with AR surfaces are shown by the histogram of Fig. 2-168(a). This figure summarizes data for four different glass compositions produced by the three companies over a period of one year. All glass compositions had

Fig. 2-168. Histogram of 1-ns, 1.064- μm damage thresholds of (a) graded-index AR surfaces, and (b) thin-film AR coatings.

about the same range of damage thresholds at comparable stages of development. Thresholds have generally improved throughout the development period and at present are usually above 10 J/cm^2 . For comparison, thresholds of four-layer $\text{SiO}_2/\text{TiO}_2$ thin-film AR coatings are shown in Fig. 2-168(b); these electron-beam-evaporated coatings, designed and deposited by OCLI, are state-of-the-art coatings used at 1.064- μm . The histograms show that the median damage threshold of graded-index AR surfaces is 2.5 times greater than the median damage threshold of commercial thin-film AR coatings. Current work is aimed at increasing the melt size of production batches and producing prototype windows and lenses for testing.

High-Reflection Dielectric Films. A typical HR film consists of 15 quarter-wave layers of alternating high- and low-index materials. The first and last layers are the high-index material, usually TiO_2 in films designed for the near IR. The preferred low-index material is SiO_2 .

A reflector, by definition, folds the incident beam back upon itself. Coherent reflections from the several surfaces of the HR stack produce an oscillatory standing-wave electric field with a distribution⁸⁹ that has intense maxima in the air in front of the HR film, a zero at the air-film interface, a maximum at the first high-low interface, and alternating nulls and maxima on successive interfaces. The intensity of the field drops rapidly inside the stack and is very small at the substrate interface.

We have found that HR damage thresholds are significantly improved by addition of a half-wave overcoat of a type routinely used to provide physical protection for mirrors. OCLI proposed a study of the influence of overcoats on damage, and they fabricated a number of samples for tests.

Damage thresholds (1-ns, 1.064- μm) for a series of overcoated mirrors are shown in Fig. 2-169. The mirrors were $\text{TiO}_2/\text{SiO}_2$, and the overcoats were SiO_2 . Table 2-38 compares 1-ns, 1.064- μm damage thresholds of overcoated and nonovercoated mirrors. The increase in damage threshold of overcoated reflectors is not related to an alteration of electric fields since the presence of the overcoat does not alter the electric-field distribution in the reflector; in fact, a large electric-field maximum occurs in the overcoat layer itself.

Fig. 2-169. Histogram of 1-ns, 1.064- μm damage thresholds of overcoated $\text{SiO}_2/\text{TiO}_2$ mirrors.

Table 2-38. Damage thresholds in J/cm^2 for $\text{TiO}_2/\text{SiO}_2$ HR coatings, with and without overcoats, as measured with 1-ns, 1.064- μm laser pulses.

	Overcoated (12 samples)	Nonovercoated (16 samples)
Maximum	20.3	13.5
Minimum	8.0	5.0
Median	14.4	9.2

The nature of damage in overcoated mirrors is unique. At fluences of 9 to 10 J/cm^2 , overcoated mirrors emit visible light but suffer no damage visible by Nomarski microscopy at 100 times magnification. The first damage visible by microscopy occurs at fluence levels above the threshold for induced light emission and consists of pits 1 to 5 μm in diameter; these pits frequently occur at existing film defects. At higher fluence levels, the overcoat apparently melts and lifts over regions of film that contain no visible defects; this lifted area of the coating, which may be about 100 to 150 μm in diameter, may have a small rupture at the center.

We have two possible explanations for the improved damage resistance of overcoated mirrors. First, absorption of the laser light by the titania (TiO_2) layer may depend on exposure of the titania film to the atmosphere; and second, the total residual stress in, and the mechanical strength of, the coating may be changed by the presence of an overcoat layer. These possibilities were studied by preparing additional coatings on which overcoats were deposited after various time delays; control parts were included to isolate the effects of thermal and vacuum cycling. The highest damage thresholds were obtained from those coatings that had received overcoats immediately; however, some improvement was observed even for coatings that were not overcoated until after a delay of several months.

Substituted High-Index Layers. The large refractive index and good mechanical stability of titania have made this the preferred material for use in combination with SiO_2 in visible-light and near-IR mirrors. Materials with lower refractive indices (e.g., Al_2O_3 , Ta_2O_5 , or ZrO_2) might have damage resistance superior to TiO_2 , but their use requires application of more quarter-wave layers to achieve high reflectivity. However, because the electric field maxima decrease rapidly at interfaces further from the air interface, the possible advantages of alternative high-index materials could be realized without increasing the complexity of the coating by depositing additional high-index/low-index pairs on the basic $\text{TiO}_2/\text{SiO}_2$ quarter-wave stack.

To evaluate this prospect, OCLI fabricated a set of 20 $\text{TiO}_2/\text{SiO}_2$ mirrors that were overcoated with either one or two additional layer pairs of

Table 2-39. Field strength, absorption, and damage threshold for shifted-stack HR coatings.

Wavelength of maximum reflection (μm)	Standing-wave field in first TiO_2 layer			Absorption (ppm)	Damage threshold (J/cm^2)
	Peak	Average	Interface		
1.193	0.92	0.29	0.92	590	8.0
1.071	0.83	0.40	0.83	450	8.9
0.915	1.34	1.14	0.92	2300	9.0

selected alternative materials. The high-index materials in the study were ZrO_2 , Ta_2O_5 , Al_2O_3 , and an amorphous TiO_2 (an OCLI proprietary material). As compared to the damage thresholds of $\text{TiO}_2/\text{SiO}_2$ mirrors used as a baseline, the ZrO_2 and Ta_2O_5 mirrors had higher thresholds, the amorphous TiO_2 had the same threshold, and the Al_2O_3 mirror had a lower threshold. However, the baseline $\text{TiO}_2/\text{SiO}_2$ mirrors themselves had anomalously low thresholds in this series of experiments, making these results suspect. In a repeat experiment, two $\text{Ta}_2\text{O}_5/\text{SiO}_2$ film pairs were added to each of six 11-layer $\text{TiO}_2/\text{SiO}_2$ mirrors. Three of these six mirrors were also overcoated with a $\lambda/2$ SiO_2 layer. While the overcoated mirror thresholds were greater than the nonovercoated thresholds, no improvement resulted from the added $\text{Ta}_2\text{O}_5/\text{SiO}_2$ layers.

Modified Electric-Field Distributions. The coating design for a mirror can be altered to reduce either the peak or the average standing-wave intensity in the outer TiO_2 layer or the standing-wave intensity at the first $\text{TiO}_2/\text{SiO}_2$ interface. These coating alterations can possibly reduce total absorption, which is believed largely due to either the TiO_2 or the interface.⁸⁹⁻⁹¹ Both cases were tested.

OCLI coated three $\text{TiO}_2/\text{SiO}_2$ mirrors for maximum reflectivity at 1.19, 1.07, and 0.915 μm . The peak and average standing-wave intensities in the outer TiO_2 layer are different if the mirrors are irradiated at 1.064 μm . Table 2-39 gives the peak and average field strengths in the outermost titania layer, the field strength at the first interface, the total absorption (measured by laser calorimetry at OCLI), and the damage threshold for each coating. Interestingly, although the three mirrors had large differences in peak and average field strengths and in absorption, their damage thresholds were nearly equal, as were the standing-wave intensities at the first interface.

To test the influence of the standing-wave intensity at the first interface on damage threshold, OCLI then prepared two additional sets of $\text{TiO}_2/\text{SiO}_2$ mirrors: one set with normal quarter-wave stack reflectors, and a second set with non-quarter-wave outer layers on the reflectors. The standing-wave intensity at the first $\text{TiO}_2/\text{SiO}_2$ interface in the normal design was 1.5 times greater than the intensity at the same interface in the modified design. Several coating runs were made, alternating between designs; surprisingly, however, the modified design with reduced interface intensity had the lowest damage thresholds. We cannot, therefore, predict relative damage thresholds of HR stacks on the basis of any measure of standing-wave intensity.

Absorption. To determine a correlation between damage threshold and coating absorption, OCLI prepared a series of HR coatings deposited at different oxygen pressures. Coating absorptions of 10^{-5} to 10^{-2} of the incident beam were measured by laser calorimetry at OCLI.

Damage thresholds measured with 1-ns, 1.064- μm pulses generally decreased with increasing absorption for mirrors with total absorption greater than 10^{-4} ; thresholds did not correlate with absorption when absorption was less than 10^{-4} . We believe that a calorimeter measures spatially and temporally integrated absorption at small absorbing centers, while the 1-ns thresholds depend on the local linear or nonlinear absorption, which can exceed the calorimetric average.

Polished Bare-Glass Surfaces. Our studies of bare-glass surfaces fall into several categories:

- Measurements to establish the mean 1-ns damage threshold. Most of these measurements were made at 1.064 μm , but some were made at 0.532 μm .
- Attempts to improve polished surfaces by modifying the polishing process.
- Attempts to remove or to improve the polished surface by etching or annealing.

● Studies of fractured or cleaved surfaces to determine the upper limit for surface-damage thresholds.

Progress in these areas is discussed below.

We measured 1-ns, 1.064- μm thresholds for 14 BK-7 glass and fused silica surfaces that were polished by standard materials and procedures specified for laser components. The rms roughness of the surfaces was approximately 10 Å, as measured by stylus at the Naval Weapons Center, and there was minimal subsurface fracture, as revealed by surface etching. The samples were cleaned immediately prior to testing to remove dust, which will burn and induce damage at fluence levels below 14 J/cm². Damage thresholds of the 14 samples are shown by the histogram in Fig. 2-170. The median threshold was 16 J/cm², and 80% of the thresholds, including those of all freshly polished surfaces, exceeded 14 J/cm². Thresholds for three surfaces stored for one year prior to testing were less than 14 J/cm².

Analysis by the Chemistry and Material Science Department at LLL demonstrated⁹⁰ that commercially available polishing compounds have metallic impurities at concentrations of up to 1000 ppm per element and total impurity contents of several percent.

Polishing compounds with total impurity levels of less than 100 ppm (CeO₂, Al₂O₃) have been obtained, and a significant effort has been made to use these compounds to produce surfaces with improved damage thresholds. This effort has had little success to date. Of the many surfaces fabricated with pure compounds, only two—both fused

silica—had thresholds that exceeded the mean of 16 J/cm²; they were damaged at 22 J/cm². These fused-silica surfaces were polished by the Chemistry and Material Science Department using 99.99% pure CeO₂ in a polish-etch-polish procedure with a nylon lap; the intermediate HF etch provided a one-time cleaning and allowed evaluation of subsurface fracture.

If the surface zone (Beilby layer) could be removed or modified after polishing, it might be possible to retain present optical polishing procedures and then use a posttreatment to obtain good damage resistance. We have explored the effects of removing the surface layer by sputter etching, electron-beam heating, ion planing, acid etching, and annealing by CO₂ laser beams. This work, also, has been largely discouraging, probably because many processes for surface removal recontaminate or physically damage the surface. Of these methods, only the technique of using a CO₂ laser beam scanned across the polished surface of fused silica⁹² produced a significant increase in damage threshold. Strong absorption of the CO₂ radiation caused melting and vaporization of material from the surface, leaving it very smooth and in an annealed condition. Damage thresholds of these etched-and-annealed surfaces were found to be more than twice the median threshold of 16 J/cm² for polished surfaces. This improvement in the damage threshold possibly results from impurities being vaporized or from surface and subsurface microcracks being annealed by the CO₂ laser scan.

Damage thresholds (1-ns, 1.064- μm) of freshly fractured surfaces of BK-7 and fused silica ranged from less than 5 J/cm² to more than 40 J/cm². This wide range of thresholds undoubtedly resulted from the numerous microscopic—and damage-causing—glass particles that littered the surfaces of the test specimens after the glass blanks had been broken to prepare the specimens. If a technique can be developed to eliminate formation of the glass debris, broken (fresh) glass surfaces have good potential as test surfaces in contamination studies.

Detailed descriptions of the damage-threshold studies described above are available.⁹²⁻⁹⁴

Damage Thresholds at 0.266 μm . The growing interest in shorter wavelengths for fusion lasers increases the need for a broad data base of optical

Fig. 2-170. Histogram of 1-ns, 1.064- μm damage thresholds of polished, uncoated surfaces of BK-7 and fused silica.

Fig. 2-171. Optics for generating fourth-harmonic wavelength.

properties of materials that are useful at wavelengths near 0.266 μm , which is the fourth harmonic of the fundamental 1.064 μm Nd:glass line and which is very close to the 0.248- μm wavelength of KrI. Using the wavelength of 0.266 μm , and pulse durations of 0.1 and 0.7 ns, we have surveyed damage thresholds of some 30 samples comprising a representative set of currently available materials and coatings.⁹⁵ These subnanosecond data complement data at 22 ns published in 1978.⁹⁶ In the current study, we tested 18 thin films—including five total-reflector films, three metallic reflectors, two AR films, and a series of eight half-wave fluoride and oxide films—and 12 bare surfaces—including many of the important UV window materials. The latter (UV) materials include alkali-fluoride and alkaline-earth-fluoride single crystals, hot-forged lithium fluoride, fused silica, sapphire, BK-7 glass, potassium dihydrogen phosphate (KDP), and cesium dideuterium arsenate (CD*A). The samples tested in this survey were representative of current off-the-shelf components and did not represent attempts to develop special materials with high damage thresholds.

The laser used for the 0.1-ns measurements was the passively mode-locked Nd:YAG glass laser, which was used in the past for short-pulse, 1.064- μm

damage studies.⁹⁷ The 0.7-ns data were obtained after installation of an actively mode-locked and Q-switched oscillator, which provides pulses with durations ranging from 0.1 to 1.2 ns.⁹⁸

The energy of the 1.064- μm , linearly polarized laser pulse was determined by a calorimeter that sampled the beam via an uncoated BK-7 beam splitter (Fig. 2-171). The second-harmonic wavelength (0.532 μm) was generated by an angle-tuned deuterated potassium dihydrogen phosphate (KD*P) crystal (Type I) with a conversion efficiency as high as 80% for 100-ps pulses. The 1.064- μm light remaining after the KD*P crystal had been traversed was spatially separated from the second harmonic by a prism that was set approximately at minimum deviation. The 0.532- μm beam was similarly sampled for energy content via a BK-7 beamsplitter; the beam then entered an angle-tuned KDP or temperature-tuned ammonium dihydrogen phosphate (ADP) crystal for fourth-harmonic (0.266 μm) generation; the maximum conversion efficiency at this stage was 30%. The 0.532- μm light remaining after the ADP crystal had been traversed was spatially separated by a quartz prism.

The 0.266- μm optical circuit is shown in Fig. 2-172. The beam was focused by a lens having a focal length of 2 m, and the focal plane occurred approximately 400 mm beyond the front surface of the sample. After passing through the lens, the beam

Fig. 2-172. O.

sed for determining damage thresholds at 0.266 μm

was split into two parts by a partially reflecting mirror, with 48% of the energy going to an absorbing glass calorimeter (GG-19 glass). A second bare beam splitter directed energy to a multiple-exposure mirror. (The offset angle of both beam splitters was 3°.) A multiple-exposure photograph of each shot was taken with Plus-X film in a plane optically equivalent to the plane of the front surface of the sample. The laser spot at the sample plane was 1.0 mm in diameter.

All the samples were irradiated at 5° from normal incidence, with one shot per site. The damage-threshold criterion was the existence of front-surface alteration, as determined either by visual inspection or by Nomarski microscopy.

Our standard procedure was to fire enough shots with 0.266- μm light to reduce the threshold uncertainty to $\pm 10\%$. When the beam-profile data were analyzed, we found a significant variation in the beam shape, particularly in the effective area of the beam, from shot to shot. In some cases, this variation produced a narrowing in the uncertainty of the peak-fluence value at threshold; in other cases, the variation increased the uncertainty.

The multiple-exposure images of the beam were analyzed by the same techniques that were used for the 1.064- μm laser-damage experiments.⁹⁹ Experience has shown that the combination of the highly stable absorbing-glass calorimeter and our photocalibration codes yield peak-fluence values accurate to within $\pm 10\%$ for each shot.

The damage thresholds for the bare surfaces tested are shown in Table 2-40. There is a variation of about one order of magnitude for the data group.

Table 2-40. Damage thresholds of bare surfaces at two laser pulse lengths and wavelength of 0.266 μm .

Material	Fluence (J/cm^2)	
	0.1 ns	0.7 ns
LiF	0.60 ± 0.39	—
BaF ₂	0.50 ± 0.13	2.06 ± 0.72
SrF ₂	0.47 ± 0.12	1.54 ± 0.51
CuF ₂	0.65 ± 0.15	2.37 ± 0.83
MgF ₂	1.32 ± 0.32	2.69 ± 0.41
LaF ₃	1.80 ± 0.89	3.10 ± 0.70
Al ₂ O ₃	0.75 ± 0.26	—
Silica	3.00 ± 0.96	10.00 ± 3.00
BK-7	2.90 ± 0.84	1.94 ± 0.71
CD*A	1.10 ± 0.27	—
KDP	$> (1.70 \pm 0.25)$	6.48 ± 1.40
LiF	—	14.30 ± 2.50
LiF (hot forged)	—	14.40 ± 2.50

The first six fluoride samples had an average damage threshold of 1 J/cm^2 at 0.1 ns and 2 to 3 J/cm^2 at 0.7 ns. We hypothesize that the general clustering of these thresholds may be due more to the surface-finishing techniques than to any intrinsic material behavior.

The remaining samples listed in the table are from various sources. The silica and BK-7, in particular, were substrates intended for coating-damage studies with 1.064- μm light. The silica sample was particularly damage resistant, at least in a relative sense. The polishing techniques used for this sample, although developed for 1.064- μm testing, are more advanced than the simple hand polishing used for our fluoride samples. Thus, it is conceivable that, with improved surface preparation,

the fluoride damage thresholds might be considerably higher.

In light of the widespread application of silica optics in UV laser systems, it is encouraging to note that the silica damage threshold is high among these samples. An unexpected result is that, at least for the short pulses, the BK-7 threshold was almost as high as that for silica, and was higher than that for the fluorides, in spite of the high bulk-absorption coefficient of BK-7 (about 6 cm^{-1} at $0.266 \mu\text{m}$). We interpret this result as further evidence that surface properties are, to a large extent, masking the bulk properties of these samples.

The KDP damage threshold of about 6.5 J/cm^2 at 0.7 ns is a relatively high threshold, which is encouraging for the application of KDP to fourth-harmonic generation (from 0.532 to $0.266 \mu\text{m}$). The bottom two LiF samples in Table 2-40 were damage tested at $1.064 \mu\text{m}$ as well as at $0.266 \mu\text{m}$. Essentially no difference was found between the single-crystal and the hot-forged LiF samples at either wavelength. Although the $1.064\text{-}\mu\text{m}$ damage thresholds for these samples were rather disappointingly low, the $0.266\text{-}\mu\text{m}$ damage thresholds¹⁰⁰ for the same materials were the highest thresholds measured. Hot-forging of materials to increase the clear aperture may have important applications for UV fusion lasers.

We tested eight half-wave layers of fluorides and oxides on silica substrates, as shown in Table 2-41. With the exception of titanium oxide, the thresholds are clustered very closely, are essentially the same at both pulse durations, and are lower than those for either the AR films or the HR films.

We also tested several total reflector and AR films, whose damage thresholds are listed in Table 2-42. The dielectric reflectors average about 1.0 J/cm^2 at 0.1 ns and about 1.8 J/cm^2 at 0.7 ns . At 0.1 ns , the damage thresholds for the AR films at $0.266 \mu\text{m}$ were slightly higher than those for the reflectors; this result is in contrast to the situation at $1.064 \mu\text{m}$, in which thresholds for AR films are typically a factor of two lower than for HR films. For 0.7-ns pulses, the thresholds for AR films were, on the average, about as high as those for the HR films. The metallic reflectors exhibited much lower damage thresholds than the dielectric reflectors.

Table 2-41. Damage thresholds for eight half-wave, single-layer films at two laser pulses and wavelength of $0.266 \mu\text{m}$.

	Fluence (J/cm^2)	
	0.1 ns	0.7 ns
Y_2O_3	0.10 ± 0.035	0.26 ± 0.04
ZrO_2	0.51 ± 0.26	0.62 ± 0.14
SiO_2	0.72 ± 0.26	0.44 ± 0.13
AlF_3	0.65 ± 0.15	0.50 ± 0.07
LaF_3	0.70 ± 0.21	0.74 ± 0.20
MgF_2	0.80 ± 0.32	1.24 ± 0.33
P1 (OCLI proprietary)	0.95 ± 0.25	0.66 ± 0.10
P2 (OCLI proprietary)	0.85 ± 0.231	—

Table 2-42. Damage thresholds of reflector and AR films at two laser pulses and wavelength of $0.266 \mu\text{m}$.

	Fluence (J/cm^2)	
	0.1 ns	0.7 ns
Dielectric reflectors		
a	1.30 ± 0.25	3.85 ± 1.1
b	0.50 ± 0.12	0.405 ± 0.085
c	0.92 ± 0.20	1.86 ± 0.55
d	0.85 ± 0.23	1.54 ± 0.26
e	—	1.43 ± 0.26
Metallic reflectors		
a	0.23 ± 0.06	0.60 ± 0.21
b	0.10 ± 0.04	0.066 ± 0.013
c	0.13 ± 0.05	0.045 ± 0.017
AR films		
a	1.10 ± 0.27	1.20 ± 0.12
b	1.60 ± 0.54	0.72 ± 0.16

Because only one sample of each specific type was tested in this survey, minor distinctions between materials should not be made on the bases of these data. Our conclusions are that, at 0.1 ns , the generally available damage threshold is about 1 J/cm^2 , with the important exceptions of silica and KDP, which have higher thresholds. At 0.7 ns , damage thresholds of 2 to 3 J/cm^2 are to be expected, with the exceptions of silica, KDP, and lithium fluoride, which also have higher-than-average damage thresholds.

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Amplifier Development

We finalized the optical design for the Nova laser system in 1979, and we selected clear apertures of 460, 315, 208, 150, and 100 mm for the disk amplifiers. The largest three amplifiers will employ the rectangular pumping geometry recently developed at LLL, while the smaller amplifiers will use Shiva hardware.

Extensive testing of the 340-mm Nova prototype amplifier¹⁰¹ and other prototype amplifiers with rectangular pump geometries has allowed us to significantly improve the design and performance expected in the new sizes of Nova amplifiers. We have also explored new concepts of staging the preamplifier sections of the system, and we have performed extensive optical tests on an off-axis multipass amplifier that was designed to reduce the number of amplifiers in the front end of Nova.

Nova Amplifier Design. The most striking change in amplifier designs for Nova has occurred with the largest amplifiers. We decided to use a 460-mm clear-aperture amplifier containing two elliptical disks. The large size of this amplifier requires two major design innovations: first, each of the elliptical disks must be split on its minor axis to suppress parasitic processes and to achieve the highest gains; second, the longitudinal flashlamps that would be required would be considerably longer than the ones that we now use (1460 vs 1120 mm). Because of the unknowns associated with this longer lamp—i.e., circuit compatibility, quartz availability, increased energy per circuit, lifetime and explosion characteristics, and cost per lamp—we decided to use a transverse-lamp pumping geometry that will use a large number of short lamps mounted at right angles to the beam direction. (The basic pump-cavity design for the 460-mm amplifier and a detailed summary of the mechanical design of Nova amplifiers are given in "Mechanical Subsystem," above.) The smaller amplifiers will still use longitudinal lamps.

Using the GAINPK code,¹⁰² we simulated performances of the Nova 460-, 315-, and 208-mm amplifiers. Figure 2-173 shows the results of these

simulations, and Table 2-43 lists the design points for these amplifiers. The basis for the simulations, described below, is expected to be quite conservative, since it rests on measured performances of nonoptimized prototypes, also described below.

Fig. 2-173. Calculated performances of 460-, 315-, and 208-mm Nova amplifiers with fluorophosphate disks. Parameters for the simulation are from Table 2-43.

Prototype Testing. The Nova 460-mm amplifiers, which will use transverse pumping geometry, blast shields, and a redesigned pump cavity, will more closely resemble the original rectangular-disk amplifier (RDA) prototype than does the 340-mm Nova prototype amplifier that was discussed in the last annual report.¹⁰¹ We found that the conventional electrical isolation designs used in the 340-mm amplifier (i.e., separate 60-kV isolation of the flashlamp reflector, wall reflectors, and case) resulted in a large volume for the pump cavity. Furthermore, mounting of the blast shield as part of the electrical isolation system resulted in light leaks from the pump cavity.

We have tested the 340-mm prototype, the original RDA prototype, and a new RDA prototype, all in a number of configurations, to explore the effects of blast shields, number and configuration of lamps, reflector configuration, and pump-cavity volume. The results of these tests were used to establish the simulation parameters for the results shown in Table 2-43 and Fig. 2-173.

The basic theoretical tool used to analyze the experimental data is the code GAINPK.¹⁰² The inputs to the code are spectroscopic and decay properties of the glass, flashlamp and cavity

Table 2-43. Nova amplifier design summary.

Amplifier size (mm)	460	315	210
Small-signal gain ^a	1.65	1.65	1.90
Extractable stored energy @ 4.5 J/cm ² (kJ)	6.06	2.99	1.69
Bank input energy ^a (kJ)	560	290	160
Flashlamp explosion energy fraction	0.18	0.23	0.20
No. of disks	2 (split)	2	3
Disk dimensions (mm)	488 × 856	338 × 608	226 × 401
Disk thickness ^a (mm)	38.0	48.5	32
Doping ^a ($\cdot 10^{20}$ atoms/cm ³)	2.0	2.0	3.0
No. of lamps	80	20	16
Lamp dimensions (mm)	20 × 480	15 × 1120	15 × 1120
Bank circuit			
Energy/circuit @ 22 kV (kJ)	50	37.5	25
Inductance	450 μH	650 μH	450 μH
Capacitance	208 μF	156 μF	104 μF
No. of lamps/circuit	5	2	2
Disk volume/cavity volume ^b	0.064	0.097	0.090
Shield glass thickness (mm)	6	6	6

^aFluorophosphate glass LG-810, E-309, or LHG-10.

^bSee "Mechanical Subsystems," above, for detailed mechanical specifications.

parameters, and disk dimensions. Comparative testing was performed with one set of 300-mm clear-aperture ED-2 disks so that direct comparisons could be made between amplifiers with variations in pumping geometry or cavity design. We use the numerical fitting techniques of GAINPK to fit cavity pumping efficiency to the measured data; the cavity pumping efficiency per unit volume, η , is calculated from the relation

$$\eta(J) = \frac{A[1 - \exp(-J/350)]}{J^B} \quad (27)$$

where J is the lamp current density, A is the cavity transfer slope efficiency, and B is the power of the current. A is a measure of the effectiveness of converting lamp output energy to stored energy in the glass (at low currents), and B accounts for the observed reduction in efficiency at higher current densities due to flashlamp self-absorption. The code finds the best choice of A and B to fit the experimental data; we can then use the changes in A and B , along with glass parameters, to predict the performance of configurations that are of interest for Nova amplifiers. Variations in A of less than 5% are within experimental error.

Shield Glass in 340-mm and RDA Prototype Amplifiers. We have designed a blast shield into all of the Nova amplifiers. We may not require this shield in the final production amplifiers, but the effects of the shield glass must be accounted for in analyses of amplifier performances.

Early in 1979, we tested a Pilkington water-clear plate glass that showed excellent resistance (as good as fused silica) to damage from flashlamp irradiation. This glass also had excellent transmission characteristics and did not show color-center formation. We tested both the 340-mm prototype amplifier and the RDA prototype amplifier with a 6-mm-thick shield of this glass. As we mentioned previously, the shield glass is used as part of the insulation in the 340-mm amplifier, a design that creates light leaks and places for flashlamp light to get lost. The RDA prototype, on the other hand, can be configured so that the shield glass is entirely inside the pump cavity.

Figure 2-174 shows the results of the shield-glass testing with the standard 300-mm ED-2 disks. Each point, and its associated error bar, is the average of five shots. The GAINPK-generated fits

to the experimental data are shown as solid lines in Fig. 2-174. The 340-mm amplifier used 20 lamps with a single-cusp reflector, and the RDA prototype amplifier used 14 lamps with a double-cusp reflector. The A and B parameters are shown in Table 2-44. The efficiency of the 340-mm amplifier with the blast shields in place is 7% below that of the configuration containing gaps for the glass and 21% below that of the configuration where the gaps are closed by moving the flashlamp reflector inward, toward the disks. The addition of shield glass to the RDA prototype results in a 16% drop in efficiency; however, it may be possible to reduce this loss by surface treatment of the shield glass.

Lamp and Reflector Tests. In seeking the best amplifier configuration, we have performed a number of lamp and reflector tests, and a series of 16- and 20-lamp tests on single- and double-cusp reflectors was described briefly in the 1978 Annual Report.¹⁰¹ Table 2-44 shows the results of these tests again, in the form of GAINPK fits to the experimental points. Each of the A and B results represents at least 20 shots within the energy range shown in Fig. 2-173.

As we discussed in the last annual report,¹⁰¹ the number of lamps affects efficiency more than reflector shape, as may be seen from the single- and double-cusp reflector tests: increasing the number of lamps decreases amplifier efficiency.

Our standard flashlamp and interior reflectors are polished, silver-plated copper sheets that are rather expensive; consequently, we tested polished, anodized aluminum (Alzac) reflectors in the 340-mm amplifier to see if this relatively inexpensive material would make a suitable reflector. In this test, all of the sidewall reflectors were replaced with Alzac, while silver-plated flashlamp reflectors were retained. As indicated in Table 2-44, aluminum sidewall reflectors result in an efficiency drop of 12%; thus, this material is not suitable for use in a high-efficiency amplifier.

The RDA prototype has also been tested with several reflector shapes. The 14-lamp, double-cusp test showed the highest efficiency; however, a test with a zigzag or "W" reflector was very nearly as good. Figure 2-175 shows the W reflector and the corresponding double-cusp, or Winston, reflector.

Fig. 2-174. Performances of (a) 340-mm and (b) RDA prototype amplifiers with and without blast shields. Two edge-clad ED-2 disks, 300 mm in diameter and doped with 1.2% Nd, were used.

If the effects of differing numbers of lamps are accounted for, the W reflector is only about 5% less efficient than the optimum double-cusp reflector. Additional tests with more lamps and flat reflectors showed that the most important factors in flashlamp reflector design are the number of lamps and a configuration that prevents adjacent lamps from seeing one another. The exact shape of the reflector does not seem to be as important in the rectangular amplifier as it is in geometries where the lamp must be imaged into the laser medium (e.g., rod amplifiers). The reason for this relative insensitivity to reflector shape may be found by considering the rectangular type of amplifier as a thermodynamic oven rather than as an imaged illumination system.

Transverse vs Longitudinal Lamps. We know that the operating characteristics of rectangular am-

plifiers are very sensitive to cavity volume, leakage losses, and disturbances in the circulation of light in the pump cavity. The 460-mm Nova amplifier requires a transverse-lamp pump geometry, and we built a second RDA prototype, Datum III, to gather data on this configuration. Figures 2-176 and 2-177 show construction details of the Datum III amplifier. We split the flashlamp reflectors into three pieces and arranged them either into two 8-lamp longitudinal reflectors (1120-mm arc length) or two 24-lamp reflectors (370-mm arc length) so that the same reflector geometry and flashlamp arc length per circuit could be tested (20×1120 mm/circuit and 60×370 mm/circuit). We also designed this prototype amplifier so that the end reflectors could be moved in and out to simulate end pumping from adjacent amplifiers arranged in a variety of geometries. This feature allows us to simulate the differences in amplifier construction that are necessitated by the use of either longi-

Table 2-44. GAINPK cavity-efficiency parameters.

Tests ^a	Configuration	Transfer efficiency (A)	Current exponent (B)
Blast shields	340-mm 20-lamp SC ^b w/ shield	1.00	0.97
	– w/o shield, gaps	1.07	1.01
	SC w/o shield, no gaps	1.26	1.05
Reflector/lamps	RDA 14-lamp DC ^c w/ shield	1.28	0.97
	– DC w/o shield	1.53	0.97
	340-mm, no gaps 16-lamp DC	1.22	0.91
	20-lamp DC	1.17	1.03
	20-lamp SC	1.26	1.05
	Alzac, 20-lamp SC	1.11	1.01
	RDA 14-lamp DC	1.53	0.97
	16-lamp W	1.38	1.01
	14-lamp flat	1.29	0.95
	28-lamp SC	1.12	1.34
Lamps (transverse and longitudinal)	Datum III 16 long. lamps, SC ends out	1.43	1.08
	ends in	1.43	1.02
	48 trans lamps, SC ends out	1.24	0.96
	ends in	1.26	0.90

^aAll tests were made with two ED-2 disks, 301 × 579 × 33.9 mm, doped with 1.2% Nd.

^bSC = single-cusp reflector.

^cDC = double-cusp reflector.

tudinal lamps or transverse lamps. The longitudinal-lamp geometry requires the amplifier to have a longer overall length to accommodate flashlamp insulators and wire interconnections; the transverse-lamp geometry allows much closer coupling between amplifiers.

Figure 2-178 shows the results of two of the tests conducted on Datum III to simulate the performance of a 460-mm amplifier equipped with either longitudinal or transverse lamps. The longitudinal-lamp test with the end reflectors moved out showed the same gain coefficient (stored energy) as the transverse-lamp test with the end reflectors moved in. The transverse-lamp configuration is, therefore, expected to be equal in performance to the longitudinal-lamp configuration at the design operating points.

Spectral Reflectance of Reflectors. We have performed reflectance measurements on samples of our standard reflector material (silver-plated copper sheet) to determine how its reflectance varies with tarnishing. A Cary-17 spectrometer with a spectral-reflectance attachment was used to measure the reflectance of freshly polished, slightly tarnished (two days exposure to clean-room environment),

and severely tarnished samples of standard reflector material; samples of freshly evaporated silver films on glass substrates were also tested to provide a comparison with our standard material. With the naked eye, the slightly tarnished sample can be seen to be less reflective only, when viewed in a side-by-side comparison with untarnished material.

The results of the reflectance tests are presented in Fig. 2-179. Two features of the data are particularly noteworthy: the reflectance of freshly polished standard materials is significantly less than that of freshly evaporated silver films; and small amounts of tarnishing significantly reduce reflectance of the standard material at shorter wavelengths. These measurements indicate that significant improvements in amplifier efficiency may be possible if reflector performance and resistance to tarnishing can be improved.

Performance Testing of Amplifier Glasses. We use a standard amplifier test for evaluating the performance of new laser glasses with respect to ED-2.¹⁰² Briefly, we determine the gain characteristics of a set of standard ED-2 liquid-clad 50-mm (A-size) disks in a 100-mm (B-75) amplifier. Disks of

Fig. 2-175. Dimensions of (a) zigzag, or W, reflector; and (b) double-cusp reflector (all units in mm).

test glass (also A size) are then exchanged for the standard disks, and the measurements are repeated. GAINPK simulation of the ED-2 disks is used to determine the cavity pump parameters, which are then used in the simulation of the test disks.

Testing the standard disks each time ensures that small changes in cavity pump efficiency due to aging are taken into account. We find that the

relative performance of laser glasses cannot be predicted on the basis of spectroscopic parameters alone. The calculated Judd-Ofelt cross sections and flashlamp absorption efficiencies used as input to the GAINPK code do not completely describe the relative performance of most tested laser glasses to better than $\pm 5\%$.

In general, GAINPK predicts higher performances for most test glasses, relative to ED-2, than are actually measured. Two possible sources for this

Fig. 2-176. Drawing of the Datum III RDA prototype amplifier assembly showing the two possible flashlamp configurations. The transverse and longitudinal configurations use the same three-section flashlamp reflector.

Fig. 2-177. Fluorophosphate 340-mm disks in the Datum III prototype amplifier.

Fig. 2-178. Results of transverse-lamp and longitudinal-lamp tests on Datum III. The longitudinal-lamp test (curve A) used sixteen 15- by 1120-mm lamps with end reflectors out to the ends of the lamps. The transverse-lamp test (curve B) used forty-eight 15- by 370-mm lamps with close-in end reflectors.

Fig. 2-179. Spectral reflectance of standard silver-plated reflector material.

discrepancy are related to the measured cross section and the absorption efficiency of ED-2. If the calculated Judd-Ofelt cross section of ED-2 is too low with respect to the true cross section by some amount, then, in simulating the ED-2 measurements with GAINPK, we would have to use a cavity

Table 2-45. Gain-test correction factors for GAINPK simulation.

Glass	Correction factor ^a
ED-2	Standard
ED-3	1.05
EV-2	0.92
E-181	0.91
E-309	0.93
Q-88	0.93
LG-810	0.86
LHG-10	0.84
LHG-8	0.98

^aMultiply cavity efficiency, cross section, or absorption efficiency by the factor shown.

efficiency that is too high in order to fit the data. If this high cavity efficiency is used to simulate another glass whose true cross section is correctly predicted by Judd-Ofelt, then the simulation would be too high with respect to the measured data. A similar argument holds for the spectroscopic flashlamp absorption efficiency of ED-2 vs other glasses. A correction factor must be applied to most glasses to find their correct performance with respect to ED-2. So far as the GAINPK simulation is concerned, it does not matter if the correction is applied to the cross section, the cavity efficiency (A), or the flashlamp absorption efficiency of the glass.

Table 2-45 lists the factors that must be used to accurately simulate the standard gain-test performance of the listed glasses using the GAINPK code. We caution that these factors may be peculiar to the code and to the way the spectroscopic data and pumping models are used in this code. Note that most corrections are in the range of 5 to 10%; these corrections are used in simulating the performance of larger amplifiers by multiplying cross section or absorption efficiency when the prediction is based on a test in which ED-2 was used.

Gain Spectral Response of Laser Materials. We have tested numerous rod and disk amplifiers at the four Nd:YAG wavelengths: 1.052, 1.061, 1.064, and 1.074 μm . Our testing is normally done at the YAG line that most closely matches the spectral peak of the material. In an actual laser system, the wavelength would be chosen to exactly match the amplifier material, so we are very concerned that the proper correction is applied when testing is performed at one wavelength while the amplifier would

Table 2-46. Nd³⁺ spectral and gain coefficient ratios.

Material	λ	$\alpha/\alpha_{1.052}$	$\frac{\sigma(\lambda)}{\sigma_{1.052}} (\lambda^5)$	Deviation (%)	Type
ED-2	1.052	0.458 ^a	0.485 ^a	-6	Amp 6 disks
	1.061	1.043	1.036	+1	
	1.064	1	1	-	
	1.074	0.774	0.737	+5	
YAG	1.052	0.430 ^a	-	-	10-mm rod
	1.061	0.650	-	-	
	1.064	1.	-	-	
	1.074	0.312	-	-	
Q-88 (disks)	1.061	0.796	0.858	-7	Amp (6 disks)
	1.064	0.731	0.779	-6	
	1.074	0.413	0.434	-5	
Q-88 (rod)	1.061	0.779	0.858	-9	Rod
	1.064	0.729	0.779	-6	
	1.074	0.402	0.434	-7	
LG-812	1.061	0.886	0.873	+1	Std A disk
	1.064	0.786	0.786	0	
	1.074	0.482	0.456	+6	
LHG-8	1.061	0.723	0.728	-1	Std A disk
	1.064	0.665	0.662	-	
	1.074	0.368	0.360	+2	
E-309	1.061	0.867	0.874	-1	Std A disk
	1.064	0.768	0.784	-2	
	1.074	0.476	0.462	+3	

^a $\alpha/\alpha_{1.064}$ for these materials.

be operated at a slightly different wavelength. The theoretical variation of cross section with wavelength is found from¹⁰³

$$\sigma(\lambda) = \sigma_{\text{peak}} \left(\frac{\lambda}{\lambda_{\text{peak}}} \right)^5 \quad (28)$$

In Table 2-46, we compare the results of several tests at the four YAG wavelengths. The calculated λ^5 cross-section ratios and the measured gain-coefficient ratios are given for a variety of glasses and amplifiers. Only small deviations from the calculated values are noted, so the λ^5 correction for cross-sectional changes appears to hold quite well.

Multipass Amplifier. We have directed a considerable effort in previous years toward the development of multipass amplifiers. Using small apertures, we analyzed and demonstrated the use of the regenerative amplifier for stable pulse generation, amplification, and storage,^{104,105} and we developed a temporal pulse compressor¹⁰⁶ using a saturable dye intracavity to a regenerative amplifier. We have also analyzed multipass geometries for

output-stage applications,¹⁰⁷ and we showed that these geometries have the potential for significantly improving the performance-to-cost ratios of solid-state lasers. In 1979, we examined a multipass geometry for a driver stage to replace sections of the currently used linear chain of amplifiers.

There are two basically different types of multipass geometries: the resonator type and the off-angle type, both of which are illustrated schematically in Fig. 2-180. The difference between these geometries lies in the degree of spatial overlap of the various passes. For the resonator, or regenerative, amplifier, the pulse is injected into a resonant cavity and the multiple passes overlap completely, both in the near field and in the far field. For the off-angle amplifier, the passes are at sufficiently different angles that the passes can be spatially separated.

The resonator type of amplifier allows an unlimited number of passes, thereby providing a very high gain. It also allows maximum use of the amplifier clear aperture, since there is no angular

Fig. 2-180. The two basic types of multipass amplifiers are (a) resonator, and (b) off-angle.

separation between the different passes; however, it requires a fast temporal switch (10^{-7} s) to isolate a single output pulse, and the switch must have very high discrimination (i.e., an on-transmission/off-transmission ratio of about 10^{10}) to protect targets against prepulses. The current technology for fast, high-quality switches limits the resonator-type multipass amplifier to clear apertures of 100 mm or less.

The off-angle type of amplifier suffers from poor use of the amplifier clear aperture¹⁰⁸ due to the requisite angle between passes. Since the total angle of the passes increases with the number of passes, the off-angle geometries are limited to fewer passes—and smaller net gains—than are the resonator types. On the other hand, the off-angle type can be made at any aperture size because a single output pulse can be spatially isolated and a temporal switch is not required. Because of the latter characteristic, we have looked into optimizing the off-angle geometry for a high-gain driver.

A major design problem with the off-angle geometry is fill factor. Vignetting at the amplifier reduces the maximum beam diameter that can propagate without clipping. For circular beams, the fill factor decreases as the square of the total angle between beams, giving a very strong incentive for minimizing this angle. The most easily visualized off-angle geometries achieve spatial separation of the passes in the near field of the amplifier, as shown in Fig. 2-180(b), but the resulting large angle between beams reduces the fill factor. If the geometry is modified to achieve separation in the far field, the angle between adjacent beams can be reduced to a few times the diffraction spread of the beam in the near field, just enough to allow spatial separation in the far field; this minimizes vignetting for the off-angle geometry.

Figure 2-181 shows an off-angle geometry that uses two partially reflecting mirrors, R_1 and R_2 , and two lenses to accomplish separation in the far field. The spacings are such that the plane of R_1 is relay imaged¹⁰⁵ to R_2 , which is tilted at a small angle,

Fig. 2-181. The relayed, off-angle multipass geometry investigated as a possible high-gain driver stage.

$\alpha/2$, to create the angular separation between passes. A collimated beam injected through R_1 is focused through a spatial-filter pinhole by the first lens and is then recollimated and imaged onto R_2 by the second lens. On reflection, the beam picks up an angle, α , for its second pass and is focused through a new pinhole at the distance of above the first pass. The third pass is focused αf below the first, since R_1 is not tilted. After each subsequent round trip, the beam angle is incremented by α at R_2 , and the focal position moves αf further from the axis. The relaying property of the two lenses always returns the beam to the same transverse location on R_1 and R_2 ; therefore, the amplifier is located as close as possible to one of the mirrors to maximize fill factor. The output pulse is extracted through R_2 after the desired number of passes; further passes are blocked by a beam dump in the focal plane of the lens.

The off-angle geometry of Fig. 2-181 is a compact, viable geometry that minimizes the vignetting problem by achieving the separation between passes in the far field. The principal disadvantage of this geometry is that partially transmitting mirrors are needed to couple in and out of the geometry, and the resulting reflection losses reduce the extraction efficiency of the amplifier. On the other hand, this geometry allows the maximum possible number of passes for a given fill factor without the need for a switch, providing relatively high gain in a geometry that can be scaled for any desired amplifier aperture.

Three aspects of the type of multipass amplifier shown in Fig. 2-181 required experimental in-

vestigation: self-lasing, the accumulation of beam aberrations due to many passes through the same components, and amplified spontaneous emission (ASE). The first two aspects are the most important because they limit gain and beam quality and they are difficult to estimate. ASE is the most easily estimated of the three, but its importance in multipass amplifiers requires confirmation.

We investigated these three aspects with an experimental multipass amplifier of the type shown in Fig. 2-181, using an existing 88-mm, f 20 spatial filter, complete with lenses and pinhole manipulators, and an existing 40-mm, ED-2 rod amplifier to minimize costs. All optics were standard production quality for lasers. The experimental multipass amplifier had the following characteristics:

- Number of passes = 11.
- Beam diameter = 25 mm.
- Pinhole diameter = 1.7 mm, $\approx 10 \times$ diffraction limited.
- Pinhole spacing = 3.4 mm, $\approx 2 \times$ pinhole diameter.

We drove the multipass amplifier directly with the switched-out pulse from a mode-locked, Q-switched oscillator using a 0.7-ns pulse. A flat transverse-profile beam was created by overfilling a hard aperture and then relay imaging the aperture to the input of the amplifier. We chose the pinhole diameters shown above because they would pass

Fig. 2-182. Two variations of the relayed, off-angle geometry, showing beam centerlines only.

enough of the spatial harmonics to avoid ring structure on the beam, and we used a linear array of 11 pinholes to isolate the various passes and prevent feedback between them. The choices of pinhole diameters and spacings gave an angular separation of 2 mrad (α in Fig. 2-181). The clear apertures required at the amplifier and lenses were 35 and 60 mm, respectively, for the specified 11 passes and the beam diameter of 25 mm. Although these apertures are 40 and 140% larger, respectively, than the beam diameter, scaling to larger apertures quickly reduces these percentages. For example, a 250-mm beam diameter and an effective $f/20$ lens requires clear apertures of only 260 mm at the amplifier and 270 mm at the lenses (only 4 and 8% larger, respectively, than the beam diameter).

The self-lasing threshold was determined by backscattering from the beam dumps used to limit the number of passes, and the particular choice of beam paths shown in Fig. 2-181 was found to be very unfavorable from a self-lasing point of view. Figure 2-182(a) shows the same geometry with five passes (with beam centerlines only).

We see that ASE makes exactly twice as many passes as the injected pulse. An ASE photon emitted backwards along the direction of path 5 makes 10 passes before hitting the beam dump. The number of passes for the injected pulse can be increased to 9 for the geometry of Fig. 2-182(a) by injecting backwards along path 4, thereby using paths 1 through 4 twice. However, a large retropulse would result, traveling exactly back in the direction of the injected pulse. Figure 2-182(b) shows a slightly different arrangement of beam paths that avoids the coaxial retropulse and holds the number of ASE paths to one more than the injected pulse. This geometry uses each pinhole only once, and the backward-going ASE is blocked at a different spot than the forward ASE.

We determined the backscattering fraction, S , from the beam dumps by measuring the maximum unsaturated pulse gain at the self-lasing threshold. The two are related by

$$G_{\text{net}}|_{\text{max}} = \frac{(1 - R_1)(1 - R_2)}{R_1 R_2 G T} \frac{1}{S} \quad (29)$$

for mirror reflectivities, R_1 and R_2 , single-pass amplifier gain, G , and single-pass transmission, T (excluding mirror losses). We obtained the largest value of $G_{\text{net}/\text{max}}$ by using beam dumps made of copper tubing oriented end-on to the beam to form "get lost" holes. The inside diameter of the copper tubing was 50% larger than the pinhole diameters to prevent scattering from the edge of the tubing. We measured $G_{\text{net}/\text{max}} = 2000$ at the self-lasing threshold for $R_1 = 0.8$, $R_2 = 0.5$, and $GT = 3.7$, giving $S = 3 \times 10^{-5}$. The value of S is determined entirely by the scattering characteristics of the beam dumps and the angular acceptance of the spatial filter pinholes, and it is entirely independent of amplifier gain, reflectivities, and number of passes.

We increased the net gain of the multipass amplifier by adding a Q-switch, a thin-film polarizer, and a 50-mm Pockels cell. We hoped to amplify the injected pulse enough to study the saturation characteristics of the amplifier, but our maximum output energy at a net gain of 5×10^4 was only 300 mJ, about 2% of the saturation fluence. Self-lasing again limited the net gain, but the source of the backscatter appeared to be the Q-switch itself rather than the beam dumps. Also, the holdoff of the Q-switch was poor due to the angle between the forward-going pass and its corresponding reflection.

We determined output-beam quality by examining both the near field and the far field of an amplified output pulse. The near field showed distinct ring structure and evidence of clipping on the pinholes; the far-field image was about 5 times diffraction limited. We investigated the source of these problems using the oscillator as a cw probe beam (no Q-switching, mode locking, or pulse selection) and found a buildup of distortion in the 40-mm rod amplifier during the time the rod was being pumped by the flashlamps. The spherical component of this "active" distortion in the amplifier changed the focal position between the lenses; after 11 passes, the shift was enough to cause an observed clipping of the beam on the 11th pinhole. The nonspherical component of distortion caused poor far-field beam quality.

In a "passive" state (i.e., without the amplifier being fired), the near field of the probe looked very good, showing no diffraction rings or clipping, and its far field was 1.5 times the diffraction limit. This passive distortion appeared to be limited by air turbulence, not by aberrations in the optics, and the far

field might have been improved by completely enclosing the beam paths with beam tubes. A fraction of a second after the amplifier was fired, the near field and far field of the probe showed the same qualitative structure as the amplified pulse, confirming that pump-induced aberrations were the principal source of the observed level of beam quality.

These studies with the probe beam showed that the accumulation of passive aberrations in multipass geometries can be held to tolerable levels but that active aberrations need to be reduced for almost any application. Pump-induced (active) aberrations are not as bad in disk amplifiers as they are in rod amplifiers because of the different pumping geometries. This influence of geometry on active aberrations gives hope that large-aperture multipass amplifiers can be designed, but the relationship of geometry to resultant aberrations must be experimentally determined.

We measured the ASE energy from the experimental multipass amplifier below its self-lasing threshold. Figure 2-183 shows the data points for ASE energy plotted against net small-signal gain. The solid line in Fig. 2-183 is a calculation based on independently measured values of the multipass parameters; the agreement between the experimental and calculated data indicates that we have achieved a good understanding of ASE from multipass amplifiers. The dashed line in Fig. 2-183

Fig. 2-183. Amplified spontaneous emission (ASE) from the experimental multipass amplifier compared to that from an equivalent chain amplifier.

shows calculated ASE from a linear chain of amplifiers with the same small-signal gain. As may be seen, the experimental multipass amplifier put out about 10 times the ASE energy of an equivalent chain amplifier. The ratio of multipass to chain ASE is approximately given by

$$\frac{ASE(multipass)}{ASE(chain)} = \left[\frac{R_1 G}{1 - R_1} \right]^r \left[\frac{\ln G_{net}}{(k+1) \ln G} \right]^k, \quad (30)$$

where G_{net} is the unsaturated gain of either the multipass or the chain, G is the single-pass amplifier gain, R_1 is the input mirror reflectivity, k is the number of passes for the multipass, and r accounts for the ASE that makes less than $k+1$ passes in the multipass. Values of r range from 1.2 to 1.8 for typical multipass parameters. This ratio (r) is large because ASE makes one more pass than the pulse in the multipass and because ASE does not see the transmission loss of R_1 that is seen by an injected pulse; these effects are in the first term of Eq. (30). The last term of Eq. (30) accounts for the difference in spectral line narrowing and temporal narrowing between the multipass and chain amplifiers, and it assumes that both the initial line shape and pulse width are Gaussian. This term is significant, $\sim 1/3$, because the large transmission loss of the multipass requires that $G^k \gg G_{net}$, so that considerably more spectral and temporal narrowing occurs in the multipass than in the chain amplifier.

As shown by Eq. (30), ASE energy from the multipass amplifier will always be greater than that from a chain amplifier with the same small-signal gain. Furthermore, to maximize output fluence from the multipass amplifier (as discussed below), R_1 should be increased from the value of 80% that we used experimentally to over 95%, thereby increasing the ratio even further. Thus, ASE is seen to be a serious problem for this type of multipass amplifier in applications where only very small ASE energies are tolerable.

To determine the maximum performance characteristics of our experimental type of multipass amplifier, we optimized mirror reflectivities and numbers of passes for maximum output under the constraint of the self-lasing threshold. The net unsaturated gain is given by

$$G_{net} = (1 - R_1)(1 - R_2)(R_1 R_2)^{(k-1)/2} (GT)^k. \quad (31)$$

Optimizing R_1 and R_2 for maximum G_{net} gives

$$R_1 = R_2 = (k-1)/(k+1) \quad (32)$$

and

$$G_{net|max} = \left(\frac{4}{k^2 - 1} \right) \left[\left(\frac{k-1}{k+1} \right) GT \right]^k. \quad (33)$$

However, this optimization holds only for those values of GT and k that keep the multipass amplifier below threshold. The self-lasing threshold is given by $SG_m = 1$, where S is the backscattering fraction discussed earlier and G_m is the gain at threshold seen by ASE between scatterings from the beam dumps. Therefore, larger values of GT and k require that the optimization of R_1 and R_2 be constrained such that $SG_m \leq 1$. Since ASE makes one more pass than the pulse, the self-lasing constraint is

$$G_m = [R_1 R_2 G^2 T^2]^{[(k+1)/2]} < \frac{1}{S}. \quad (34)$$

Optimizing Eq. (31), subject to Eq. (34), gives

$$R_1 = R_2 = \left[S^{1/(k+1)} GT \right]^{-1} \quad (35)$$

and

$$G_{net|max} = GT(1 - R_1)^2 / S^{(k-1)/k+1}. \quad (36)$$

Optimum reflectivities and unsaturated gain values are, therefore, given by either Eqs. (31) and (32) or Eqs. (35) and (36), whichever pair gives the smaller reflectivity values.

Figure 2-184 shows the unsaturated $G_{net|max}$, given by either Eq. (33) or Eq. (36), plotted against GT . Results for several values of k are shown with $S \approx 3 \times 10^{-5}$, the experimentally determined value. The straight-line positions of each curve reflect Eq. (33), and the curved sections are given by Eq. (36), where the reflectivities are constrained to remain below the lasing threshold; the mirror reflectivities are constant for the straight-line sections but vary continuously for the curved sections. Figure 2-184 shows that very large unsaturated gains are possible from this type of device, comparable to or even slightly larger than G_m . However, saturation reduces G_{net} very rapidly as the output fluence increases.

Fig. 2-184. Net unsaturated gain of an off-angle multipass amplifier maximized by varying mirror reflectivities, subject to the self-lasing constraint. S = backscattering fraction; k = no. of passes.

Fig. 2-185. Net saturated gain of an off-angle multipass amplifier that was optimized for maximum output by varying mirror reflectivities and number of passes. Terms are defined as for Fig. 2-184.

We calculated the expected saturation using the recurrence relations of Ref. 101 for the increase in pulse fluence and the decrease in amplifier gain on each pass. Figures 2-185 through 2-187 show results optimized for $G = 7.4$ and $T = 0.82$. We obtained Fig. 2-185 by varying R_1 , R_2 , and k to give the

Fig. 2-186. Optimized values of mirror reflectivities that were used in computing curves shown in Fig. 2-185. The solid and dashed lines are for $S = 10^{-4}$ and $S = 10^{-5}$, respectively.

Fig. 2-187. Saturation characteristics of two specific multipass amplifier designs optimized for saturated gains (G_{sat}) of 1000 and 100. For G_{sat} of 1000, the optimized parameters were found to be $R_1 = 0.72$, $R_2 = 0.18$, and $k = 11$; for G_{sat} of 100, the optimized parameters were found to be $R_1 = 0.88$, $R_2 = 0.32$, and $k = 7$.

maximum saturated gain at a given output fluence, subject, as before, to the self-lasing constraint of Eq. (34). The two sets of curves are for S values of 10^{-4} and 10^{-5} , which bracket the experimental value; they show that net gain at a given output fluence is

roughly proportional to $1/S$ but that the highest output fluence is insensitive to S . The arc segments on each curve show where the given number of passes optimizes performance. Figure 2-186 shows the optimum R_1 and R_2 values corresponding to Fig. 2-185. Together, Figs. 2-185 and 2-186 show a large range of optimized performances for reasonable values of mirror reflectivities and numbers of passes.

Figure 2-187 shows saturation characteristics—net output fluence vs input fluence, both normalized to the amplifier saturation fluence and optimized for saturated gains of 1000 and 100—for two multipass amplifier designs. For both cases, $G = 7.4$, $T = 0.82$, and $S = 10^{-4}$, the latter being three times smaller than the measured value to provide a reasonable safety margin. The major difference between these saturation characteristics and those of a linear chain of amplifiers occurs at high output fluences: there is a maximum output fluence for the multipass amplifier that cannot be exceeded by overdriving, but the output from a chain amplifier continues to increase with increasing input.

Summary and Conclusions. We have tested several rectangular-disk amplifier prototypes to accurately simulate the performances of Nova amplifiers. Tests made with differing flashlamp reflectors, numbers of flashlamps, pumping configurations, and glasses give us great confidence that we can predict amplifier performance with high precision. From these tests, we have arrived at design guidelines for optimizing optical performance. (A second set of guidelines is necessary so that mechanical, electrical, and longevity requirements are met; these guidelines are described in "Mechanical Subsystems," above.) The optical pump-cavity guidelines are

- Minimize cavity volume.
- Maximize wall reflectivity.
- Minimize light leaks.
- Prevent lamp self-absorption.
- Minimize nonreflective surfaces.

These guidelines, used in the final Nova amplifier designs, will produce the most effective solid-state laser amplifiers.

The most promising application for a multipass amplifier is as a large-aperture driver stage for the final output stage of a laser chain. The saturated

gain of 100 obtainable from the multipass amplifier means that this amplifier could be driven from a preamplifier whose aperture is 10 times smaller. For example, a 460-mm multipass amplifier for Nova could be driven from a 50-mm rod amplifier, eliminating the 100-, 150-, 208-, and 315-mm Nova stages. To match the performance of the linear-chain amplifier for Nova, the multipass amplifier would require a booster amplifier between it and the three-head Nova output stage.

Initial estimates show that costs and performances of the two types of amplifier—multipass and linear-chain—would be comparable; however, two potential operating advantages would result from using the multipass amplifier. First, the threat of damage would be entirely eliminated in the multipass amplifier (the linear-chain amplifier has potential damage fluences at the output of each intermediate stage), and the threat of damage due to operational error is eliminated because the multipass amplifier cannot deliver more than its designed maximum output (too much drive reduces the output). Second, the multipass amplifier trades the very large number of small, different parts used in linear-chain amplifiers for a few very large, similar parts, resulting in potential inventory and maintenance savings.

The greatest potential for improvement of the multipass amplifier lies with the development of a large-aperture switch that, used as a cavity dumper, would allow the use of maximum-reflectance mirrors, thereby greatly increasing output fluence. The switch would not be required to provide discrimination against prepulses because the off-angle nature of the multipass amplifier allows the prepulses to be removed with a spatial filter. Thus, the off-angle multipass amplifier eliminates the need for large extinction ratios in the large-aperture switch and increases the probability that such a switch could be developed.

The multipass amplifier will not be used on Nova because its advantages are insufficient to offset the cost and time required for further development. This type of amplifier may, however, find application to other types of laser systems.

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Oscillator Development

The actively mode-locked, Q-switched (AMQ) oscillators have continued to work reliably with Argus and Shiva. During 1979, therefore, we directed our main effort toward improving these oscillators in the following ways:

- Making the oscillator systems easier to assemble and maintain, and making them easy to modify for future developments.
- Improving system reliability.
- Making electronic controls more immune to electrical noise.
- Improving the reliability of single-pulse switchout.
- Improving the output-beam quality of the oscillators.

We also started design and implementation of a system of two oscillators and a regenerative amplifier, which we plan to install on Shiva during the first half of 1980.

We established Nd:YLF as the baseline oscillator material for Nova after evaluating two alternative materials for this application: Nd:YLF at 1.053 μm , and Nd:YAG at 1.052 μm . Although characterization of these two systems has not yet been completed, we favor the 1.053- μm line in YLF.

This line is further away from the peak gain in fluorophosphate glasses (approximately 1.051 μm) than the 1.052- μm line in YAG, but the much higher gain line at 1.064 μm in YAG is difficult to suppress in the oscillators and even more difficult to suppress in the preamplifiers. Consequently, we decided that Nd:YLF was the better choice.

New Argus Oscillator. Early in 1978, after completion of the Shiva oscillator, we started a major redesign of the AMQ oscillator. The objective of this redesign was to obtain an oscillator that was easier to assemble and maintain, that retained the good mechanical stability of the Shiva oscillator, and that could easily be modified for additional components and future uses. This redesign effort in 1979 led to the construction and assembly of five new oscillators, which were disposed of as follows: we installed a new AMQ oscillator on Argus and another on ILS (a small laser system used to support research and development on solid-state lasers); we are debugging a new AMQ oscillator and a single-axial-mode, long-pulse oscillator for Shiva; and we are assembling a regenerative amplifier for Shiva. The success of our redesign effort was demonstrated by the fact that the basic oscillator package could easily be modified to a single-axial-mode, long-pulse oscillator with a short (~ 400 mm) laser cavity and no modulator, whereas the regenerative amplifier required a 1600-mm long resonator structure. In comparison, the standard AMQ oscillator has a 1300-mm resonator. We can also easily convert the single-axial-mode, long-pulse oscillator to a standard AMQ oscillator.

The new Argus oscillator, which is representative of these five new oscillators, is shown in Fig. 2-188. For the baseplate of this Argus oscillator, we chose the NRC-type breadboard plate. This is a 2-in.-thick honeycomb-core structure with a pattern of 1/4-20 holes on 1-in. centers. This structure has good damping and rigidity properties, and the hole pattern allows very flexible positioning of components. This flexibility is further enhanced by mounting the pump cavity, modulator, Q-switch, and intracavity shutter on slotted plates, which in turn are mounted on the baseplate.

The resonator structure is kinematically mounted on the baseplate. Note in Fig. 2-188 that the resonator structure consists of four 1-in.-diam

Fig. 2-188. The new Argus oscillator.

Invar bars with aluminum spacing plates. The intracavity elements, such as the etalon mount, the iris mount, and both mirrors, are attached to these spacing plates, which slide on the Invar bars. Design flexibility is further enhanced by mounting the etalon and iris mounts in slots on the spacing plates.

Other important features of the Argus oscillator are a He-Ne alignment-laser device mounted inside the oscillator structure and a Q-switch mounted on an adjustable up-down slide. Since we are using an acousto-optical Q-switch (with the acoustic beam propagating downwards from the transducer at a speed of 5.96×10^5 cm/s), the up-down adjustment allows the Q-switch delay time to be mechanically adjusted by about 1 μ s. This is a handy feature for synchronizing the buildup time of several oscillators.

Figure 2-189(a) shows the pump cavity for the Brewster's-angled YAG (or YLF) rod. The elliptical reflectors can easily be removed for inspection of the pump cavity. Figure 2-189(b) shows the etalon carousel, with space for up to five etalons. In operation, this carousel allows the laser operator to easily select a particular etalon without removing any optical components; any pulse from 100 ps to 1 ns can

be selected in a matter of minutes by selecting the right etalon and by adjusting the rf drive to the modulator. Figures 2-189(c) and 2-189(d) show the modulator and Q-switch mounts, respectively. In both devices, the substrate mount can easily be removed from the housing for inspection. Note, also, the adjustable up-down slide for the Q-switch.

In daily operation, the Argus oscillator has been very stable and reliable. Usually, the oscillator comes up perfectly mode-locked and Q-switched, with no adjustment being required. The successful design of this oscillator was further tested by an unscheduled drop-test during the magnitude 5.5 earthquake at Livermore on January 24, 1980: the oscillator fell off the table. After some minor repairs on the cables and a slight readjustment, the oscillator worked perfectly.

Figure 2-190 shows the pulse width for the Argus oscillator as a function of the dB setting of the attenuator on the modulator driver for various etalons. With two etalons, we can span the range from 100 ps to 1 ns. Note that the coated 9.5-mm etalon with 10% reflectivity did not stretch the pulse by much more than could be achieved with the 11-mm uncoated etalon. Operation of the oscillator with a 30% reflecting etalon was very poor, with the oscillator going out at strong rf drive and with no

Fig. 2-189. Oscillator components: (a) pump cavity, (b) etalon carousel, (c) modulator, (d) Q-switch.

mode-locking at weak rf drive. With an etalon somewhat longer than 9.5 mm, and with reflectivity more than 10% but less than 30%, we should be able to obtain somewhat longer pulses; however, even under optimum conditions, pulses longer than 1.3 ns cannot be expected from this device. In operation, the calibration curve shown in Fig. 2-190 is quite reliable, allowing the laser operator to select the desired pulse width by selecting the etalon and rf level from the curve. Note that, on this calibration curve, the pulse width flattens out at high rf drive due to saturation of the rf amplifier, at which point the output of the oscillator drops by about 50%. With the rf drive less than about -25 dB, the noise level between pulses becomes measurable and then increases rapidly with decreasing rf drive. The useful rf-drive level to the modulator for this device is between the -5 dB and -20 dB settings on the attenuator, allowing very good operation from 100 ps to 1 ns.

Along with the redesign of the oscillator, we also reviewed all the electronic controls, and we made many changes to improve noise immunity. These changes led to a very reliable control package for a single oscillator, and, with the modular features of the design, the controls can easily be expanded for multiple oscillators. This was done for Argus, where we developed a control package for two oscillators and a regenerative pulse compressor.

Single-Pulse Switchout System. In all of the single-pulse switchout systems with the AMQ oscillator, we have used a 10-mm-diam. dual-crystal KD*P Pockels cell with a half-wave voltage of about 3.7 kV (3.2 kV static half-wave voltage). In past years, we developed a high-voltage driver consisting of an 8-parallel, 14-series avalanche transistor stack with a rise time of a few nanoseconds. These devices were very successful, with some

Fig. 2-190. Calibration curve for Argus oscillator, showing range of pulses available.

achieving more than 10^9 shots; however, when these devices failed, they were sometimes difficult to repair. Also, transistor characteristics were uncertain from batch to batch, requiring extensive selection of transistors. We found a better device in the

form of a planar triode, and the 1978 Annual Report¹⁰⁹ describes a typical circuit for one such device, the Eimac 8941 planar triode.

We built a switchout system for Argus that uses Eimac Y690 planar triodes (a 15-kV version of the Eimac 8941). To optimize the use of the Eimac Y690, we chose a line impedance from the tube to

the Pockels cell of $130\ \Omega$, which is obtained by making a twisted pair of the appropriate wires. With this impedance, we obtained the 3.7-kV voltage swing on the Pockels cell with the drive available at the grid of the tube, while still obtaining a reasonable rise time (~ 3 ns). The drive to the planar triode was obtained from four series 2N5551 avalanche transistors connected to the grid with a $50\text{-}\Omega$ line and matched into the grid through a bridge-T network. To obtain the desired 3.7-kV output, the grid had to be driven positive, drawing substantial current and mismatching the $50\text{-}\Omega$ input line, thus limiting the output-voltage swing. Also, we required in Argus a three-stage switchout system with three Pockels cells. Each Pockels cell requires its own planar triode drive, each of which is driven by a separate avalanche-transistor driver. Relative timing shifts between these drivers could cause problems; however, this arrangement provided a reliable solution for Argus.

A better switchout system is now under development for Shiva, where we use two or three tubes in parallel in the output stage for each Pockels cell. With this arrangement, we get enough current into a $50\text{-}\Omega$ line to swing 4.0 kV with approximately a 1-ns rise time. One planar-triode preamplifier stage then drives all the output stages, giving very low jitter between the output of each stage. Details of this design are given in "Fast Pulse Development," below.

Introduction of the planar triode for drivers of the switchout system provides a considerable improvement in reliability and maintenance, and we are continuing to develop these devices to improve the rise time. One application that we are now investigating involves slicing nanosecond pulses (ranging from 1 to 10 ns) from the output of a single-axial-mode, long-pulse oscillator.

Oscillator Beam Quality. When we first installed the AMQ oscillators on Argus and Shiva, we observed that the beam from the oscillator on the far field was about 20 to 30% elliptical, with the major axis horizontal. At the output of the oscillator, the beam has the same ellipticity but with the major axis vertical, as expected. In neither Argus nor Shiva does the oscillator beam shape determine the shape of the beam in the large-aperture part of the system; beam shaping there is done by a hard aperture. However, between the oscillator and the hard aperture, the beam ellipticity can cause unwanted

clipping and rippling on the beam further down the system.

The major components in the cavity—the modulator, Q-switch, and Nd:YAG rod—are all Brewster's-angle components, which are known to introduce some astigmatism into the cavity and cause an elliptical beam. Figure 2-191 shows the configuration for a Brewster's-angle component and defines the axes for this system. Note that, in the x-direction, the beam expands inside the component by the index of refraction, n , and this expansion causes the astigmatism in the cavity. The effective length for beam propagation through the optical element in the y direction is L/n , where L is the length of the component, and is the same as for a normal component. In the x-direction, however, the effective length is L/n^3 because the beam expands in this direction inside the component, as noted above.

When we consider a particular oscillator with a flat output coupler, a 3-m radius-of-curvature mirror, and a cavity length such that the round-trip time is 8 ns, we obtain the following spot sizes at the flat mirror: $\omega_x = 0.692$ mm and $\omega_y = 0.696$ mm. (We define ω as the beam radius at the $1/e$ amplitude of the beam.) These results obviously do not agree with our observed 20 to 30% ellipticity of the beam.

We carefully measured the spot size at the flat mirror of the oscillator by measuring the transmitted energy through a slit of known width in both

Fig. 2-191. Beam propagation through a Brewster's-angle component.

directions and then repeating this measurement for a range of slits that transmitted from about 20 to 90% of the incident energy. By this method, we measured spot sizes of $\omega_x = 0.52 \pm 0.02$ and $\omega_y = 0.61 \pm 0.02$, and we confirmed that the beam is indeed Gaussian.

We also have to take into account thermal focusing in the Nd:YAG rod. During development of the oscillator, this thermal focusing led to the use of repetitive pulsing instead of cw operation of the Krypton-arc pump lamps. If the rod has a thermal focal length, f_t , in the y-direction, then, in the x-direction, the effective focal length is $f_x = f_t/n^2$, where n is the index of refraction. This relationship is again due to the fact that the beam expands by the factor n in the x-direction inside the Brewster's-angle component. If we now calculate the spot size as a function of the focal length, f_t , which is the focal length that would be measured in a normal rod, we obtain the results shown in Fig. 2-192. When we made these calculations, we modified the effective mirror curvature in both directions by the thermal focal length, since the Nd:YAG rod is close to the curved mirror. In Fig. 2-192, we also plot the experimental spot-size measurements, and it is very clear that, indeed, the thermal focusing causes the beam ellipticity. The thermal focal length in the rod is approximately 11 m in the y direction.

So that we could keep a Brewster's-angle Nd:YAG rod in the oscillator systems, we designed a device to correct the ellipticity. The simplest solution is to put the asymmetrical beam through a prism, as shown in Fig. 2-193. This prism, which expands the beam in one direction, should be placed in the beam waist for both x and y directions; in practice, we put the prism as close as possible to the flat output coupler of the oscillator. The best design uses a prism with an angle between the faces less than about 10° and places the prism almost at Brewster's angle to the beam. In this way, we get very high transmission and small beam deviation.

In Fig. 2-193, we plot the beam magnification for a quartz prism, with angles from 1° to 10° , as a function of angle of incidence. All of these prisms have a maximum transmission of more than 99% for the angle of incidence between 55° and 60° ; in this range, the 6° prism gives the desired beam magnification for the Argus oscillator. The beam deviation we get with this prism is only about 6° .

Fig. 2-192. Ellipticity in output beam of oscillator caused by thermal focusing in Brewster's-angle rod.

Fig. 2-193. Magnification of beam by asymmetric propagation through a quartz prism.

We installed a 6° prism on the Argus oscillator and experimentally adjusted the angle until we obtained the same transmission through a slit in both horizontal and vertical directions. By this method, we obtained an angle of incidence of 64° , which implies a magnification of 1.34, a transmission of 98.8%, and a beam deviation of 7.2° . The beam ap-

peared to be circular in the far field. Thus, with this simple prism, we have obtained a method for easily correcting the astigmatism in the oscillator beam.

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Large-Aperture Harmonic Generation

In 1979, we began a research effort to support the harmonic conversion of Nd:glass fusion lasers to shorter wavelengths. In this effort, we are investigating the harmonic generation processes to maximize conversion efficiency and operational ease. To increase the usable beam area, we brought into existence the harmonic crystal array. Finally, we upgraded a 1-J, 1064-nm laser to provide a facility for measurements at the second, third, and fourth harmonics.

Harmonic Crystal Array. Harmonic frequency conversion of existing Nd:glass fusion lasers offers a cost-effective and rapid means to investigate the wavelength dependence of fusion performance. To make use of the full energy deliverable by the fusion laser, the clear aperture of the harmonic generator must be as large as the output aperture of the laser. For the Argus laser, this aperture is 28 cm. For the Nova laser, this aperture is 46 cm at the final amplifier position and 74 cm after the final spatial filter. The aperture requirement for the harmonic generator is illustrated (see Fig. 2-194) in relation to current industry single-crystal growth capability. It does not appear possible to grow single-crystal plates of 46- to 74-cm diameter by 1983 for use on the Nova laser. A different approach is required.

This approach is the *harmonic generator crystal array*. This device incorporates two or more nonlinear crystal segments in a planar array. Figure 2-195 illustrates several possible configurations. A basic necessity of the device is that each segment must be oriented to the phase-match direction. With this requirement, all array configurations fall into one of two classes:

- Those configurations which allow perimeter access to at least one edge of each segment.

Fig. 2-194. Harmonic generator apertures required for fusion lasers. The Argus output aperture is 28 cm. The Nova output aperture is 46 cm at the final amplifier and 74 cm after the final spatial filter. The Nova harmonic crystal aperture requirement is bounded by these apertures. At present, the maximum clear aperture obtainable in single-crystal form is approximately 15 cm.

- Those which do not.

For the first category, phase-matching alignment can be achieved by holding each segment along its accessible edge(s); orientational adjustments are then performed by conventional micrometer screws associated with the holders. This arrangement is illustrated schematically in Fig. 2-196 for a 2 by 2 array.

For the second category, the static housing design must provide fixed alignment of all the crystal segments which have no edge access. Furthermore, this design must hold the interior segments securely in place with a mechanism that will not lead to optical damage. These are significant additional requirements. In 1979, we concentrated on the development of the 2 by 2 array. Two 2 by 2 KDP array prototypes of 5- and 10-cm clear apertures were constructed and are pictured in Fig. 2-197. We measured their performance in four key areas¹¹⁰:

- Alignment stability.
- Wavefront distortion.
- Conversion efficiency.
- Obscuration/diffraction.

The mechanical stability of our 2 by 2 array housing is excellent and fully adequate to preserve phase-matched alignment.

Fig. 2-195. Harmonic crystal array configurations: 1 by 2, 2 by 2, 3 by 3, 2 by 4, and 4 by 8.

We measured good wavefront distortion on the first set of carefully fabricated crystal segments (10-cm array). Figures 2-198(a) and 2-198(b) display the dry and oil-filled wavefront interferograms, respectively, of the 10-cm array. We learned that blocked polishing is important to minimize edge and corner roll-off. This effect is visible in Fig. 2-198(a) on one segment which was polished individually; the other three segments were polished with a fourth segment in a set. We also verified that our segment holder design caused no distortion on the outer edge of the segments. Note the straightness of the fringes at the edge of the clear aperture in Fig. 2-198(a).

We compared the conversion efficiency of our 5-cm array prototype with a single crystal, using identical laser input quality. The laser beam used was approximately 3 cm in diameter ($1/e^2$) and was centered in the array aperture for realistic illumination of the gaps between crystal segments. The data are illustrated in Fig. 2-199. After normalizing for

the different crystal thickness and cuts, the performance of the two generators is identical.

The array conversion efficiency is negligibly affected by the gap regions. This is consistent with the amount of obscuration presented by the gaps. For the 5-cm array having a 0.3-mm gap width, less than 2% of the area of the array is gap area. (For a 60-cm 2 by 2 array with 0.5-mm gap width, 0.2% of the aperture is gap area.) Diffraction at the segment edges has little effect on overall conversion efficiency within the crystal because the crystal thickness is small relative to the diffraction length. This situation is illustrated in Fig. 2-200, where we show photographs of the beam profile of unconverted (1064-nm) light and second harmonic light generated in the 5-cm prototype. The photographs show the beam profiles at three different locations beyond the array. At the closest location, the fundamental and harmonic beams show little modulation, accounting—along with the small gap area—for the negligible effect on conversion efficiency from the gap regions.

Fig. 2-196. Schematic design of a 2 by 2 harmonic crystal array. Each crystal segment is held and oriented for phase matching by its holder assembly. The segment assemblies are contained within the array housing (indicated by the dashed perimeter) which permits filling with index-matching fluid.

Fig. 2-197. Photographs of 2×2 array prototypes: (a) 5-cm aperture, (b) 10-cm aperture.

The expected development of far-field intensity modulation due to diffraction by the segment edges is evident in Fig. 2-200. Optimized index-matching fluids and the technique of image-relaying can be used to minimize this modulation. Its impact must be considered in the overall design of a fusion laser system.

In summary, during 1979 we designed the first harmonic crystal array, constructed and tested two prototypes, and measured their performance

characteristics. The encouraging results point the way for frequency multiplication on the Nova fusion laser.

Upgraded 1-J Laser for Harmonic-Wavelength Experiments. Since 1973, the 1-J Nd:YAG-glass laser, named ILS,¹¹¹ has been dedicated to damage threshold,¹¹² nonlinear refractive index,¹¹³ and

Fig. 2-198. Transmission wavefront interferograms of (a) dry and (b) index-matching-oil-filled 10-cm 2 by 2 array prototype. The edge roll-off evident in (a) on the lower-right segment was eliminated in the remaining three segments by polishing in blocked formation. For the oil-filled array (b), these 0.6328- μm interferograms indicate a wavefront distortion at 1.064- μm of approximately $\lambda/6$. Distortion at this level is very good for this prototype. (Crystals furnished by Interactive Radiation.)

other basic measurements. In 1979, we upgraded this laser to facilitate measurements at the second, third, and fourth harmonics of 1064 nm. The major

improvements are variable pulse duration capability, preamplifier repetition-rate, and output energy stability. Figure 2-201(a) is a schematic diagram of the laser components and experimental areas and Fig. 2-201(b) is a photograph of the upgraded ILS laser.

Fig. 2-199. Second-harmonic conversion efficiency for the 5-cm 2 by 2 array vs a single crystal. The solid points illustrate that the array conversion efficiency is not significantly reduced by the intercrystal gap regions. The array raw data (open circles) were scaled to remove the effect of its Type II cut and different thickness, using the relation $\eta_{II} = \tanh^2(1.59 \tanh^{-1} \sqrt{\eta})$, where η is conversion efficiency for Type I or Type II and 1.59 is the ratio of the nonlinear coefficients and crystal thicknesses.

The actively mode-locked and Q-switched oscillator (AMQO) features state-of-art stability in pulse duration and pulse-train energy stability. (See article on "Oscillator Development.") The single-pulse switchout (SO) employs no spark gap. The SO timing is electronically selectable in 1-ns increments referenced to the opening of the AMQO Q-switch. The high-voltage Pockels cell firing pulse is obtained from a planar-triode amplifier circuit (see article on "Fast Pulse Development") This switchout stability and the properties of the AMQO result in a single-pulse output that is reproducible to better than $\pm 5\%$. The pulse duration is continuously selectable over the range 1.0 to 0.1 ns.

The switched-out pulse (~ 0.2 mJ) is amplified by two YAG preamps of 10-mm aperture. The preamps were designed by the Component Development Group to provide high-gain and low-thermal lensing at a 1-Hz pulse repetition rate. A Pockels cell isolator (PCI), driven electronically, provides gain separation between the preamps at the 1-Hz firing rate. The preamplified pulses (≤ 40 mJ) at 1 Hz are very useful for rapid alignment of harmonic generation crystals in experiments at harmonic wavelengths.

Fig. 2-200. Spatial-profile photographs of the second-harmonic (532 nm) pulse generated in the 5-cm 2 by 2 array, and of the remnant fundamental (1064 nm) pulse at 0.2, 2.0, and 6.0 meters beyond the array. These photographs illustrate the development of diffractive modulation from the crystal edges as the pulses propagate away from the near field.

Fig. 2-201. (a) The ILS laser system, upgraded by new actively mode-locked and Q-switched oscillator (AMQO), electronic switch-out (SO) and Pockels cell isolator (PCI), high-repetition-rate preamps (PA1, PA2), vacuum spatial filter (SF), spodizer (A), and Faraday rotator isolators (FR1, FR2). A1 and A2 are 16-mm and 32-mm Nd:glass amplifiers. (b) Photograph of the ILS laser.

Fig. 2-202. Harmonic crystal alignment technique suited to low-repetition-rate lasers. A negative lens (b) is used to illuminate the harmonic crystal with a cone of light rays, distributed about the beam line defined by the cross hairs (a). The phase-matching ("sync") pattern (d) is recorded on film; its location, relative to the cross-hair center, indicates the direction for rotating the crystal into best phase matching (c). This technique typically requires three to four laser shots.

The preamp output pulse is spatially smoothed and expanded in a vacuum spatial filter/telescope (SF). The pulses may then be diverted to an area for low-energy/high-repetition-rate experiments or directed into the main amplifier chain. Faraday rotators (FR1, FR2) and a second expanding telescope (T) separate the 16-mm and 32-mm Nd:glass (ED-2) amplifiers (A1 and A2). The final amplifier restricts the pulse repetition rate to $(5 \text{ min})^{-1}$. Output energy of 1 J or more can be extracted over the full pulse-duration range in a smooth, well-behaved pulse. The pulse-to-pulse energy reproducibility is $\pm 5\%$.

The laser output is then directed to one of several experimental areas and converted by harmonic generation to the required wavelength. We developed a simple technique to align the harmonic crystals for maximum energy conversion. This technique, described in Fig. 2-202, is particularly suited to large-aperture, low-repetition-rate lasers because it requires few laser shots.

In 1979, the upgraded ILS laser was used for experiments on harmonic generation conversion efficiency, harmonic crystal array evaluation,¹¹⁰ and on 266-nm laser-induced damage (see article on "Damage Studies").

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Large-Aperture Pockels Cells

Introduction. We are considering using 10-cm clear aperture KD*P Pockels cells for use on Nova for suppression of amplified spontaneous emission.

We have examined several configurations for this large Pockels cell including conventional cylindrical ring electrode (CRE) cells,¹¹⁴ contacted liquid electrode (CLE) cells, and isolated liquid electrode (ILE) cells. We also considered other designs using transparent conductive coatings, grid electrodes, high-field dielectric pusher geometries and new materials. In the following paragraphs, we describe the design and trade-offs associated with each configuration.

Cylindrical Ring Electrode Cells. Conventional CRE cells require a crystal length to aperture ratio of 1.0 to 1.3 depending on the desired field uniformity. This very large aspect ratio requires a very large crystal of KD*P with the associated problems of cost, growth time, crystal quality, and yield. This technology is well-known, however, so that newer designs must offer some competitive advantage in order to be considered.

Figure 2-203 shows the CRE geometry. The capacitance of the crystal with electrodes for a length to diameter ratio of 1.3 is

$$C \approx \frac{\pi K^2 \epsilon}{2(L - W)} \approx 54 \text{ pF}, \quad (37)$$

using a 50- Ω driver. This would result in an electrical rise time of $\tau_{0.95} = 3RC \approx 8.2 \text{ ns}$. A summary of the characteristics of a 10-cm CRE cell is given in Table 2-47. V_π is the drive voltage necessary to produce π rad retardation. The transmission loss is based on the attenuation of 0.006 cm^{-1} observed in the 90% deuterated KD*P crystals in the Shiva β (5 cm) Pockels cells and assumes AR coated, index matched windows. The B nonlinear growth coef-

Fig. 2-203. Cylindrical ring electrode (CRE) geometry.

Table 2-47. 10-cm Pockels cell summary.

Type	CRE	CLE	ILE	Pusher
Risetime	8 ns(50 Ω)	6 ns(10 Ω)	<10 ns(50 Ω)	<10 ns
Voltage ($\times V_m$)	1.3	1.1	3.1	>5
Transmission	0.90	0.97	>0.97	>0.97
Crystal volume (cm^3)	900-1100	200	200	200
B	0.9	0.8	0.35	0.3

Table 2-48. Liquid electrodes for CLE Pockels cells.

Solvent	Refractive index (n_o)	Dielectric coefficient (ϵ)	Nonlinear coefficient [$\sim \gamma (\cdot 10^{16} \text{W/cm}^2)$]	Attenuation coefficient [$\alpha (1.064 \text{cm}^{-1})$]	Resistivity [$\rho^a (\Omega \text{cm})$]
Acetonitrile	1.344	7.5	28 ^b	0.008	16
Acetone	1.359	20.7	4.2 ^b	0.0305	28
Acrylonitrile	1.391	33.0	13.7	~0.008	17
Benzonitrile	1.529	25.2	77	0.008	76

^aLowest observed with silver perchlorate or tetraethyl ammonium fluoroborate electrolytes.

^bMeasured.

ficient assumes 13 cm of KD*P and two 2-cm fused silica windows, and $3 \times 10^9 \text{ W/cm}^2$ incident on the cell and given by,

$$B \approx \frac{2\pi}{\lambda} \sum \gamma_i l_i, \quad (38)$$

where the γ_i are the nonlinear coefficients and l_i are the lengths of the components.

Contacted Liquid Electrode Cells. James Thorne at the University of Utah¹¹⁵ has found several solvent/electrolyte combinations that offer fairly low resistivity, high transparency to 1.05- to 1.06- μm light, and do not dissolve KD*P. A summary of their properties is given in Table 2-48. We have calculated the performance of a CLE cell based on the geometry in Fig. 2-204. We have assumed that the cell can be approximated by a parallel plate transmission line with capacitance, inductance, and resistance per unit length given by

$$\begin{aligned} C &= \frac{\epsilon \text{KD*P}}{36\pi} \cdot 10^{-11} \text{ b/a (f/cm)} \\ L &= 4\pi \cdot 10^{-9} \text{ a/b (H/cm)} \\ R &= 2 \frac{\rho}{tb} (\Omega \text{ 1 cm}), \end{aligned} \quad (39)$$

where a is the KD*P thickness, b is the crystal size, t is the electrode thickness and ρ is the electrode resistivity. Using Laplace transform techniques,¹¹⁶ we solve the transmission line equations for the elec-

trical rise time at the center of the cell. Driving a rectangular cell from two sides results in a rise time found from

$$\tau_{0.95} = 0.33 b^2 RC \text{ (2 sided)}. \quad (40)$$

A circularly driven cell has a rise time of

$$\tau_{0.95} = 0.15 b^2 RC \text{ (circular)}. \quad (41)$$

We choose to approximate the cell with the relation,

$$\tau_{0.95} = 0.25 b^2 RC \quad (42)$$

The 10-cm KD*P crystal is assumed to have a thickness of 2 cm. This can be made smaller if desired at a greater fabrication and mounting cost. From Table 2-48, we use a resistivity of $\rho = 25 \Omega \text{ cm}$ and an electrode thickness of $t = 0.5 \text{ cm}$.

$$\begin{aligned} R &= 10 \Omega/\text{cm} \\ C &= 22.5 \text{ pF/cm} \\ \tau_{0.95} &= 5.6 \text{ ns}. \end{aligned} \quad (43)$$

This rise time assumes the cell is driven by a matching driver with impedance

$$Z \approx \frac{120}{\sqrt{\epsilon}} a/b = 10.5 \Omega. \quad (44)$$

Fig. 2-204. Contacted liquid electrode (CLE) geometry.

If we terminate the driving line close to the cell with 10.5Ω and calculate the rise time from total cell capacitance, we have

$$\tau_{0.95} \approx 3 RC_{\text{total}} = 7.1 \text{ ns} \quad (45)$$

This cell can be treated as a simple lumped capacitance as long as the electrode resistivity is less than $\sim 30 \Omega \text{ cm}$. Table 2-47 lists the characteristics of this cell assuming 2-cm KD*P crystals, 2-cm fused silica windows (AR coated), and 0.5-cm thick electrodes with refractive index 1.344 and resistivity $25 \Omega \text{ cm}$. B is calculated by summing the individual contributions as for the CRE cell. As can be seen from the table, the reduction in crystal volume and increased transmission are significant. There is a penalty in rise time if the driver impedance remains at 50Ω . A question which must be answered about the CLE cell is the effect of stimulated scattering processes such as stimulated Raman and Brillouin scattering in the liquid electrode.

Isolated Liquid Electrode Cells. If the crystal is isolated from the electrode by a window, then a dramatic reduction in electrode resistivity can be obtained. J. Thorne¹¹⁷ tested many liquid/electrolyte combinations and has found that a 6 N solution of deuterium chloride in heavy water has a resistivity of $2 \Omega \text{ cm}$ and has excellent transmission characteristics. Other electrolytes (such as fuming nitric acid) were rejected for materials compatibility reasons and/or because their resistivity was higher.

Figure 2-205 shows a geometry for the ILE cell. A thin window isolates the crystal. The window can

Fig. 2-205. Isolated liquid electrode (ILE) geometry.

be index matched to the KD*P and to the electrode by selecting the glass (or other material) and adding ZnCl_2 to the electrode liquid to raise its index. The insertion of the thin window results in a decrease in the voltage across the KD*P. The window acts as a capacitive voltage divider. The voltage across the crystal is given by

$$V_{\text{KD*P}} = V_0 \left(\frac{\epsilon_2 t}{2\epsilon_1 d + \epsilon_2 t} \right) \quad (46)$$

where ϵ_1 is the dielectric coefficient of the KD*P and ϵ_2 is the dielectric coefficient of the window. If we use a 2-cm KD*P crystal and 0.2-cm isolation windows, the voltage across the crystal is

$$V_{\text{KD*P}} = 0.33 V_0 \quad (47)$$

We can increase this voltage by increasing the crystal thickness or decreasing the window thickness. The rise time of this cell is reduced since the capacitance per unit length is smaller,

$$\begin{aligned} C &= \left(\frac{1}{C_{\text{KD*P}}} + \frac{2}{C_{\text{window}}} \right)^{-1} = 7.4 \cdot 10^{-12} \text{ F/cm} \\ L &= 4\pi \cdot 10^{-9} \frac{a+d}{b} = 3 \cdot 10^{-9} \text{ H/cm} \\ R &= \frac{2\rho}{tb} = 0.2 \Omega/\text{cm} \\ Z &\approx \sqrt{L/C} \approx 20 \Omega \\ \tau_{0.95} &\approx 0.25 b^2 RC = 0.1 \text{ ns} \end{aligned} \quad (48)$$

Driven as a capacitor from a $50\text{-}\Omega$ line, the cell has a rise time of $\tau \approx 3RC = 11 \text{ ns}$. We can expect this cell to be limited by the driving circuitry. Table 2-47

lists the characteristics of the ILE cell using 2-cm KD*P, 0.2-cm electrodes of 2 Ω cm resistivity, 0.2-cm isolation windows, and 2-cm external windows of fused silica with no index matching. The drive voltage can probably be reduced to $2\sqrt{V\pi}$ without great difficulty.

Dielectric Pusher Cells. The CRE electrode geometry is part of a general class of configurations that trade off crystal geometry, field uniformity, and drive voltage. In the case of the CRE cell, the high dielectric constant of the crystal and an increased crystal length are traded to place the electrodes outside the clear aperture without increasing the drive voltage appreciably. Figure 2-206 shows an example of a configuration in which the crystal is allowed to become thin. To obtain a uniform field as large as possible in the crystal, high dielectric coefficient material is used to "push" the field from the electrodes. Our example could have the following values:

$$\begin{aligned}\epsilon_1 &= 20 \text{ (ceramic)} \\ \epsilon_3 &= 2 \text{ (teflon)} \\ \epsilon_4 &= 5 \text{ (glass)} \\ \epsilon_5 &= 77 \text{ (D}_2\text{O)} \\ \epsilon_6 &= 5 \text{ (glass)}\end{aligned}\quad (49)$$

Field calculations have shown that this technique can produce extremely uniform fields in the KD*P. This comes at a penalty of increased drive voltage ($>10\sqrt{V\pi}$) in most cases. This technique looks very promising but requires new types of drivers to be usable. Table 2-47 lists the characteristics of this design.

Fig. 2-206. A dielectric pusher Pockels cell geometry. The various materials are used to maximize the crystal field while preserving field uniformity.

Other Techniques for Large-Aperture Cells. A grid placed on the crystal or on a window can be used to apply a field. The diffraction from the electrode wires may not be a serious disadvantage since we are considering segmentation of amplifier disks and frequency conversion crystals.

Conductive film electrodes of indium/tin oxide have been produced with resistivities as low as 0.017 Ω cm (Ref. 118). The thickness of the film ($\sim 3.4\ \mu\text{m}$) meant that the resistance was

$$R = \frac{2\rho}{tb} = 100\ \Omega/\text{cm} \quad (50)$$

for a 10 cm wide electrode. This results in a rise time an order of magnitude longer than for the CLE cell. These electrodes showed a 3% transmission loss. Although the damage thresholds are high ($>3\text{J}/\text{cm}^2$), the resistivity must drop or the transmission must increase (using thicker layers) before this technique is competitive with liquid electrodes.

Other materials available for the active materials such as lanthanum doped lead zirconate-titanate (PLZT) are too slow ($>100\text{ ns}$) due to a combination of high dielectric coefficient and low response times.¹¹⁹

Summary. Liquid electrode Pockels cells look very promising for reducing crystal volumes in large aperture devices. Crystals of KD*P have been ordered for delivery early in 1980 that will be used to build 5-cm clear aperture prototypes of ILE and CLE cells. The same crystals will also be used to test grid electrode and dielectric pusher geometries.

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Compensated Pulsed Alternator

The compensated pulsed alternator (compulsator) is a device for mechanically (rotationally) storing energy, taken at low power from the utility company, and converting it into electrical energy at very high power levels. The interest in this device stems from a desire to find an alternative to expensive and bulky capacitive energy storage for very large loads, such as the Nova flashlamps. The theory of operation of the compulsator has been described elsewhere.^{120,121} Basically it is a single-phase alternator that utilizes principles of flux compression and inductance compensation to provide a very high power output pulse.

A prototype compulsator was built by the University of Texas' Center for Electromechanics (CEM) at their Austin laboratory. This machine is eventually expected to deliver 180 to 200 kJ of energy into a load comprising 16 parallel Shiva laser flashlamps. The machine has been mechanically spun to its 5400-rpm design speed, and successfully discharged at 4839 rpm, delivering 139 kJ at 113 MW peak power to the flashlamp load.

An electrical flashover across the output terminals on the first 5400-rpm electrical run caused runaway thermal damage to the windings at several "hot spot" locations. Approximately 2 MJ of energy were divided between the fault and the machine windings during the discharge. (The machine rotor stores 3.5 MJ at 5400 rpm.) Except for the hot-spot damage, the rotor and its windings survived the fault intact. These are the Litz-wire wave-windings, with glass-epoxy insulation, glued onto the smooth surface of the laminated-iron rotor. The fault proved that this method of construction is mechanically sound.

Two computer programs have been developed in this work. SCEPTR, at LLL, models the compulsator and its external circuitry, including the flashlamps. The model matches the measured current through the lamps with reasonable precision. It also provides any desired readout of other parameters, such as energy delivered to the lamps, torque on the machine rotor, and other data.

Another program, a space harmonic distribution analysis, is currently providing computations of the machine inductance variation vs angular position and current at CEM. This code will play a strong role in the development and cost optimization of future, large machines.

Current Program. The scope of the present work is to rewind and continue testing the prototype, and to develop a design for a large machine that will deliver ~10 MJ into flashlamps, with at least 20 GW peak power. This is an order of magnitude beyond the present 2 or 3 GW power output of the largest rotating machines presently in use. A further purpose of the program is to explore compulsator designs that can be used for repetitively charging capacitive-type pulseline loads in 10 to 100 μ s. Machines with this capability are of interest as drivers for KrF and other advanced gas lasers.

Prototype Machine Design. The prototype compulsator, Fig. 2-207, is a four-pole, single-phase alternator with four stationary field coils. It has a 47-turn wave-wound rotating armature and a matching 47-turn wave-wound compensating winding located on the stator. The air and insulation gap between the two wave-wound conductors is 0.135 in. The magnetic air gap between the field poles and the laminated iron plates of the rotor is 0.857 in. The overall diameter of the rotor is 15.79 in., its length along the major axis is 47.36 in., and its overall length, including bearing journals and pulley shaft, is 79.38 in. The moment of inertia of the rotor is 22 (kg) (m)², providing 3.52 MJ of mechanically stored energy at 5400 rpm. The back iron assembly is 32.5 in. long by 40 in. square across the flats. This assembly, including bearing housings and support struts, weighs 16 600 pounds. The rotor weighs about 3000 pounds. The machine is suspended by compliant mountings in a torque frame comprising 4 by 8 by 1/2 in. box beams in an assembly that is 62 in. square by 72 in. high. The overall compulsator, including mounting frame, weighs 22 000 pounds. The machine is powered by a 125 hp dc motor with a 4.5-in. wide timing belt. See Fig. 2-208.

Each winding has an odd number of turns (47 instead of 48), to avoid crossovers which are difficult to insulate. This machine is unique in that regard.

Fig. 2-207. Prototype compulsator.

Fig. 2-208. Prototype compulsator in its torque frame, with drive motor and belt.

Crossovers also add inductance at the minimum-inductance position, thus reducing the peak power output. A slip ring, with a full 360° set of brushes (Fig. 2-209), is located on each end of the rotor. The

Fig. 2-209. Brush assembly exposed on the prototype compulsator.

Fig. 2-210. Simplified compulsator test circuit.

brushes at the bottom of the machine connect directly to the compensating winding on the stator after passing first through a vacuum interrupter switch. The top brushes connect to the hot output terminal; the top end of the stator winding connects to the output ground terminal.

Prototype Circuit Testing. One motivation for development of the compulsator is to replace capacitors for driving many thousands of flashlamps in a large laser system. An important part of the test program, therefore, was to verify that flashlamps can indeed be driven in parallel from a single, large source. A test setup was built at LLL for this demonstration.¹²² Parallel lamp balancing to within 1% was achieved with balancing reactors in each circuit. Balancing of 3% was achieved when simple inductors were used. Fault conditions were also simulated. Faults can readily be controlled with a high-voltage fuse in each lamp circuit.

A test circuit for the prototype compulsator was also built and tested. A simplified schematic of this circuit is given in Fig. 2-210, showing 16 parallel flashlamps, with balancing inductors and fault-protecting fuses. Negative 6 kV dc voltage is impressed across the flashlamps by the power supply and a startup capacitor which stores about 12 kJ

Fig. 2-211. Overlay of current traces from 8 of 16 parallel flashlamp circuits showing degree of balancing achieved. In this test, a 250-kJ, 7-kV capacitor bank was substituted for the prototype compulsator.

(the flashlamps self-break at 12 kV). This capacitor partially discharges through the lamps after they are initially ionized by a 30-kV pulse from a trigger reactor to the insulated metal flashlamp reflector.

Energy from the startup capacitor is also diverted through the compulsator via the main ignitron switch. Thus, this capacitor has a two-fold purpose:

- It provides energy to the flashlamps that expands the lamp arcs, thus reducing the lamp impedances.

- It drives an initial starting current through the compulsator windings, enabling greater flux compression and higher output current to be reached by the machine.

The circuit was tested by substituting a 250-kJ, 7-kV capacitor bank for the compulsator.¹²³ Figure 2-211 shows an overlay of the currents from 8 of the 16 total flashlamps during a 250-kJ shot. The parallel balancing achieved is graphically demonstrated by this picture.

Static Machine Testing. The rotor of the prototype compulsator was given mechanical vibration tests; the first resonant frequency was located at 97 Hz. This corresponds to a critical speed of 5820 rpm, well above the 5400-rpm design speed, thus proving that the laminated rotor was stiff enough for this high speed operation.

The inductance as a function of rotor angular position, measured with a 1 kHz bridge, varied from 26.3 μ H at zero degrees to 176 μ H at minus 74 mechanical degrees. In capacitor discharge testing, the inductance varied from about 28 to 225 μ H. Similarly, the series resistance, measured with the capacitor discharge test, varied from about 64 to about 564 m Ω with an approximate 1-cos (2- θ) waveform. This high, variable resistance is due to eddy currents that are induced in the nonlaminated pole pieces, in the stainless steel bars between poles, and in the laminated ends of the rotor, where the windings turn around the corner. It is estimated that up to half of the machine's output energy is being used, at the higher speeds, for driving these eddy currents. Thus, elimination or reduction of eddy currents will be a major issue in future large machine designs.

Dynamic Mechanical Machine Tests. The prototype machine was spun to 3750 rpm in an initial series of tests prior to balancing the rotor. When the displacement gages indicated that the rotor was vibrating beyond the acceptable excursion limit, testing was stopped. The rotor was then balanced by inserting tungsten plugs at pre-determined, off-center locations in rings around the shaft. Mechanical testing then continued on up to the 5400-rpm design speed.

Dynamic Electrical Discharge Tests. Electrical discharges were taken from the compulsator at speeds up to 5400 rpm. Data derived from 12 of

Fig. 2-212. Prototype compulsator output energy, delivered to 16 parallel flashlamps, vs speed.

these tests are plotted in Fig. 2-212. This graph shows how the energy delivered to the flashlamp load varies with the speed of the compulsator. This net energy apparently varies with the fourth power of the speed up to about 4200 rpm. Beyond that speed, eddy-current losses may become significant. As a result, the 4839-rpm test produced a net energy of 139 kJ to the lamps instead of the 214 kJ predicted by the fourth-power curve, $W = (\text{rpm}/225)^4$.¹²³

A 5400-rpm discharge test was also made, but an external fault across the machine terminals occurred before the load switches were triggered. Because of this, no energy was deposited in the

flashlamps. The machine delivered about 1 MJ of energy to the fault and windings in the first 10 ms and about 2 MJ total in the 40 ms duration of the flash. Thus, more than half of the rotor's total 3.5 MJ of energy was delivered. This caused overheating in the windings and stopped further tests until repairs are made.

The 16-flashlamp load circuit, Fig. 2-210, was used in all the electrical discharge tests. The startup capacitor comprised four 175- μ F units in parallel, charged to 5.6 or 6.0 kV. (Two additional runs were made using 10 parallel 175- μ F units at 6.0 kV.) The output pulse was initiated by bumping the flashlamp reflector and by triggering the ignitron switch. The timing of these triggers was adjusted so that the output pulse occurred on the positive voltage swing of the compulsator. The optimum firing angle was found to be at 90 electrical degrees before minimum inductance.

The net energy delivered by the compulsator to the flashlamps, Fig. 2-212, is calculated by subtracting the energy stored in the startup capacitor (e.g., 12.6 kJ for four 175- μ F capacitors at 6 kV) from the total energy delivered to the flashlamps. The total energy W_t was deduced from the oscilloscope traces of the flashlamp current by use of the formula,¹²⁴

$$W_t = f k i_p^{3/2} \Delta t \quad (51)$$

In this formula,

- f is a unitless waveshape form factor that varies from 0.8 minimum, for a triangular wave, to 1.0 maximum,
- k is the characteristic flashlamp constant ($k = 21.6 \text{ V} \cdot (\text{A})^{1/2}$ for 16 parallel 44-in. flashlamps, with 15-mm bore and 300-Torr Xenon fill).

i_p is the peak current (A), and

Δt is the current pulse halfwidth (s).

Computer Simulation. The compulsator's performance was modeled using the circuit solving computer program SCEPTRE. SCEPTRE uses a GEAR¹²⁵ integrator to simultaneously solve a set of differential equations derived from an equivalent circuit. In addition, SCEPTRE allows the simultaneous solution of auxiliary equations which enabled the dynamic, mechanical performance of the machine to be analyzed. SCEPTRE also allows any element to be input as an equation or FORTRAN subroutine, thus facilitating the simulation of nonlinear elements such as resistors and sources.

The equivalent circuit for the compulsator's electrical performance is given in Fig. 2-213. The source term E_{AC} represents the sinusoidal alternator voltage of the machine, which is a function of angular position and frequency (θ and ω). $R_{MACHINE}$ is the resistance of the windings; it is a function of energy deposited into the windings as heat. R_{EDDY} is an equivalent term representing the loss due to stray eddy currents in the machine; it is a function of mechanical angular position as well as frequency. $L_{MACHINE}$ is the inductance of the machine; it is a function of mechanical angular position. The source $dL/dt \cdot I$ represents the additional driving voltage due to flux compression. L_{CABLE} and R_{CABLE} are the cable inductance and resistance, respectively, for the cables between the machine and switch rack.

The ignitron is modeled by a nonlinear resistor which changes its impedance exponentially from 10^6 to $10^{-3} \Omega$ with a 3 μ s time constant. L_{CABLES} is the equivalent inductance for the 16 fan-out inductors and load cables. R_{CABLES} is the equivalent resistance for the 16 load cables. C_{PILC} is the start-

Fig. 2-213. Circuit schematic for computer simulation.

Fig. 2-214. Overlay of computer printout (dashes) on scope trace of flashlamp current for the 4839-rpm shot No. 121.

up capacitor which both preionizes the lamps and drives current through the machine to start the flux compression process. R_{LAMPS} is the equivalent impedance of the 16 parallel lamps. The lamp is a non-linear resistance. The lamp model used in these simulations is based on the work of Dishington, Hook, et al.,¹²⁶ who model the lamp impedance as a function of the energy deposited into the lamps.

Auxiliary equations to the circuit are the torque equation, the equation for the energy deposited into the machine windings, and the equation for the energy deposited into the flashlamps. The torque equation is given by

$$\dot{\omega} = \frac{1}{J_{\text{w}}} \left(-E_{\text{AC}} \cdot I_{\text{MACHINE}} + \frac{1}{2} I_{\text{MACHINE}}^2 \cdot \frac{dI}{dt} \right) \quad (52)$$

The accuracy of the computer simulations is best exemplified by Fig. 2-214, where computer data are overlaid upon a scope trace recorded during the 4839-rpm discharge. This close agreement was achieved via a parametric variation of elements within their known tolerance. During this parametric study, the large effect of the loss term, REDDY, was noted. In addition, it was found that the total energy delivered to the flashlamps was

limited by the resistances of the cables and of the machine.

Conclusions. Computer simulations will be most useful as a tool for predicting the performance of various compulsators. For example, future designs should strive very hard to eliminate the eddy current loss. Different inductance variations resulting from different winding configurations can also be studied without rewinding the machine each time. Thus, by computer modeling, the performance of large machines can be readily determined, enabling cost effectiveness to be predicted before costly construction begins. In summary, we feel that the compulsator concept is rapidly proving itself to be a viable alternative to very large capacitor banks.

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Plasma Shutter

Overview. An essential element in a laser fusion system is a device to stop (or minimize the amount of) the light retroreflected from the target that propagates back down the laser chain.¹²⁷ The two schemes previously used with glass lasers are a

Fig. 2-215. Laser light from the oscillator travels through the optical laser chain toward the target. Meanwhile, signals sent from the oscillator fire the plasma shutter with timing to block the laser chain at the output spatial filter against light reflected from the target.

Faraday rotator/polarizer¹²⁸ and an exploding mirror.¹²⁹ The Faraday rotator/polarizer combination is reliable but adds to the nonlinear optical phase contributions, and its cost increases dramatically with aperture size. An alternative candidate is an inline plasma shutter.

The logical location for a fast plasma shutter is contiguous to the final spatial filter pinhole. Assuming a pinhole aperture of 4 mm and distance to the target of 60 m, the pinhole must close with an average velocity of $> 3 \text{ cm}/\mu\text{s}$. Since the critical density for the absorption and reflection of $1.06\text{-}\mu\text{m}$ light is 10^{21}cm^{-3} , the shutter plasma must achieve this density, as a minimum.

Functionally, the plasma shutter creates a plasma from an exploded wire and propels it across the optical beam path, thereby blocking the beam.

The plasma shutter, located in the final spatial filter and shown schematically in Fig. 2-215, is comprised of a high-current pulser to vaporize and propel the wire, an adjacent control, firing, and

diagnostic package, and a wire changer. The controls insert a new wire, check for continuity, and check the trigger system and charge voltage. A fiber optic signal from the master oscillator initiates the firing sequence. Abort signals, in the unlikely event of prefire, are sent directly to the master oscillator to prevent optical switchout and amplification of the laser pulse. Current timing and amplitude are recorded to diagnose any degradation of the pulser module, and to permit preventive maintenance.

We are now finishing assembly of two prototype modules. One will be used to verify the plasma parameters, to characterize the high-voltage electronics, and to ensure high reliability and long life. The other module will be used to evaluate the controls, minimize emi, and test the wire changer.

The plasma shutter, shown in perspective in Fig. 2-216, contains the pulser module connected via a coaxial electrical feedthrough to the wire which is situated in the evacuated spatial filter housing. The pulser module contains all high-voltage components and trigger electronics within an electromagnetically shielded enclosure. Eight sym-

Fig. 2-216. Perspective view of plasma shutter showing location of pinhole and plasma in the optical beam path, pulser components, chip changer, and dump tank.

metrically placed capacitors are connected through four railgap switches to the coaxial feedthrough. A thin elastomer insulator separates the high voltage from ground and provides for the low-inductance current flow path required to produce a sufficiently high current to vaporize and propel the wire. The wire, a portion of the electrodes, and an insulating nozzle are formed into a "chip" which is automatically replaced after each shot.

Current flows from the low-inductance coaxial feedthrough into the wire, as shown in Fig. 2-217. The wire heats, vaporizes, and then expands across the beam path, being directed by the nozzle. Current continues to flow through the plasma as it moves, and is accelerated across the beam path axis by the magnetic pressure of the current that feeds it. This geometry is known as the plasma railgun. Optics are protected from the plasma because of its directed motion into the dump tank. Apertures and a weak magnetic field serve to skim off essentially all of the residual ionized particles that drift down the optical beamline.

In an earlier scaled experiment,^{130,131} we measured the plasma velocity with a Faraday cup and streak camera, and the plasma angular distribu-

tion with witness plates. These data plus the geometry permit us to establish the plasma density. The excellent agreement between the data and predictions of a detailed plasma code give us confidence in the design of the Nova prototype module.

We have, for the scaled experiment, demonstrated small signal closure with a probe laser, and assessed large signal closure with the LASNEX code. The plasma appears adequate to block the Nova laser beam and can be expected to block a beam 10 times as intense. We measured plasma leakage onto optics with a radiotracer, Faraday cup, and witness plates, and established that negligible leakage occurs.

The Nova plasma shutter is designed to produce a $1.5 \text{ by } 10^{21} \text{ cm}^{-3}$ plasma of singly ionized aluminum at 30 eV over a 6-mm-diam aperture. The 6.6-kJ stored energy from the 50-kV pulser produces the plasma from a 6-mm-long $\times$ 500- μm -diam aluminum wire. The plasma is moved into position in 400 ns, which is the roundtrip time for the laser light to travel from the shutter to the target and return.

Fig. 2-217. Expanded view of plasma gun geometry showing current flow to the wire, plasma location in the optical beam path, and plasma collection geometry.

Plasma Shutter Pulser Elements. The shutter pulser uses a purposely simple circuit, the components of which are shown schematically in Fig. 2-218. An equivalent circuit is shown in Fig. 2-219. The main discharge loop contains three elements: a capacitor, a switch, and an insulator. The 10 nH total inductance is equally distributed to these three elements. To obtain the appropriate inductance, each element contains parallel components.

The eight parallel capacitors have plastic cases and rail terminals but utilize the same internal construction as the reliable Sylac capacitors developed at LASL. The four parallel railgaps are more compact versions of the successful railgaps developed by Maxwell for the AFWL Shiva with the addition of preillumination. The insulator is the same silicone

material used throughout the LLL Shiva laser for flashlamp cable insulation. This is the first use of an elastomer as the major insulator throughout a pulse power system.

With this basic and proven technology, and with our development of the improved pre-illuminated railgaps and the first use of an elastomer (silicone) dielectric in a pulse power system, we have produced a pulser which is reliable and is an order of magnitude more compact than previous pulsers of equivalent output.

Details of the trigger gap and the railgap are shown in Figs. 2-220 and 2-221, respectively. The UV is provided by a subsidiary gap located contiguous to the main gap. The function of the preilluminator is to sharpen the rise time of the trigger pulse and to irradiate the V/3 blade-triggered railgap. In the V/3 gap, the trigger blade is

Fig. 2-218. View of plasma shutter pulser showing location of the circuit elements.

Fig. 2-219. Equivalent circuit of Nova plasma shutter showing trigger and main pulser components.

Fig. 2-220. Sectioned view of trigger assembly which achieves subnanosecond jitter by UV preillumination.

Fig. 2-221. Sectioned view of low-inductance, sub-nanosecond-jitter, UV-preilluminated main railgap, which produces a current rise time of 1.25×10^{12} A/s.

located 1/3 of the gap distance from the ground electrode. The larger gap is broken first by the trigger voltage, the smaller gap is broken by the main capacitor. The UV provides initial electrons to start breakdown and preconditions the discharge channel via ionization and metastable state production. This provides prompt initiation of avalanches upon triggering and significantly speeds streamer closure velocity. This technique when used in a V/3 cascade mode provides reliable multichannel operation. Because of the preillumination, performance is reasonably insensitive to the trigger blade sharpness. We are presently examining a mixture of $\text{Ar-SF}_6\text{-N}_2$ for the switching gas to select the best mix to minimize delay and jitter and maximize the operating range. We are testing Schwarzkopf tungsten copper and Poco graphite electrode materials to select the one that minimizes erosion and prefire rate.

We have obtained both cast and molded silicone and ethylene propylene rubber (EPR) elastomer insulators for evaluation. (We have already extensively characterized silicone.) These materials have negligible corona at the gas-metal-insulator interface. They are resilient and restore compliance with the walls after each magnetically induced impulse that occurs during the shot. The dielectric breakdown field is about 3000 V/mil, four times our operating field. This threshold breakdown

field appears to be unique to elastomers. Operation well below threshold provides for very long life operation. These features permit simplified field grading, lower net inductance, and longer life than the rigid plastics normally used in pulse power systems.

Mechanical System. The consequence of a prefire or nonfire of the plasma shutter would be costly. Table 2-49 lists the beam fluence at several locations in the chain for a 1-ns pulse, and assuming various failures. The most significant damage occurs at the 31.5-cm Faraday rotator-polarizer isolation stage.

The nozzle of the pulser unit shown in Fig. 2-216 protrudes through the wall of the final spatial filter and is the only portion exposed to the hard vacuum of the spatial filter. The elastomer dielectric itself and two O-rings located adjacent to the nozzle form the vacuum seal. Alignment of the nozzle section of the plasma shutter onto the beam line will be accomplished by mounting the pulser unit on a two-axis translation stage. This movable stage will be coupled by bellows to the spatial filter. This is a relatively large unit to translate but it is necessary as the confining aperture of the nozzle section would otherwise make system alignment very difficult. That is, during alignment the pulser unit will be translated out of the beam line to allow an unobstructed off-axis view through the spatial filter.

Multiple shots of the plasma shutter require the replacement of the supporting mechanism which is in close proximity to the exploding wire. The extreme temperature and impulse pressure locally destroys this portion of the nozzle and electrodes. All of these vulnerable parts are replaceable in vacuum after each shot. The wire support chip and nozzle assembly is an injection molded high-density polyethylene part with metallic side plates. The chips, shown in Fig. 2-222, are individually molded but include the tail of the previously molded part, thus chaining the chips together. A 100-chip canister will be installed into the evacuated spatial filter and should last two to three months before reloading. The chips are pushed into position by a chain drive mechanism shown schematically in Fig. 2-216. They are pushed to preclude breaking of the chain and to ensure removal of any broken parts from within the plasma nozzle after firing. A proximity sensor in the feed mechanism will detect the

Table 2-49. Maximum beam fluence at several critical locations in the Nova amplifier chain with a normal shot, a plasma shutter nonfire, and a plasma shutter prefire. The latter occurs within 300 ns, or less, of normal fire time. Design maximums for coated and uncoated optics are 8 J/cm² and 19 J/cm², respectively.

	31.5-cm rotator	31.5-cm Disk amplifiers		46-cm Disk amplifiers	Plasma shutter	Target chamber
Normal 99% attenuation 20% off target	0.61	0.63	0.11	0.05	0.01	0.62
Failure to fire 20% reflected from target	19.8	19.8	8.6	4.1	1.37	0.62
Early fire 100% reflected back into chain	21.0	21.3	9.7	17.2	9.0	0

Fig. 2-222. Chain of chips showing plastic nozzle, support electrodes, and wire.

presence of a chip in the firing position and, after the movable nozzles have made contact with the sides of the chip, a continuity test will verify the presence of a wire. All the chip-feeding and verification steps will be computer controlled.

Plasma Shutter Electrical Systems. Reliability is the most important plasma shutter design criterion. The repair costs resulting from a single failure to block repulse energy could easily far exceed the cost of an entire plasma shutter. We have set two design standards to meet our reliability goals. If possible, no single failure shall cause repulse damage, and no single failure shall remain undetectable in normal operation. The first criterion makes the reasonable assumption that uncorrelated failures do not occur simultaneously while the second prevents the accumulation of multiple, otherwise undetectable, internal failures which would combine to allow a critical failure.

Potential failures fall into two broad categories:

- Those which prevent the shutter from firing.
- Those which cause the unit to prefire.

A completely redundant trigger system will be implemented to prevent misfires. Diagnostics will reveal single trigger failures so that corrective maintenance can be carried out. Prefires will be handled by detecting a shutter fire event and sending this signal back to the master oscillator room to close optical gates, and thereby stop the shot. This technique will be effective up to a few hundred nanoseconds prior to planned shot time.

The second pivotal shutter design point concerns electromagnetic interference. The combined peak power of 10 Nova shutters firing at once is approximately 0.5 TW, with a total energy discharge

Fig. 2-223. Block diagram of plasma shutter electronics system.

Pulser module

of 66 kJ. The plasma shutter must not interfere with other Nova systems or diagnostics when this event occurs. Conversely, other activity in the laser bay must not affect the shutters. Fulfillment of emi criteria is difficult to demonstrate prior to actual system testing, so we are taking extra care with the electronics architecture and packaging to ensure compatibility. Specifically, we will install the shutter support electronics physically close to the shutter housing and will use established emi shielding techniques to protect the electronics and to prevent interference radiation. Additionally, each shutter will "stand alone," with all power supplies and trigger generators self-contained in each unit. Except for heavily filtered and isolated ac power, all connections to the global system will be via digital, fiber-optic links.

Figure 2-223 presents a block diagram of the plasma shutter electrical system. The basic system consists of a high-voltage power supply charging capacitors which are switched across a wire using railgap switches. Supporting elements are many, and include a redundant trigger circuit, wire feed mechanism and controller, railgap gas controller, and high-voltage power supply controller. We included a timing monitor to provide diagnostics necessary to detect failures in the redundant triggers and to allow detection of jitter indicative of railgap wearout. Prime control of the shutter system is through a standard Nova fiber-optic bus-computer interface. Ancilliary control is also available for maintenance using a small local panel.

Conclusions. We have taken the plasma shutter from a new concept to a reliable system component during the past two years. This shutter incorporates the first application of advanced pulse power to a large laser system. The major innovations are the UV-preilluminated railgap and the use of an elastomer insulator. We have developed the analytic and diagnostic capability to predict performance, optimize design, and confirm operation. We have controlled the plasma in full view of the optics.

The main motivation for the shutter, and the result of its development, has been a cost savings of more than \$1 million per beam on Nova by replacing the expensive and lossy Faraday rotator with the \$50 000-per-unit plasma retropulse shutter.

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High-Speed Rotating Mechanical Shutter

High-power pulsed laser systems spontaneously emit light before their main stimulated light pulse. This spontaneous light, referred to as amplified spontaneous emission (ASE), is amplified by all subsequent active optical components in the laser chain, and may reach sufficient intensity to damage a laser fusion target before the arrival of the main high-power pulse. This light may be blocked by the use of an electro-optic shutter, such as a Pockels cell, a pulsed magneto-optic Faraday rotator, or purely mechanically by a high-speed rotating shutter or chopper wheel. A high-speed rotating mechanical shutter was studied for possible use on Nova to prevent ASE from reaching the fusion target.

To be effective, the window time of the shutter should be extremely short and as close to the desired laser pulse length as possible. The mechanical shutter approach is to place a high-speed rotating disk with a very small slot at or near the focus of a spatial filter. At this location, even the largest beam apertures reduce to less than a millimeter (diffraction limited spot size is $50\text{ }\mu\text{m}$ for a $f/20$ lens). If a wheel with a $1\text{ mm}/\mu\text{s}$ peripheral speed were placed at the spatial filter focus, then microsecond opening times could be obtained. Two major problems are

- Electrical synchronization is particularly difficult because on the Nova laser system all beams must be switched concurrently but not quite simultaneously. That is, because of differences in

shutter-to-target distances and shutter-to-master oscillator distances for individual beam lines, each shutter wheel must open at a slightly different time. This problem has been solved by the use of synchronous motors (constant speed) driven by individual phase-controllable power supplies which are in turn synchronized to a master oscillator.

- The physical location of the wheel, at the center of an evacuated spatial filter, presents some interesting mechanical problems for bearing design for ultra high-speed vacuum environments. A magnetically levitated motor armature was eventually selected and is further explained below.

Rotating Wheel Design. If a high speed shutter wheel were to operate in air and still achieve maximum speed, it would be limited to slightly under sonic velocity ($0.25\text{ mm}/\mu\text{s}$) by turbulence-induced material fatigue. By operating in a vacuum, this speed range can be extended to that limited only by the density and strength of the wheel material.

A survey of wheel designs¹³² indicates that wheel profile (mass distribution) has a significant effect on operating stress, and all profiles fall between that of a flat disk with a center hole and that of the Stodola or uniform stress profile. The Stodola wheel distributes the mass such that radial and tangential stress components are equal throughout the wheel. Since all portions of the wheel are equally stressed, the wheel achieves minimum weight and maximum peripheral speed for any given stress level. The radial or tangential stress, σ , is given by

$$\sigma = \frac{\rho(\omega r)^2}{2\ln\left(\frac{r_0}{r}\right)} \quad (53)$$

where ρ is the material density, ω the peripheral speed, and r_0/r the center-to-edge thickness ratio. A plot of the edge-to-center thickness ratio for several materials (each at a constant stress level) operating at various peripheral speeds is shown in Fig. 2-224. Each curve represents a different material evaluated at an optimum design stress as listed in Table 2-50. The operating stress level was selected based on consideration of material fatigue endurance strength, a confidence level for the material properties, correction factors for surface roughness and stress concentration, and an adjustment to take advantage of the fact that the stress level never cycles into compression during normal cyclic start-stop operation.

Table 2-50. Comparative specifications of materials selected for high speed shutter wheel use. The last column, labeled ratio of yield strength to operating stress, represents the overall factor of safety. The operating stress was selected based upon consideration of factors affecting metal fatigue, reliability, the effect of stress concentrations, surface finish, and the probability of cracks.

Material type	Typical designation	Specific gravity	Tensile yield strength MPa(kpsi)	Selected operating stress MPa(kpsi)	Ratio of yield strength to operating stress
Carbon filament epoxy	Celion 6000/5213	1.55	510 (73.9)	255 (37)	2.0
Magnesium alloy	AZ31B-H24	1.74	138 (20.0)	91.7 (13.3)	1.5
Beryllium alloy	HIP-50	1.84	345 (50.0)	178 (25.9)	1.93
Aluminum alloy	7075-T6	2.79	503 (73.0)	225 (32.6)	2.24
Titanium alloy	6Al-4V	4.54	827 (120)	353 (51.2)	2.35
Maraging steel	18Ni-300	7.70	1380 (200)	676 (98.0)	2.04

Fig. 2-224. Edge-to-center thickness ratio for a Stodola or uniform stress flywheel necessary to maintain the operating stress level given in Table 2-50 at various peripheral speeds. The circled (o) data points represent the maximum peripheral speed obtainable with a flat wheel (constant thickness) containing a small central hole and operating at the stress levels given in Table 2-50.

Since the internal stress is uniform and depends only on peripheral speed, density, and thickness ratio, the curves in Fig. 2-224 lead to an interesting conclusion. At edge speeds less than 0.1 mm/μs, the

choice of material is entirely arbitrary, whereas speeds exceeding 1 mm/μs are nearly impossible with any combination of profile or material.

Certainly carbon filament epoxies perform better than even titanium alloys but by only a small margin. This indicates that properties other than strength and density be given equal consideration during material selection. For use with a magnetic bearing motor, low wheel weight is desirable as it minimizes bearing electronics and power requirements. Low weight will also allow a smaller motor to be specified while maintaining a constant start-up time. The epoxy composite material also has the advantage of lower stored energy at any given peripheral speed. This combined with the delamination of the material during explosion compared to lethal shrapnel released by a metallic wheel at a similar speed led us to choose the composite wheel.

Little is known concerning the deformation and cracking that will occur in a filament epoxy wheel resulting from a stress concentration at the perimeter where the shutter wheel slot must be placed. A metallic wheel would benefit from a keyhole-type slot to reduce the stress concentration at the bottom of the slot, but this technique, when applied to fibrous materials, would simply expose more filament ends. Kulkarni¹³³ has proposed placing a glass-filament epoxy reinforcing band around the outer perimeter of the wheel to lower the stress level. This appears to be a viable solution but has not yet been tested.

For comparison with the uniform stress profile wheel, the maximum peripheral speed obtainable with a flat disk containing a small central hole is also shown in Fig. 2-224. A flat wheel is limited to approximately 5% of the speed of the uniform stress wheel because of its inability to support a radial stress at the center.

Motor and Bearings. In designing a shutter-wheel¹³⁴ motor-bearing support system to operate in an evacuated spatial filter, consideration was given to the following:

- A dry-lubricated mechanical bearing motor submersed in the vacuum.
- A wet ball-bearing motor driving a vacuum feedthrough shaft.
- A dry-bearing motor with vacuum-submersed rotor and externally mounted stator winding.
- A totally vacuum-submersed motor with magnetic bearings.

Only the latter magnetic bearing motor was determined to be totally satisfactory.

Because of space limitations, the wheel size was limited to 300-mm diameter, which at a peripheral speed of 1 mm/ μ s corresponds to 64 000 rpm. This relatively high rotational speed resulted in the elimination of most of the potential bearing schemes.

Magnetic bearings have several potential advantages that easily make them the first choice for supporting a high-speed wheel in a vacuum. Magnetic bearing stiffness may approach the stiffness of conventional mechanical ball bearings (100 N/ μ m), but in most cases this may not be necessary as absolute shaft location accuracy is not necessary. A ball-bearing-mounted shaft and wheel combination, for instance, must be carefully balanced to minimize forces on structures, whereas a soft magnetic suspension will allow the shaft-wheel combination to rotate about its inertial axis even if this does not correspond to the geometric center of the shaft.

ASE Shutter Wheel Control System. The control task for synchronization of several rotating

Fig. 2-225. Block diagram of shutter wheel control system.

Fig. 2-226. Shutter wheel phase control network shown in Fig. 2-225.

shutters is two-fold. First, all the wheels must be synchronized to each other; and second, the wheels must be timed to the laser pulse arrival time.

A control strategy which accomplishes this task is block diagrammed in Fig. 2-225. To synchronize the individual wheels to each other, each motor-wheel combination has its own digital, closed loop, phase control network. The phase control networks are referenced to a common timing signal. This timing signal originates from a master oscillator and is adjusted in time with the laser pulse switchout by a computer controlled phase shifter. The same computer that controls the phase shift also controls the switchout, thereby timing the wheels to the switchout.

The phase control network shown in Fig. 2-226 consists primarily of two counters and a comparator. The free running counter takes a high-frequency signal and divides by 2^{15} to obtain the motor's input frequency of 400 Hz. An up-down counter contains a value proportional to the phase

error between the sensor and reference signal and is incremented or decremented depending upon whether the sensor leads or lags the reference signal. The comparator outputs a pulse whenever the value of the bits $A_0 \rightarrow A_{13}$ are equal to the value of the bits $B_0 \rightarrow B_{13}$. Since bits A_{14} and B_{14} are not compared, the frequency of $A = B$ is 800 Hz. The signal $A = B$ in conjunction with a D-type flip flop provides a phase-shifted 400-Hz signal. The amount of phase shift equals the value contained in the phase shift counter multiplied by the period of the 13.107-MHz clock. The resolution is plus or minus one count or 76.2 ns. Operation of the controller consists of determining a leading or lagging condition, thereby increasing or decreasing the value contained in the phase shifting counter.

The rate at which the error is corrected depends upon the clock frequency of the up-down counter. Due to the highly underdamped phase characteristic

of the motor, it was found that a two-clock rate correction technique works much better than a single fixed rate. When the error is "large," the clock rate is high, $f_1 = 819.2$ kHz; as the motor approaches synchronization, the clock rate is decreased to a low value, $f_2 = 33.25$ Hz. The slow clock rate is kept much less than the sampling rate of the sensor to ensure stability.

The decision between large or small errors is made by an additional counter and comparator. The counter contains the magnitude of the phase error; when the magnitude is less than a preset value determined by the comparator, the clock is switched from its high to low rate. The best results were obtained when the clock rate was switched at an error magnitude of about 20 μ s.

Conclusions. A low-speed prototype has been built and a design study completed on the use of a very high-speed rotating wheel as a shutter to block ASE from reaching a laser fusion target. Wheel peripheral speed is limited, with the best carbon fiber epoxy materials, to approximately 1 mm/ μ s. This is consistent with long wheel life, safe operation, and reasonable system reliability. A uniform stress profile wheel with a 10:1 center to edge thickness ratio is proposed. With a millimeter wide slot at the perimeter, submicrosecond opening times may be achieved. The slot would be reinforced against cracking by using a circumferential wrapping of glass or carbon filaments in epoxy.

The wheel, motor, and shaft would be suspended by a series of magnetic bearings allowing virtually frictionless operation at 10^6 Torr vacuum.

A digital control system to synchronize the shutter wheels has been designed and prototyped. It can synchronize all wheels in the laser system to each other and to the laser pulse switchout system. Synchronization has been demonstrated at better than 2 μ s with full expectation of reaching 0.2 μ s.

Authors: I. F. Stowers, B. T. Merritt, and C. B. McFann

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Fast Pulse Development

Our fast electronic pulse requirements result from techniques used to select single pulses out of multiple pulse trains. A Pockels cell is used to modulate the polarization of the optical pulse train, permitting a polarizer to transmit the selected pulse while reflecting the remainder of the pulse train.

The Pockels cells require 4 kV to obtain our desired polarization modulation. Since our current Pockels cells are treated as lumped capacitive elements, the drive source impedance is determined by the required turn-on time of the Pockels cell. At present, a 95- Ω drive source impedance is used; in the future this will drop to 50- Ω impedance. Therefore, each Pockels cell operated at 95 Ω and 4 kV requires 42 A or 168 kW. We found that an Eimac Y690 tube with a cathode area of 2 cm² provides the required output.

Operating the planar triode required a 400-V pulse which was generated by four 2N5551 avalanche transistors in series discharging a 50- Ω charge line into a 50- Ω line to the planar triode grid. The pulse delivered to the grid was 400 V in amplitude and the grid was negatively biased to 100 V, causing the grid to be driven 300 V positive with respect to the cathode. It should be noted that the manufacturers maximum recommended grid to cathode voltage is 100 V positive; however, the tubes are normally operated at a microsecond pulse duration instead of our < 10-ns pulse durations.

Although our single planar-triode Pockels cell drivers work satisfactorily, there were several difficulties. A 400-V pulse into the planar triode grid produced no margin in output power. Further, the rise time generated by the 2N5551 is approximately 3 ns; a faster rise time is desirable. In addition, to meet required signal-to-noise conditions, two to three Pockels cells are required in a typical pulse selector.

An improved Pockels cell driver has been developed which has increased output power, multiple outputs to drive more than one Pockels cell, and a 1-ns rise time.

The second-generation planar-triode Pockels cell driver uses eight planar triodes as shown in Fig. 2-227. Due to grid-cathode capacitance and grid-

Fig. 2-227. A planar-triode pulse amplifier capable of driving two Pockels cells to 5 kV with a rise time of about 1.0 ns. Each channel has three parallel tubes to ensure adequate peak current capability.

electron interactions, grid-source impedances had to be reduced to obtain 1-ns rise times. The 2N5551 transistors were replaced with MMT2222, which switch less voltage than the 2N5551s. The grounded-cathode, grounded-grid stage provides sufficient gain to develop up to 100-kW output to the final amplifiers.

The transformers between the preamp stage and the final amplifier stage are used as power splitters as well as impedance transformers to permit low, final-stage, grid-drive impedance. These transformers are the transmission-line type in which each winding is a few turns of coaxial cable around a ferrite core.

These amplifiers also exhibit very low jitter (≈ 30 ps) and long lifetime. It should also be possible to increase the rise time of the planar triodes by driving them even faster. We have found, using a time-domain reflectometer, that for a planar triode in a 5- Ω strip-line, <120-ps rise times should be possible, and further improvements may be possible with modification to the tube envelope structure.

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Fiber Optics Developments

The high voltages and the high electrical noise environment of large laser systems makes the inherent isolation of fiber optic interconnections very attractive. For that reason we began development of fiber optics for three Nova applications:

- Low-speed, low-cost trigger links.
- High-speed, low-jitter trigger links.
- High-speed data bus links.

The low-speed trigger links were developed primarily to provide optically isolated trigger pulses to ignitrons in the Nova power conditioning system. However, by lowering the optical emitter drive current, the link can also be used for on-off control signals and as a 15 Kb/s data link. The link will also be used in conjunction with current transformers to feed back status signals from ignitrons when they are fired. The basic link is intended for use at distances less than 20 ft, although it can be extended with an increase in cost. Low cost was the most important objective for this link. It uses inexpensive plastic fiber which does not need polishing or align-

ment; the total component cost for a 20-ft link is less than \$20. The link propagation delay is less than 10 μ s and the delay jitter is less than 1 μ s.

The high-speed trigger links were developed for precise synchronization between the oscillator and the other high-speed laser elements without interconnecting wires. They carry trigger pulses with subnanosecond jitter between devices such as the oscillator, switchout, ASE Pockels cells, and plasma shutter. Wide bandwidth trigger systems are often susceptible to noise, or they operate at such high electrical power levels that they radiate noise into other systems. This trigger link operates at high optical power levels which enhances its noise immunity, but it does not radiate electrical noise.

The transmitter is a pulsed laser diode driven by an avalanche transistor. The diode emits 5 W into the fiber. At this high power level, a photodiode-receiver output can drive many devices without amplification.

The link has been tested with 160 m of fiber and we are certain there would be no problem in operation at distances up to a kilometre or more. Glass fibers, which require polishing and precise alignment, are used in this link. Therefore, costs and assembly time are greater than for the low-speed link.

We began work on a high-speed data bus link by surveying the marketplace for fiber optic links rather than building our own from components. The Hewlett-Packard link was chosen because it operates from dc to 10 Mb/s, is small, and requires only one power supply. It is also reasonably priced. The circuitry required to transmit the serial data stream over a dc link can be reasonably simple, so as soon as we received the link we began extensive testing. During the tests, two significant problems were found:

- The receiver is sensitive to emi.
- The link has a subtle jitter problem which is not apparent from the specifications.

The receiver is a high gain-bandwidth device, so its emi susceptibility was not too surprising; this can be improved, if necessary, by shielding the receiver. The jitter problem can be circumvented by running the link at slightly less than 10 Mb/s, or by making the data transmission and detection circuitry more sophisticated. Hewlett-Packard has shown interest in correcting the problems within the link itself. The section in this report on "Power Conditioning" contains a discussion of a data bus

Fig. 2-228. Left: low-speed, low-cost trigger link. Center: high-speed, low-jitter trigger link with laser diode transmitter. Right: high-speed data bus link with transmitter and receiver modules.

system that uses this link, including photographs of the link modules.

Figure 2-228 is a photograph of the three links.

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Cyclops Renovation

Introduction. Reconstruction and renovation of the old Cyclops laser¹³⁵ was begun in October 1979 for use in research areas of broad-band lasers, multipass amplifiers, short wavelength damage measurements, and Nova component development. Cyclops is being designed to address the following research projects:

- Feasibility demonstration of a master oscillator/power amplifier (MOPA) Raman laser configuration to deliver a moderately high power (10 to 100 GW) and spectrally broad-band (± 50 nm) laser output. This could reduce the deleterious effects of Raman and Brillouin scattering losses in underdense D-T target plasmas, thereby enhancing D-T target absorption, compression, and heating.

- Harmonic conversion of the Cyclops laser output to green and UV wavelengths for damage research on dielectric thin films.

- Gain saturation and intensity-dependent loss measurements of laser materials.

- Performance evaluation of multipass amplifier configurations.

In addition, the Cyclops laser facility will evaluate prototype Nova Phase I components at 1053 nm. The basic design philosophy of the new Cyclops laser is to employ the latest solid-state laser technology while retaining those previously designed laser components whose features recommend their continued use. This approach assures excellent laser performance and an overall cost-effective design.

Cyclops Design Features. The new Cyclops front end features a modified Shiva-type LiYF_4 oscillator and a three-element LiYF_4 preamplifier stage, followed by phosphate glass rod and disk amplifiers designed for laser operation at 1053 nm. This shorter wavelength coincides with the design wavelength of the Nova Phase I laser system and affords us the opportunity to prototype and/or test Nova components on an operational laser chain.

As shown in the schematic, Fig. 2-229, a 1- to 5-ns pulse is cut out of the acoustically mode-locked, Q-switched oscillator pulse using a fast double Pockels cell driven by a planar triode circuit. Oscillation at 1053 nm instead of the stronger 1047 nm line is achieved by proper cutting and orientation of the birefringent LiYF_4 crystal. The oscillator pulse

Fig. 2-229. Schematic of new Cyclops facility.

Table 2-51. Summary of Cyclops amplifier specifications.

Amplifier	Aperture (cm)	Small signal gain	Stored energy (J)	Stimulated emission cross section ($\text{cm}^2 \times 10^{-20}$) (Ref. 138)	Glass type	Nd doping (%)	Glass vol (cm^3)	$\frac{\Delta P}{\Delta B}$ (TW/neper)
Alpha rod	2.3	80	102	4.0	Q-88	1.0	196.4	0.025
Alpha rod	2.3	160	118	4.0	Q-88	1.0	196.4	0.029
Beta rod	4.6	20	279	4.0	LHG-8	0.5	785.4	0.122
Delta disk	7.6	7	1092	4.1	LHG-6	3.6	1915	0.51

Table 2-52. Flashlamp specifications for cyclops amplifiers.

Amplifier	No. of circuits	Capacity (μF)	Inductance (μH)	$3\sqrt{LC}$ (μsec)	Lamp bore (cm)	Arc length (cm)	Lamps per circuit
Alpha	1	87.6	440	589	1.3	37	6
Alpha	1	87.6	440	589	1.3	37	6
Beta	1	146	440	760	1.5	37	6
B-75N	8	87.6	440	589	1.5	112	3

is amplified by a 0.6-cm aperture LiYF_4 preamplifier followed by a pair of double-ellipse 1.0 by 7.6 cm LiYF_4 amplifiers. The LiYF_4 crystals are index-matched with a hydrated ZnCl_2 immersion fluid and have both superior rod-filling factors and more homogeneous gain profiles than are feasible with high-index Nd:YAG preamplifiers.

The entire front end can be driven at a repetition rate of from 1 to 3 Hz, and alignment of the entire chain can be carried out using the amplified pre-pulse output from the oscillator. It has also been modified to permit a portion of the high-repetition preamplifier output to be coupled out to align

and/or drive the Raman oscillator cells (see below) in support of the broad-band Raman MOPA experiments.

The four large glass amplifiers used on Cyclops for the initial experiments include:

- A hybrid 2.5-cm aperture, 6-lamp rod amplifier.
- A Shiva alpha rod amplifier.
- A Shiva beta rod amplifier.
- A Shiva beta disk amplifier.

Three different types of phosphate laser glass are used in Cyclops: Q-88 for the 2.5-cm rods, LHG-8 for the 5.0-cm rods, and LHG-6 for the B-size laser disks. Amplifier characteristics are detailed below in Table 2-51; flashlamp characteristics and bank cir-

cuits associated with these amplifiers are summarized in Table 2-52.

Cyclops Performance. The laser chain is designed to deliver an output energy of approximately 100 J in a 1-ns pulse (100 GW). Image relaying of Cyclops is not included as part of the initial staging, but to achieve a fill factor higher than 0.6 necessitates the introduction of interstage image relaying.

The significant performance advantages associated with using phosphate laser glasses in the Cyclops amplifiers are:

- Nonlinear self-focusing effects are reduced by increased gain saturation.
- The phosphate glasses generally have lower nonlinear refractive indices.
- Laser amplifiers equipped with phosphate glass generally have higher "X" factors^{136,137} than laser amplifiers comparably equipped with silicate laser glasses. The X factor is defined as the ratio of the increment in power, ΔP , divided by the increment in nonlinear phase shift, ΔB .
- More stored energy in the laser amplifiers can be extracted at constant flux owing to the generally lower saturation fluxes of the phosphate laser glasses.¹³⁸

With phosphate laser glass, the Cyclops system saturates at a somewhat lower flux than previously observed with silicate glasses and greater care is required for adequate interstage isolation. Sufficient reserve capacitor bank capacity remains to permit additional disk amplifiers if additional output power is required.

Data Processing System. The new Cyclops facility uses a modified PDP 11-34 computer system to process and evaluate data obtained on a real time basis during the course of each experiment. The interfacing of the computer system to the diagnostics (such as the silicon target vidicons) permits the direct input of spectral and temporal data. Densitometry and calorimetry are done electronically using calibrated silicon target vidicons and calorimeters interfaced with the computer and the Grinnell color monitor system.

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Basic Research

Overview

Three research programs are supported by the Division of Materials Science of the DOE Office of Basic Energy Sciences (BES). These programs are devoted to the study of optical materials for high-power lasers, such as those used for inertial confinement fusion experiments. The projects are

- Low-Index Optical Materials Research.
- Laser-Excited Fluorescence in Amorphous Solids.
- Surface Physics and Chemistry of Laser-Induced Damage.

These programs complement those of the Laser Fusion Program by exploring basic phenomena of potential importance for laser materials.

Propagation of intense laser beams through dielectric materials causes intensity-dependent changes in their optical properties. Chief among these is the nonlinear refractive index, n_2 , which determines the amount of self-focusing in materials. The resulting beam breakup limits the focusable laser power deliverable to fusion targets. These deleterious effects are minimized by using low refractive index materials for all transmitting optical components in the laser.

In the past three years, we have investigated many different low-index optical materials under the first program above. The materials having the smallest n_2 values are fluoride crystals and glasses containing low-atomic-number cations.¹³⁹ Of these, beryllium fluoride based glasses are particularly attractive for laser applications because of the combination of several favorable optical, spectroscopic, and physical properties. These are discussed in previous Laser Fusion Annual Reports¹⁴⁰ and summarized in Ref. 141.

For fusion lasers operating at shorter wavelengths, for example, rare gas halide lasers such as

KrF₂ (248 nm) and higher harmonics of the neodymium (Nd) laser wavelength, wide-band gap materials are needed to reduce both linear and nonlinear absorption. These tend to be the lower index materials of various groups (BeO in the case of oxides and BeF₂ in the case of fluorides). The fundamental band gap E_g of BeF₂ glass is estimated to be one of the largest and comparable to that of LiF. Our vacuum ultraviolet (VUV) absorption measurements to date show transmission down to ≈ 150 nm. The absorption below 150 nm may, however, be due to impurities, which are known to be present, rather than intrinsic absorption. To overcome this problem, we have collaborated with personnel of the Naval Research Laboratory on VUV reflectivity and photoelectron emission spectroscopy of amorphous BeF₂ (see Ref. 142). The Synchrotron Ultraviolet Radiation Facility (SUKF) at the National Bureau of Standards is being used for these measurements. More complex multicomponent fluoroberyllite glasses are being studied to determine the effect of compositional changes on the absorption edge.

The other nonlinear property of interest for optical materials at short wavelength is two-photon absorption (2PA). When the laser wavelength becomes $\approx E_g/2$, 2PA is energetically possible. In addition, the wavelength dispersion of the nonlinear refractive index will change (n_2 and the 2PA coefficient are related to the real and imaginary parts of the third-order susceptibility, respectively). Data on 2PA coefficients of wide-band gap optical materials is limited.¹⁴³ To measure not only values at discrete wavelengths but also the two-photon absorption spectrum, we plan to use a tunable dye laser and its harmonics as the source and a piezoelectric transducer as the detector of the photoacoustic signal resulting from 2PA. The development of sensitive photoacoustic techniques is discussed later in the section on "Photoacoustic Studies."

For solid-state lasing media, such as Nd-doped glass, we are interested in the spectroscopic properties of the Nd³⁺ ions in addition to the nonlinear optical properties. The second BES research program uses laser-induced fluorescence line narrowing (FLN) techniques to explore the site-to-site variation in the spectroscopic properties of activator ions in amorphous materials. While these

microscopic inhomogeneities are not evident for lasers operating under small-signal gain conditions, they become important for lasers operating under large-signal or saturated gain conditions where hole burning and gain reduction occur.

The observation of fluorescence line narrowing is a simple method to prove that a lasing medium is inhomogeneous and, therefore, subject to spectral hole burning.¹⁴⁴ Spectral hole burning in our Nd laser glass was confirmed in recent gain saturation studies (see previous section on "Gain Saturation Properties of Laser Materials"). Since FLN is observed in all Nd-doped glasses studied to date, spectral hole burning is a common phenomenon. The degree of hole burning is dependent on the ratio of the homogeneous to inhomogeneous line widths. We have begun an investigation of the relative magnitudes of these line widths as a function of glass composition. This should provide guidance in selecting materials which minimize the effects of hole burning.

Polarized laser-excited fluorescence studies can be used to study effects of polarization on hole burning and gain saturation.

To model the energy extraction from an inhomogeneous lasing media, we need to know the distribution of stimulated emission cross sections for the incident laser frequency and polarization. This is presently not known for Nd-doped glasses. FLN spectroscopy provides information about energy levels and transition probabilities that can be used to make estimates of the gain saturation. As described in previous annual reports,¹⁴⁵ FLN data can also be used to construct models of the local structure and Nd³⁺ coordination in oxide and fluoride glasses.¹⁴⁶ During the past year, we prepared a review of laser-excited fluorescence spectroscopy of glass¹⁴⁷ which describes these and other recent developments.

To investigate the local structure and fields at laser ion sites in glass and the site-to-site variations which cause inhomogeneous broadening, we are calculating the structure of glass from first principles. Our computer simulations of glass structure using Monte Carlo methods are described in the following section. Thus far, simple rare-earth-doped BeF₂ glass has been studied. We find that there is no single rare-earth site symmetry or nearest-neighbor coordination number, but rather a range of values. The disordered nature of glass is

also evident from the shape of calculated radial distribution functions.

Knowing the positions of anions and cations surrounding the rare-earth ion in glass, the next step is to model the interactions and calculate electronic energy levels and transition probabilities. From these results both broadband-excited and laser-excited optical spectra can be simulated. This will be done using molecular orbital self-consistent field calculations, programs for which are currently being developed.

The glass simulations can be tested critically using results from EPR studies. Measurements of the optical spectra of europium (Eu^{3+}) in BeF_2 glasses are reported in the section on "Fluorescence Line Narrowing in Beryllium Fluoride Glass" and compared with the energy level distributions predicted using a simple point charge model of the crystal field. These preliminary results show satisfactory agreement, within the limitations of the model and associated approximations. Therefore, computer simulations combined with laser-excited fluorescence spectroscopy promise to provide unique insights into the local structure and fields in amorphous materials.

As noted throughout our discussions of solid-state laser technology, thresholds for laser-induced damage continue to be a limiting factor in the design and performance of fusion lasers. The lowest damage thresholds occur at surfaces, in thin-film coatings, and at film-substrate interfaces. The third BES program is a study of the physical and chemical properties of surfaces governing optical damage thresholds.

One source of damage is absorption. This is difficult to measure in thin films using traditional optical techniques. In a later section on "Photoacoustic Studies," we show that photoacoustic techniques can be used to measure small absorption coefficients. Photoacoustic methods also provide a convenient way to detect damage thresholds.

To address the effects of surface physics and chemistry on damage thresholds, we built an ultra-high vacuum chamber for *in situ* sample preparation damage testing, and measurement of neutral and charged particle emission and surface diagnostics. This is described in the section on "Surface Physics and Chemistry of Laser-Induced Damage." Carefully controlled surface preparation and characterization and accurate threshold measure-

ments should yield new insights into the stubborn problem of laser-induced damage.

We have continued our survey of laser host materials in the search for special characteristics and property extrema.¹⁴⁸ Halide glasses were considered because the local fields should be relatively weak, resulting in narrow fluorescence bandwidths, and the phonon frequencies are low, resulting in more fluorescing states with high quantum efficiency. Thus far, we have had only limited success in preparing rare-earth-doped ZnCl_2 -based glasses. We did, however, investigate a series of mixed-anion, chlorophosphate glasses. These glasses exhibit the largest simulated emission cross section for the $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{11/2}$ transition of Nd^{3+} in any glass measured to date.

Another material discussed in the section on "Cubic Zirconia" is the crystal ZrO_2 , which is stabilized in the cubic phase by the addition of compounds such as CaO or Y_2O_3 . The optical spectra of Nd^{3+} is characteristic of a randomly disordered solid host. The material has some of the properties of a glass (isotropic, inhomogeneously broadened spectra with small effective cross sections) while retaining other physical properties of a crystal.

In addition to investigating host materials, we also surveyed possible transitions of all lanthanide and actinide ions for optically-pumped laser action.¹⁴⁹

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Monte Carlo Glass Simulations

As used in statistical mechanics, the Monte Carlo (MC) technique is a way of enumerating, with proper weights, the microstates of the canonical ensemble. This is done with no simplifying assumptions. The technique has proven to be a powerful one for computing equilibrium liquids with particles subject to ionic forces.¹⁵⁰ Because a glass is a frozen liquid, the application of the MC technique to glass structure is a reasonable extrapolation of a well-developed method.

Since the atoms of a fluid diffuse rapidly, the fluid cannot have a single structure as does a crystal. Rather a fluid structure is described statistically, so particular structures appear with a certain probability. It is just this feature that is modeled in the Monte Carlo technique. The temperature, density, and interatomic potentials are provided as input; the results of a MC calculation are a series of "snapshots" of the positions of all the particles. Each snapshot is termed a *configuration*. Using a computer, millions of configurations can be generated with the result that more probable structures appear more often than less probable ones. The structural and thermodynamic properties of the fluid are then computed by averaging over all the configurations.

The Monte Carlo technique is feasible when the atomic constituents of the fluid interact via two-body potentials. This is the case for highly ionic

materials such as alkali and alkaline-earth fluorides for which the dominant interionic interactions are the Coulomb potential and a short-range repulsion. We have applied the method to compute the structure at rare-earth sites in vitreous BeF₂. Preliminary experiments showed that the microscopic system could be modeled adequately by one containing on the order of several hundred particles. The particles are enclosed in a cubic box, or cell, whose size is chosen to give the correct density. As long as the box is larger than the length characteristic of significant structural correlations, a reasonable fluid structure is computed. The standard method of minimizing the effect of the cell boundary is by imposing periodic boundary conditions so that the cell is replicated through all space.

Our model glass system consisted of 199 ions: 65 Be²⁺, 133 F⁻, and 1 Eu³⁺ in a cubic cell of side 13.82 Å (the density of 2.06 g/cm³ corresponding to the doping concentration of 1.3 mole % EuF₃). Because of its simple energy level structure, Eu³⁺ provides a convenient experimental probe of the local fields.¹⁵¹ (The simulations are also expected to be applicable to Nd³⁺ because its size differs very little from that of Eu³⁺.) The interionic potential energy included a Coulomb term and Born-Mayer repulsion for ions *i* and *j* of the form $A_{ij} \exp(-\sigma r)$. The Coulomb potential was evaluated as the Ewald sum using the Hansen approximation.¹⁵² The A_{ij} for Be-F ions was the same as used by Woodcock et al.¹⁵³ For Eu-F ions it was chosen to make the first peak in the Eu-F radial distribution function (RDF) occur at 2.35 Å, the sum of the Pauling radii¹⁵⁴; for Eu-Be ions it was set equal to zero. The value of $\sigma = 3.448 \text{ Å}^{-1}$ for all ions.

Computations were made with an array processor (Floating Point Systems Model 120 B) and a PDP-11/55 host computer; this combination generated 250 000 configurations per hour. A high-temperature fluid was simulated first by making a run of 16 million steps (individual ion displacements) at a temperature of 1667 K where sufficient diffusion occurs to insure complete randomization of the fluid. Glasses were formed by starting with one of the high-temperature fluid configurations and carrying out the MC process while slowly lowering the temperature. During the cooling process, the step size was adjusted to keep the acceptance rate between 40 and 50%; a total of 200 000 steps were made. At the final temperature

(900 K) no diffusion occurred. Every 100 000th configuration of the initial high-temperature fluid was quenched in this way. Because the model system contained only one rare earth (RE) ion, 159 dif-

Fig. 2-230. One configuration of a Monte Carlo simulated glass. Blue balls represent beryllium (Be), bronze balls represent fluorine (F), and the green ball in the center represents a rare-earth ion. This computer-generated display can be rotated in space to examine the graphics. This simple glass is made up of continuous random network of BeF_4 tetrahedra. Note the large voids in the network.

ferent initial fluid configurations were quenched. The collection of these low-temperature configurations is the glass. Other details of the simulation are the same as described elsewhere.¹⁵⁵

Figure 2-230 shows a picture of a single configuration generated as described above. In beryllium fluoride (BeF_2), the Be^{2+} ions are coordinated by four F ions to form fairly regular tetrahedra. This is the extent of the short-range order. The BeF_4 tetrahedra are joined at the vertices so that each F is bound to two Be. The linked BeF_4 tetrahedra are clearly visible in the figure. However, whereas in a crystal there is a definite Be-F-Be angle that is replicated periodically throughout the solid, in a glass the Be-F-Be angle fluctuates randomly between approximately 120° and 180° and the tetrahedra form a three-dimensional random network. The fluctuating Be-F-Be angle ensures the lack of long-range order.

Of particular interest is the structure in the vicinity of the rare-earth ion. We have generated hundreds of different configurations each of which represents a different rare-earth site in the glass. Three examples are shown in Fig. 2-231. In these figures, heavier lines are drawn between the RE and the F within $2.75 \text{ \AA}$ of it. The local geometry is different in each case. It is just these variations in site geometry that are the origin of the inhomogeneous spectroscopic properties. The graphic presentations in Figs. 2-230 and 2-231 are generated using the

Fig. 2-231. Local environments of a rare-earth (green ball) in three different computer-simulated BeF_2 glasses. Each rare-earth site in a glass has a different geometric arrangement of neighboring ions. The first-neighbor fluorines (bronze balls) within $2.75 \text{ \AA}$ of the rare-earth ion are joined to it by the heavier bonds. The sites, from left to right, have fivefold, sixfold, and sevenfold fluorine coordination.

program ATOMLIL¹⁵⁶ and are very convenient for visualizing the structural variations.

To describe the structure in the neighborhood of the RE ion, it is customary to use radial distribution functions (RDFs). An RDF is a microscopic ion density. For example, the RE-F RDF gives the number of F ions per unit volume within a distance r of the RE. Calculated Eu-F and Eu-Be RDFs obtained by averaging over 159 sites comprising a simulated glass are shown in Fig. 2-232. Europium ions of charge +3 attract a number of fluorine ions of charge -1. This is reflected in the first peak in the Eu-F RDF which gives the average distribution of F ions in the first coordination shell of Eu. Note that there is a range of Eu-F distances, some as small as 2.1 Å. For beryllium ions, which have a charge +2, similar calculations show that the strong Eu-Be electrostatic repulsion pushes the Be ions out to distances greater than 3.1 Å.

The average number of F ions surrounding the Eu ion, average coordination number $N(r)$, is obtained by counting the number of F ions within a distance r of each Eu site and then averaging this number over all configurations of the glass. A plot of $N(r)$ is included in Fig. 2-232. Whereas the average coordination number at, for example,

2.75 Å is 6.5, the actual site coordination varies from fivefold to eightfold.

The different local environments at each RE site is the aspect of structure most relevant for the optical properties of rare-earth laser glass. This is manifested in a broad distribution of Eu-F distances and Eu coordination numbers. To quantify this, we examined the fraction of all configurations in which a RE ion had exactly n fluorine neighbors within a distance, r . This is plotted in Fig. 2-233 for several values of n . For any distance r there are configurations with differing numbers of neighbors. The sites in Fig. 2-231 illustrate examples of fivefold, sixfold, and sevenfold coordination for $r \approx 2.75$ Å.

The general picture of the rare-earth ion that emerges from our computer simulations is one in which the RE ion is surrounded by fluorine ligands, with the closer ligands being bonded to one, and only one, Be ion. This feature is clearly visible in Fig. 2-230. The fluorines surrounding the RE ion form an irregular coordination polyhedron that is bonded to BeF_4 tetrahedra only at the corners in agreement with Pauling's second rule for ionic structures.¹⁵⁴ Thus, those BeF_4 tetrahedra adjacent to the RE are aligned so as to point one F toward the RE. The other three are much farther away. This description reveals that there is indeed some short-range order about the RE ion; however, the order is not complete because of the site-to-site variations in Eu-F distances and coordination numbers. It is also clear that within 4 Å of the RE ion, the structure of pure BeF_2 glass is greatly distorted by the presence of the RE. If one were to choose any other random point in the glass, the distribution of Be and F ions would have none of the features discussed above. For example, near the RE many F are bonded to only one Be, but in undoped BeF_2 glass virtually all F are bonded to at least two Be ions. In addition, the tetrahedra are not aligned so as to point an F toward an arbitrary point.

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Fig. 2-232. Calculated radial distribution functions (RDF) for Eu-doped BeF_2 glass. The RDF is a microscopic ion density. The Eu-F and Eu-Be curves represent the number of F or Be ions per unit volume at a distance r from a europium ion. The first peak in the curves corresponds to the nearest-neighbor distance. The quantity N , as described in the text, is the average F coordination number at distance r .

Fig. 2-233. The fraction of Eu ions in a BeF_2 glass that have exactly n fluorine neighbors within a distance r , plotted as a function of r for several values of n . For any given r , this quantity is computed by counting the number of Eu ions for which there are exactly n F ions within distance r , and dividing by the total number of sites. The calculation is repeated for various values of n and r . The very broad distribution of RE-F distances and coordination numbers revealed by this figure implies disordered rare-earth sites.

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Fluorescence Line Narrowing in Beryllium Fluoride Glass

We have measured and calculated the fluorescence line narrowed (FLN) spectra of a Eu^{3+} -doped BeF_2 glass (Figs. 2-234 through 2-236). The FLN spectra were measured at 30 K. The $^7\text{F}_0 \rightarrow ^5\text{D}_0$ transition of Eu^{3+} was excited by a CMX-4 flashlamp-pumped dye laser. The dye Rhodamine 6G was used in the solvent trifluoroethylene in order to provide strong lasing in the required frequency region about 578 nm. The $^7\text{F}_0 \rightarrow ^5\text{D}_0$ absorption band is very weak, and photon counting equip-

ment was required to detect the signal. We found that significant Eu-Eu energy transfer occurs in the sample (0.5 wt% EuF_3) even at 30 K when short-wavelength excitation was used. The reason is that when the Eu ions with large $^7\text{F}_0 - ^5\text{D}_0$ separations are excited, the energy can migrate to sites with lower separations, energy being conserved by phonon emission. Because of this energy transfer, it was necessary to gate the recording apparatus so only photons emitted within 500 μs of the excitation were collected.

The resultant $^5\text{D}_0 \rightarrow ^7\text{F}_1$ FLN spectra, as well as the broadband-excited spectra, are shown in Fig. 2-234. The $^7\text{F}_0 - ^5\text{D}_0$ absorption band is shown with arrows indicating the excitation wavelengths used. Note that the $^7\text{F}_1$ bands vary systematically as a function of excitation wavelength, with one level moving to shorter wavelength and the other two

Fig. 2-234. Line-narrowed fluorescence spectrum of the $^5D_0 \rightarrow ^7F_1$ transition of trivalent europium in beryllium fluoride glass as a function of laser excitation wavelength. Each spectrum arises from that subset of ions with 5D_0 to 7F_0 energy differences resonant with the laser frequency. Variations in the positions of the three lines result from site-to-site variations in energy levels and transition strengths at different sites.

moving a smaller amount to longer wavelengths as the excitation wavelength decreases. In addition, the intensity of the shortest wavelength 7F_1 transition decreases with decreasing excitation wavelength. At 30 K, all of the 7F_1 levels are partially resolved even in the broadband excited emission.

We have compared the FLN measurements with theoretical calculations of Eu^{3+} energy levels based on the Monte Carlo simulations described in the previous section.¹⁵⁷ Knowing the ion positions in the glass, we calculated the electronic energy levels of Eu^{3+} using a point charge model of the crystal field (CF). While such a calculation is only of qualitative significance, it offers further insight into the structure at the RE sites. To limit the number of parameters, we restrict ourselves to the 7F_0 and 7F_1 manifolds of Eu^{3+} for which the second-order CF terms are of overwhelming importance. The point-charge CF is given by

$$V = -A \sum_L \frac{q_L}{R_L^3} \sum_{q=-2}^2 Y_q^2(\theta_L, \phi_L) U^2_q \quad (54)$$

Fig. 2-235. Calculated 7F_0 and 7F_1 energy levels for each europium site in a simulated beryllium fluoride glass, as computed from a point charge model. The sites are ordered with the 7F_0 energy decreasing to the right; the 5D_0 energy is assumed to be approximately constant. The site-dependent energy differences are the origin of the inhomogeneous broadening observed in broadband-excited fluorescence spectra. The increasing separation of the lowest 7F_1 level from the other two levels with increasing 5D_0 to 7F_0 energy corresponds to the behavior shown in Fig. 2-234.

Fig. 2-236. Measured fluorescence spectra (smooth curves) and calculated energy level distributions (histograms) for Eu^{3+} in BeF_2 glass. Energy levels were calculated using a point-charge model of the crystal field. The two top curves are broadband-excited spectra; the two bottom curves are narrowband laser-excited spectra.

where ligand l of charge q_L is at distance R_L from the RE ion. Y^2 is a second-order spherical harmonic, U^2 is the reduced tensor operator for the f electrons of Eu^{3+} , and A is a positive free parameter. To clarify the relation between energy and structure, only F ligands within $2.75 \text{ \AA}$ of the RE ion are assumed to contribute to the CF. The energy levels of the 7F_0 and 7F_1 manifolds of Eu^{3+} for 159 configurations of the glass were computed from Eq. (54) by diagonalizing the 16×16 matrix in the basis of the $J = 0, 1, 2, 3$ manifolds of the 7F term. The results are shown in Fig. 2-235. The constant A and the centers of gravity of the manifolds were chosen to give the best fit to the observed spectra.

The comparison between theory and experiment is shown in Fig. 2-236. The two upper curves in Fig. 2-236 are the experimental fluorescence spectra for broadband excitation into levels above 5D_0 . The histograms are the calculated distribution of Eu^{3+} energy levels for 159 sites given in Fig. 2-235. (The energy of the 5D_0 level was taken to be constant.) Although the site dependence of the transition probabilities is unknown at present, the asymmetry of the ${}^5D_0 \rightarrow {}^7F_0$ profile and the magnitude of the inhomogeneous broadening of the ${}^5D_0 \rightarrow {}^7F_1$ band are both successfully modeled.

The two lower curves in Fig. 2-236 show the emission observed for excitation on the short- and long-wavelength sides of the ${}^7F_0 - {}^5D_0$ band. The histograms are calculated distributions of 7F_1 energies for those sites having ${}^7F_0 - {}^5D_0$ energies within $\pm 0.2 \text{ nm}$ of the excitation wavelength. The histograms again model the overall splitting and distribution of the 7F_1 energy levels for different sites. The smallest and the largest 7F_1 splittings observed experimentally, differed by a factor of ~ 4 ; the calculated energy levels in Fig. 2-235 show a similar range of relative splittings.

Finally, we note that we have simulated glasses under several different quenching conditions and there are only small changes in the properties discussed here.

The point charge model used to calculate the energy levels of Eu^{3+} in BeF_2 glass is only an approximation; hence, the correlation with observed optical spectra merely confirms the essential correctness of the glass structure simulations. In ad-

dition to the energy level structure, a more complete test of the site-dependent properties will include both intensity and polarization of the optical spectra. We are currently performing full SCF-CI calculations for the energy levels of Eu. We are also extending the simulations to treat more complex glasses containing modifier cations which are known to affect spectroscopic properties.

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Photoacoustic Studies

Laser Damage in Thin Films. One of the most serious problems encountered with high-energy laser systems is the occurrence of irreversible, destructive alteration of optical components when these components are irradiated with a sufficiently energetic laser pulse. Such damage can occur both within the bulk of the materials and on the surface. Laser-induced damage is, at present, a serious limiting factor in the design of high-power laser systems.

Data on laser damage is difficult to obtain, with most of this data presently acquired through microscopic visual inspection of samples after laser irradiation.¹⁵⁸ This process, although valuable, is tedious. There is a need for developing other means for detecting and quantifying laser damage.

We have developed a photoacoustic method¹⁵⁹ that is capable of detecting the occurrence of laser damage and providing quantitative data not only about damage thresholds but also about energy-transfer processes when damage occurs.¹⁶⁰ In the photoacoustic experiment depicted in Fig. 2-237, a pulsed Nd:glass laser, operating at nominally 1 J at 1 ns, is used in a single-shot mode to excite a transient photoacoustic signal in the sample. The beam is focused by a lens so that a high-energy flux will strike the sample. Neutral density filters, F , are inserted into the beam to vary the energy flux, E , at the sample from 200 mJ/cm^2 to 20 J/cm^2 . A portion of the beam is diverted by the beam splitter into a

Fig. 2-237. Schematic of experimental setup for piezoelectric photoacoustic detection with a pulsed laser. The symbols are L (laser), C (calorimeter), BS (beam splitter), F (neutral density filter), and S (sample).

calorimeter which provides a measurement of the average energy in the pulse.

A piezoelectric transducer, in the form of a disk, is cemented to a gold mirror and the mirrored transducer is acoustically bonded to the center of the rear surface of the sample with a viscous fluid, such as glycerine or silicone oil. Care is taken to ensure that no direct light falls on the transducer and the mirror minimizes the absorption of scattered light by the transducer. The output of the transducer is fed directly into an oscilloscope and the oscilloscope trace is photographed when the laser is fired.

The photoacoustic signal is generated by the light that is absorbed by the sample. This light is converted into heat at the absorption site, which in turn produces an acoustic shockwave that eventually reaches the transducer. An example of this is shown in the oscilloscope trace of Fig. 2-238. Here a 20 mJ pulse is absorbed by a high-reflection optical film having a surface absorption of $\sim 10^{-3}$. The photoacoustic signal exhibits a 4.5 μ s delay, which corresponds to the transit time for the sound wave generated in the film to reach the transducer, 2 cm away. The ringing is primarily at the ~ 1 MHz resonance frequency of the mirrored transducer. In these experiments, we measure the magnitude and time delay only of the first or second peak in the signal.

We have performed laser damage studies on a number of high-reflection (HR) films on silica substrates. The results for one of these samples with a multilayer $\text{SiO}_2/\text{TiO}_2$ film structure are shown in Fig. 2-239 and are typical for all of the dielectric samples studied. The visually-determined laser

Fig. 2-238. Oscilloscope trace of the photoacoustic signal when a 20-mJ pulse strikes an HR dielectric film with a surface absorption of $\sim 10^{-3}$.

Fig. 2-239. Photoacoustic signal as a function of incident light flux for a laser-damage study of an $\text{SiO}_2/\text{TiO}_2$ HR dielectric film.

damage threshold for the sample, indicated by the dotted vertical line, is $5.5 (\pm 0.5) \text{ J/cm}^2$. The photoacoustic signal, q , shows an essentially linear dependence on energy flux, E , below damage threshold. This is characteristic of linear absorption processes.

When the energy flux exceeds 5 J/cm^2 , the photoacoustic signal undergoes an abrupt increase of two to three times its values at 5 J/cm^2 . For energy fluxes above 6 J/cm^2 , the photoacoustic

signal appears to follow a simple power-law behavior E^n with n equal to 4 ± 1 for this sample. We have as yet not correlated this exponent value with any sample parameter.

The data in Fig. 2-239 show that, for a dielectric HR film, abrupt and major changes in the photoacoustic signal appear when damage occurs. One might be tempted to assume that the observed increase in signal is due to acoustic emission from the microcracking, fracturing, and other aspects of mechanical damage that occur at and above threshold.¹⁶¹ This, however, is not so for a photoacoustic signal. Below threshold, the absorbed photons always give up their total energy to phonons or localized heat and they do so almost instantaneously, since the laser pulse is only 1 ns in duration. That is, a photoacoustic signal is always immediately produced when the photons are absorbed. Furthermore, below threshold, all of the energy in the absorbed photons shows up as heat and acoustic signal and none is stored for later release. At threshold, some of the photon energy is obviously used to disrupt bonds and to impart significant kinetic energy to ions that are driven from the surface. Thus, at and above threshold, a sizable fraction of the energy of the absorbed photons is no longer available to excite phonons and produce an acoustic signal. One would, therefore, expect that a photoacoustic signal would actually undergo a relative *decrease* when damage occurs, rather than an increase. It is known, for example, that a photoacoustic signal decreases during an endothermic phase transition since here, as well, some of the photon energy goes into the phase transition rather than into acoustic phonons.¹⁶²

The presence of an increased photoacoustic signal at and above damage threshold *cannot* be attributed, therefore, to an acoustic emission process from the occurrence of mechanical damage. Instead, this observation indicates that there is, in addition, a significant increase in the number of photons *absorbed* by the sample. This increased absorption might occur at the damage site itself, or within the plasma generated directly above the damage site.¹⁶³ If the increased absorption occurs in the plasma, then this added energy will be transferred to the sample via electrons. Thus, it is not the presence of mechanical damage that

Fig. 2-240. Photoacoustic signal as a function of incident light flux for a laser-damage study on a reflective aluminum film.

produces an increased photoacoustic signal, but rather the presence of increased photon absorption.

Where laser damage is accompanied by mechanical damage, but with no significant increase in optical absorption, the photoacoustic signal will not exhibit a dramatic increase. This appears to be the case for more highly absorbing materials where laser damage proceeds via a melting mechanism. This is illustrated in Fig. 2-240 where we show the photoacoustic signal obtained in a damage study on a metallic HR film. We note that at the damage threshold, the photoacoustic signal actually exhibits a relative decrease and that even for values of E considerably greater than threshold, the slope of the q vs E line only slightly exceeds one. This is in sharp contrast of the results in Fig. 2-239 for a low-absorbing dielectric HR film.

Photoacoustics provides several important advantages for the detection and study of laser-induced damage:

- It gives quantitative information on energy transfer in the presence of damage and possibly new information on the damage process itself.
- It provides a simple nonvisual means for determining damage threshold.
- It provides an opportunity for performing onsite automatic detection of damage in the optical components of a high-energy laser system.

Real-Time Laser Damage Monitoring With Photoacoustics. Laser-induced damage in dielectric films results, as we described above, in a dramatic increase in the strength of a photoacoustic signal. This then provides an opportunity for performing

onsite automatic detection of damage in the optical components of high-energy laser systems, particularly those utilizing dielectric thin films.

The experimental arrangement used to demonstrate the feasibility of photoacoustic monitoring of laser damage is the same as in Fig. 2-237. The sample, however, is a rectangular block of BK-7 glass, 215-mm long, 100-mm high, and 20-mm thick, with a polarizing dielectric coating on one side. The photoacoustic detector is acoustically bonded to the top of the sample with glycerine.

A photoacoustic signal is produced whenever any of the laser light is absorbed by the dielectric film, even if there is no damage. It is true, as we have shown above, that the signal from a focused beam that causes damage in a dielectric film can be appreciably greater (10 to 100 times) than the signal produced from a focused beam that causes no damage. However, in operating laser systems, damage occurs at small localized sites on a sample that is irradiated with a large-area unfocused beam. Thus, it is not necessarily true that the photoacoustic signal from the small damage site (or sites) will be greater than the overall photoacoustic signal that arises from the large-area linear absorption in the rest of the sample.

To investigate the photoacoustic signal that arises from linear absorption in a large area, we positioned a negative lens in the beam path and diverged the beam so that we had beam diameters at the thin-film surface ranging from 4 to 40 mm. While changing the beam diameter, we kept the energy per pulse constant. We obtained no observable signals above noise from beams of diameters 40, 20, and 10 mm. However, when the beam was reduced to 4 mm, a signal was obtained. In all cases, no damage was generated.

Since the total energy in the beam was the same for all shots, these results are, at first, somewhat surprising. We can, however, explain our results in terms of destructive phase interference. As we can see from Fig. 2-238, the photoacoustic detector is highly resonant at ~ 1 MHz. Thus, of all the acoustic waves produced by the nanosecond laser pulse heating, only those waves at ~ 1 MHz are detected. Since the sound velocity is $\sim 5 \times 10^5$ cm/sec, these waves have a wavelength of ~ 5 mm. Therefore, if we have a beam that is much larger than 5 mm, there will be destructive phase interference at the transducer because signals originating

from different positions in the illuminated area will have different phases at the transducer. Only when the beam diameter becomes comparable to or smaller than the acoustic wavelength is strong destructive phase interference absent. It is for this reason that we obtain no observable photoacoustic signal for beam diameters of 10 mm or larger, but see a signal when the beam diameter is 4 mm.

As long as the laser beam diameter is considerably greater than 1.2 wavelength of the acoustic waves that we are detecting, there will be essentially no observable photoacoustic signal from the large-area linear absorption. However, damage signals will be observable since they usually originate from areas smaller than the acoustic wavelength. To illustrate this effect, we have increased the laser intensity and diverged the beam to ~ 15 mm. Figure 2-241(a) shows the trace recorded when no damage was observed. As before, we see no photoacoustic signal. In Fig. 2-241(b), we see the trace recorded when small site damage occurred

Fig. 2-241. Oscilloscope traces for laser shots with beam diameter at 1.5 cm. (a) no damage this shot; (b) small-site damage this shot.

Fig. 2-242. Schematic of experimental setup for automatic recording of photoacoustic signal delay.

Fig. 2-243. Variation of recorded delay times as a function of distance between damage site and the photoacoustic detector.

within the 15-mm beam area. A photoacoustic signal is now clearly visible, and the delay to the first peak corresponds to the distance between the actual damage site and the detector.

Not only can we detect the occurrence of damage in a dielectric film, even in the presence of large-area beam absorption, but we can also deter-

mine the location of the damage site by measuring the signal delay time. To illustrate this capability, we performed the experiment schematically shown in Fig. 2-242. The gate of the timer shown in Fig. 2-242 is opened by the photomultiplier detecting the laser pulse. The gate is closed by the first positive pulse in the photoacoustic signal. The delay time is then read directly from the timer as the time during which the gate is opened. In Fig. 2-243, we have plotted the gate open times recorded by the timer for several distances between damage site and transducer. We obtain a linear graph whose slope is the sound velocity in the material. In an actual system, the damage site location would be determined by triangulation using two or three photoacoustic detectors, each giving a separate delay time.

Absorption Measurements of Optical Materials and Thin Films. High-energy laser systems employ many components with thin-film optical coatings such as lenses, reflectors, and polarizers. These optical components must exhibit very low optical absorptions and high damage thresholds at the laser

wavelength. For reflecting components, such as mirrors, it is sufficient that only the high-reflector (HR) films have low absorption and high threshold, while for transmitting components, such as lenses, both the antireflection (AR) coating on the surface and the bulk glass itself must possess low absorption and high damage thresholds. Typically, high-energy laser systems require that total absorption in an HR film, or an AR film and substrate, not exceed 10^{-4} of the incident radiation, and absorption levels in the low 10^{-5} region are preferred.¹⁶⁴

Currently, the only reliable method for accurate measurements of such low surface and bulk optical absorptions is laser calorimetry.¹⁶⁵ In this method, the optical absorption is detected by illuminating the sample with an appropriate high-power cw laser (5 to 10 W) for a fairly long period of time (≥ 10 minutes) and detecting the subsequent temperature rise in thermistors directly in contact with the sample. This technique is well-developed and quite sensitive, capable of measuring absorptions down to 5×10^{-6} . Laser calorimetry is, however, a difficult and time-consuming procedure and is not ideally suited for quick, routine monitoring of many samples. It also does not readily lend itself for scanning to test for thin-film and substrate uniformity.

We have shown in our studies on laser damage that the photoacoustic method can detect low absorptions.¹⁶⁶ The samples used in the low-absorption experiment are disks of silica or BK-7 glass, 5 cm in diameter and 1 cm thick with a thin-film coating on one side. Suitable neutral density filters are inserted into the beam to keep the energy flux at the sample below the threshold for laser-induced damage. The piezoelectric transducer is acoustically coupled with glycerine to the center of the uncoated rear surface of the sample. The output of the transducer is fed directly into an oscilloscope and the trace photographed when the laser is fired. The magnitude of the first or second peak in the photoacoustic signal (see Fig. 2-238) is read directly from the photograph.

In Table 2-53, we present our results for several laser shots at the same site on an HR $\text{TiO}_2/\text{SiO}_2$ -coated sample. By measuring the magnitude of the first peak in the photoacoustic signal, we avoid complications from the acoustic reflections from the various boundaries that arrive at later times. From Table 2-53, shot-to-shot repeatability for any one site is within $\pm 5\%$ at 10^{-4} absorption.

Table 2-53. Shot-to-shot repeatability – same site of an HR $\text{TiO}_2/\text{SiO}_2$ thin film with $\sim 10^{-4}$ absorption.

Laser energy, E_0 (J/cm ²)	PAS signal, q (mV)	q/E_0
0.041	0.11	2.68
0.042	0.12	2.86
0.038	0.10	2.63
0.040	0.11	2.75
Average = 2.73 ± 0.05		

Table 2-54. Site-to-site variation of an HR $\text{TiO}_2/\text{SiO}_2$ thin film with $\sim 10^{-4}$ absorption.

Site	q/E_0^a
1	3.87
2	4.65
3	3.72

^aAverage of 5 shots/site.

In Table 2-54, we show the averages of sets of five laser shots with each set of five taken at a different site of the same sample. In obtaining this data, the sample disk, which is mounted in a rotating holder, is rotated about its axis to present a new site to the fixed laser beam. Since the transducer is acoustically coupled to the sample with a fluid at the center of the rear surface, rotation of the sample can be done without moving the transducer. This ensures the same site-to-transducer distance for all sites. Furthermore, the circular geometry of the sample and transducer, and the fact that both the laser beam and transducer remain fixed in space, eliminate complications that might arise from directional variations in signal propagation and detection. The data of Table 2-54 indicate that site-to-site variation is considerably greater than shot-to-shot variation, suggesting that the absorption properties of this HR film are not highly uniform.

In Table 2-55 are absorption values measured by the pulsed piezoelectric method for a number of high-reflection films and a bare silica substrate. These values are compared with the results of laser calorimetry¹⁶⁷ obtained for the same type of films, although not for the same samples. Since our system has not been previously calibrated, we have taken

Table 2-55. Absorption measurements of $\text{HfTiO}_2/\text{SiO}_2$ films and of an uncoated silice substrate.

Sample	Laser calorimetry	PAS
1 HR film	$1.3 \times 10^{-2} \pm 10\%$	$0.6 \times 10^{-2} (\pm 2\%)$
2 HR film ^a	$1.2 \times 10^{-4} \pm 20\%$	$1.2 \times 10^{-4} (\pm 2\%)$
3 HR film	$1.4 \times 10^{-5} \pm 50\%$	$2.5 \times 10^{-5} (\pm 10\%)$
4 Fused silica substrate (8mm)	$4 \times 10^{-5} \pm 30\%$	$2.8 \times 10^{-5} (\pm 10\%)$

^aThe PAS results were normalized against this measurement.

the 10^{-4} sample as a reference point. Over an absorption range that varies by almost 10^3 , the photoacoustic results differ from the laser calorimetry results by no more than a factor of two. This difference may itself be simply due to the fact that the laser calorimetry was performed on different samples. Finally, we point out that the pulsed piezoelectric method is comparatively simple and rapid, with several measurements on a sample possible in under 15 min using a laser of 50 to 100 mJ energy operating in a single-shot mode.

Photoacoustics thus provides an easy and rapid means for obtaining low-absorption measurements on optical components and thin films. The pulsed piezoelectric technique can measure absorptions accurately in the 10^{-5} range, and can probably be extended into the 10^{-6} range. Although the experiments reported here were performed with a single-shot, high-power pulsed laser, it is clear that much more convenient and less costly configuration could employ a 1 to 5 mJ laser operating at $\sim 1 \mu\text{s}$ and at a 10 to 20 Hz repetition rate. The photoacoustic signal would be measured with a boxcar integrator properly gated to record only the absorption signal or by a transient signal analyzer. We can expect that such systems will be more sensitive than the single-shot system because of the averaging capabilities inherent in repetitive pulse and boxcar or digital signal averaging.

In summary, photoacoustics provides a means for performing low-absorption measurements on optical materials and thin films with a sensitivity that can approach that of laser calorimetry. In addition, the photoacoustic method is easier to use and much quicker. Finally, with photoacoustics, scanning of thin films and optical materials for uniformity and homogeneity can be readily performed.

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Surface Physics and Chemistry of Laser-Induced Damage

This program of basic research into the surface physical and chemical processes which affect laser damage threshold complements the directed research and development of damage-resistant materials which is reviewed in a previous section on "Damage Studies." The goals of this study are to

- Determine the physical mechanisms of surface and bulk material damage.
- Determine the relation between damage thresholds of the bulk and atomically clean surfaces.
- Determine dependence of the threshold on physical structure of the surface.
- Determine the effect of surface absorption of foreign atoms, deposition of one or more atomic layers of foreign atoms, and of surface chemical reactions such as segregation of constituents or migration of impurities to the surface.

The basic approach taken in these experiments is to prepare and characterize the surface in ultra-high vacuum (UHV) and measure the damage threshold *in situ*. We built a UHV sample chamber containing implements for crystal cleaving, sample

Fig. 2-244. Schematic diagram of vacuum chamber apparatus for study of surface physics and chemistry of laser-induced damage.

manipulation, and measurement of neutral and charged particle emission during laser beam irradiation. A schematic diagram of the vacuum chamber apparatus is shown in Fig. 2-244. This apparatus was used in a series of experiments in which polished or cleaved surfaces of NaCl, KCl, and SiO₂ were irradiated by a Nd:glass laser. We measured the number of desorbed neutral and charged particles as a function of the laser pulse fluence. We found that particle desorption occurs at irradiation fluences considerably below those which cause visible damage to the surface. Since thermal heating of the surface does not occur at low fluences, the observed desorption implies that the laser radiation interacts strongly with surface atoms, either with the constituents of the insulator or with adsorbed foreign atoms.

Neutral and charged particles were emitted in a constant ratio over the range of fluences investigated. The dependence of particle emission on fluence suggests a power law which is consistent with a multiphoton excitation of electrons across the material's fundamental band gap. These results are preliminary; however, they are important

because they indicate that we do receive information about non-linear laser interactions in the first monolayers.

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Neodymium Laser Materials

Chlorophosphate Glass. The structures of NaPO₃ and ZnCl₂ glasses are well established and both components are miscible in all proportions. The addition of ≥ 40 mole % ZnCl₂ to a sodium metaphosphate glass narrows the Nd³⁺ fluorescence bandwidth. We have found that the associated stimulated emission cross section of a chlorophosphate glass is the largest we have measured in any glass.

Recent studies of the Na

PO₃-ZnCl₂ glass system demonstrated a continuous breakdown of the metaphosphate polymeric structure upon the addition of ZnCl₂ and also showed evidence of mixed oxychloride coordination shells for the cations.¹⁶⁸ We observed¹⁶⁹ a similar mixed-anion coordination at Nd³⁺ sites in fluorophosphate glasses, where the fluorine to oxygen ion ratio ranged from zero to greater than two. The fluorescence bandwidths in these glasses are broader than in simple phosphate or fluoride glasses and the effective stimulated emission cross sections are smaller. This occurs because the fluorescence wavelengths of Nd³⁺ in pure oxide and pure fluoride glasses differ considerably (for example, 1047 to 1049 nm in fluoroberyllate glasses vs 1053 to 1055 nm in phosphate glasses). This nephelauxetic shift results from the expansion of the 4f electron shell of the rare-earth ion when it is introduced into a solid. This reduces the electrostatic and spin-orbit coupling parameters and the electronic states shift to lower energies. The more covalent the bonding, the greater the shift. Since the

covalency is greater for chlorine than for fluorine ligands, the wavelength of a chlorine-coordinated ion fluorescence is expected to be more nearly equal to that of an oxygen-coordinated ion in a phosphate glass. To explore the effect of the addition of chlorine on the spectroscopic properties of Nd^{3+} , we examined several chlorophosphate glasses.

A series of Nd-doped chlorophosphate glasses were prepared for us by R. Almeida of UCLA. All samples were melted in glazed porcelain crucibles between 920 and 1120 K and cast into preheated graphite molds at about 873 K. Although glass formation was obtained throughout the entire composition from 0 to 100% ZnCl_2 , melts containing more than 42 mole % ZnCl_2 had to be severely quenched and yielded poor-quality, easily crystallized glasses. In addition, the substitutional limit for Nd_2O_3 in the high- ZnCl_2 -content glasses was low, 0.1 mole %. The chlorine content of the final glasses was determined using Volhard's method; the neodymium content was determined by spectrochemical analysis. Some water was present in all glasses.

The densities and refractive indices of several chlorophosphate glass compositions are given in Table 2-56. The ratio of the number of chloride to oxygen anions never exceeded 0.5. The Abbe value v , given by $(n_D - 1)/(n_F - n_C)$, is included in Table 2-56. The nonlinear refractive index n_2 , estimated¹⁷⁰ from n_D and v , is in the range 1 to 2×10^{-13} esu.

The absorption and fluorescence spectra were recorded at 295 K. The Judd–Ofelt intensity parameters were derived from the absorption spectra and used to predict the radiative transition probabilities.¹⁷¹ The results are summarized in Table 2-57. The parameter Ω_2 decreases with increasing ZnCl_2 , whereas, Ω_4 and Ω_6 show only small

changes. The effective line width of the $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{11/2}$ fluorescence band decreases monotonically with the addition of ZnCl_2 . This, combined with the increasing refractive index, results in the large values for the simulated emission cross section σ . The estimated uncertainty in the σ values in Table 2-57 is $\pm 0.4 \times 10^{-20} \text{ cm}^2$. The fluorescence branch ratio was in the range 0.49 to 0.50 for all glasses in Table 2-57. The wavelength of the fluorescence peak was $1055.0 \pm 0.5 \text{ nm}$.

The fluorescence decays were measured over three e-folding times and were nearly exponential (characteristic of phosphate glasses) with decay times between 320 and 340 μs for glasses with ≈ 20 and 40 mole % ZnCl_2 . The lifetime of NaPO_3 is reported to be 360 μs ; however, it was shorter in our glasses, presumably because of the presence of water. The Nd^{3+} concentrations were $\sim 3 \times 10^{19} \text{ cm}^{-3}$, therefore, ion-ion self-quenching should be negligible. The measured fluorescence decay times are in reasonable agreement with the predicted radiative lifetimes τ_R , assuming negligible non-radiative decay by multiphonon emission. The τ_R values are systematically lower than experimental values, a characteristic common to Judd–Ofelt analysis of Nd^{3+} optical spectra.¹⁷¹

The change in fluorescence line shape and width with composition is shown for three glasses in Fig. 2-245: zinc metaphosphate, sodium metaphosphate, and mixed $\text{NaPO}_3\text{-ZnCl}_2$ glass. The width is smaller for the monovalent modifier cation Na than for divalent Zn. A further narrowing occurs when O^{2-} is partially replaced by Cl^- . No Stark structure is resolved in any of the glass spectra, thus indicating that the structural disorder is sufficient to create associated inhomogeneous broadening greater than the separation of individual Stark levels. This disorder is not apparent by a nonexponential dependence of the fluorescence decay. This, however, may be because the highest spectral density of sites have approximately the same excited-state lifetimes.¹⁷²

The stimulated emission cross section of the 37 mole % ZnCl_2 phosphate glass is the largest we have observed for any oxide or halide glass. (The largest value observed previously was that for a tellurite glass, as reported in the 1978 Annual Report.)¹⁷³ The addition of chlorine or other halides, such as bromine and iodine, to other glasses may have similar effects. (The amount of halide that can be in-

Table 2-56. Compositions and properties of chlorophosphate glasses.

Composition ^a (mole %)	Cl/O ratio	Density (g·cm ⁻³)	n_D	v_D
99.9 NaPO ₃	0	2.525	1.485	66
81.3 NaPO ₃ ·18.6 ZnCl ₂	0.15	2.692	1.527	58
66.6 NaPO ₃ ·33.3 ZnCl ₂	0.33	2.721	1.547	49
62.4 NaPO ₃ ·37.5 ZnCl ₂	0.40	2.720	1.55	48

^aAll samples contain 0.1 mole % Nd_2O_3 .

Table 2-57. Spectroscopic properties of Nd³⁺-doped chlorophosphate glasses at 295 K.

Glass ^a (mole %)	Judd-Ofelt parameters (pm ²)			$\lambda_{\text{eff}}(\text{nm})$	⁴ F _{3/2} → ⁴ I _{11/2} fluorescence	
	Ω_2	Ω_4	Ω_6		$\tau_R(\mu\text{s})$	$\sigma(10^{-20}\text{cm}^2)$
99.9 NaPO ₃	3.8	5.3	6.0	23.3	350	4.6
81.3 NaPO ₃ ·18.6 ZnCl ₂	3.5	5.4	6.6	22.6	300	5.2
66.6 NaPO ₃ ·33.3 ZnCl ₂	2.4	5.9	6.2	21.7	290	5.4

^aAll samples contain 0.1 mole % Nd₂O₃.

Fig. 2-245. Comparison of the ⁴F_{3/2} → ⁴I_{11/2} fluorescence spectra of Nd³⁺ in metaphosphate and chlorophosphate glasses at 295 K.

roduced may be limited, however.) The nephelauxetic shift will be greater for Br or I and, depending upon the wavelength of the pure oxide glass, may lead to undesired spectral shift and inhomogeneous broadening.

Cubic Zirconia. Mixed crystals (solid solutions) have a statistically disordered structure. Activator ions added to these materials are distributed in sites of different symmetries and local fields. The superposition of spectra from individual centers leads to inhomogeneously broadened absorption and fluorescence lines. The spectroscopic properties of activator ions in mixed crystals are frequently intermediate to those of single crystals, which are homogeneous, and those of glasses, which are very inhomogeneous. In the case of glass, inhomogeneous broadening is favorable for efficient optical pumping and good energy storage. Thus, mixed crystals may be of interest for high average power laser applications if these spectroscopic features can be achieved while retaining other

favorable physical properties of crystals, such as mechanical and thermal properties.

Examples of mixed or disordered Nd laser crystals exhibiting inhomogeneously broadened optical spectra include the yttrifluorides (CaF₂-YF₃) (Ref. 174) and the garnets (Y₃Lu₃Al₅O₁₂) (Ref. 175) and Y₃(Al, Ga)₅O₁₂ (Ref. 176). The variation of the Nd³⁺ optical line width with ThO₂ addition in the polycrystalline ceramic Y₂O₃-ThO₂ has also been studied.¹⁷⁷

We have examined another mixed crystal, cubic zirconia (CZ). Zirconium oxide, ZrO₂, has several crystalline phases (polymorphs).¹⁷⁸ Normally, the structure is monoclinic. Above 2573 K, the structure becomes cubic (O_h²-Fm $\bar{3}$ m) but on cooling reverts to the monoclinic phase. However, the cubic phase can be stabilized at ambient temperatures by adding compounds such as CaO or Y₂O₃ to the melt in concentrations ranging up to ≥ 15 wt%. While the resulting crystal is optically isotropic, on a microscopic scale it is a randomly disordered solid solution.

A cubic zirconia crystal doped with Nd₂O₃ was prepared for us by R. E. Belt and R. A. Hartzell of Airtron using a skull melting technique. Neodymium ions enter the lattice substitutionally at Zr⁴⁺ ions (the ionic radii, *f*, of the components are Zr⁴⁺: 0.79, Y³⁺: 0.92, Ca²⁺: 0.99, and Nd³⁺: 1.04). The combination of the charge compensation scheme and the stabilizing additive(s) results in site-to-site differences in the local environments and fields experienced by Nd³⁺. This is evident from the spectroscopic properties.

The room-temperature absorption spectrum of Nd³⁺ in CZ is shown in Fig. 2-246. The host is transparent from approximately 0.4 to 6.0 μm .

Fig. 2-246. Absorption spectrum of Nd^{3+} -doped cubic zirconia recorded at 295 K. Nd_2O_3 concentration: 0.45 wt.%; sample length: 10.0 mm.

Some Stark structure is resolved in the optical spectra. Judd-Ofelt intensity parameters were derived from the absorption spectrum and have the following values (pm^2):

- $\Omega_2 = 1.24 \pm 0.18$
- $\Omega_4 = 1.07 \pm 0.26$
- $\Omega_6 = 1.20 \pm 0.12$

These are among the smallest values observed for Nd^{3+} in any solid host. The large Stark splittings suggest that the noncentrosymmetric field necessary for electric-dipole transitions may arise from the second coordination shell.

The $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{11/2}$ fluorescence spectrum is shown in Fig. 2-247. The Stark structure is only partially resolved. For comparison we have included in Fig. 2-247 the spectrum of Nd^{3+} in another oxide host, $\text{Y}_3\text{Al}_5\text{O}_{12}$ (YAG). Using the Judd-Ofelt parameters, we determined the effective stimulated emission cross section in a manner similar to that used by Krupke¹⁷¹ for treating Nd^{3+} in glass. The peak cross section is $\sim 1.9 \times 10^{-20} \text{ cm}^2$ at 1062 nm, a wavelength equal to that of high-gain silicate glasses such as FD-2 and LSG-91H.

Site-to-site differences are also revealed by the fluorescence decay which is nonexponential and varies from an initial lifetime of 370 μs to a lifetime of 680 μs at the third e-folding time. The radiative lifetime predicted from the Judd-Ofelt parameters is an effective average over the different sites. The

Fig. 2-247. Comparison of the $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{11/2}$ fluorescence spectra of Nd^{3+} in cubic zirconia and $\text{Y}_3\text{Al}_5\text{O}_{12}$ (YAG) at 295 K. (Peaks are normalized to unity.)

value of 480 μs is in reasonable agreement with the observed values. Similar nonexponential fluorescence decay behavior and agreement between measured and predicted lifetimes are observed for Nd^{3+} -doped glasses.¹⁷⁹

Laser action of Nd^{3+} in CZ has been reported by Aleksandrov et al.¹⁸⁰ at 1.0609 μm and by Aleksandrov et al.,¹⁸¹ at 1.3320 μm . The Stark splittings of the $^4\text{I}_{11/2}$ and $^4\text{I}_{9/2}$ manifolds are large. The highest Stark level of the $^4\text{I}_{9/2}$ manifold occurs at 954 cm^{-1} at 295 K compared to values of $\geq 880 \text{ cm}^{-1}$ in garnet crystals (see tables in Ref. 174). This is attractive for 4-level $^4\text{F}_{3/2} \rightarrow ^4\text{I}_{9/2}$ laser action.

The refractive index of CZ is high ($n_D \approx 2.19$, $n_D \approx 33$), which is one of the reasons for its success as an imitation diamond.¹⁷⁸ The estimated nonlinear refractive index n_2 is also high, $\sim 10^{-12}$ esu. This is unattractive for high intensity laser applications where self-focusing must be controlled. The values of all physical and spectroscopic properties will vary slightly depending upon the exact nature and amount of stabilizer added to form CZ.

The thermal conductivity of crystals is generally much greater than that of glasses for temperatures ≥ 300 K. The conductivity of CZ is disappointing in this respect. Because of the disordered nature of the stabilized material, the phonon mean free path is expected to be small. This probably accounts for the low values of conductivity, <0.02 W/cm- $^{\circ}$ C.¹⁸²

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