259
2/11/80

Dr: 668

UCRL-50021-78

Laser Program **Annual Report ~ 1978**

Volume 2

MASTER

Lawrence
Livermore
Laboratory

Laser Program **Annual Report – 1978** **Volume 2**

Scientific Editor: Michael J. Monsler
Publication Editor: Brian D. Jarman

MS date: March 1979

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

LAWRENCE LIVERMORE LABORATORY
University of California • Livermore, California • 94550

Available from : National Technical Information Service • U.S. Department of Commerce
5285 Port Royal Road • Springfield, VA 22161 • \$14.00 per copy • (Microfiche \$3.00)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Key

FOREWORD

This volume consists of Sections 5 through 7 of the 1978 Laser Program Annual Report. The remaining sections are published under separate cover in Volume 1 (Sections 1 through 4) and Volume 3 (Sections 8 through 10).

CONTENTS

Section 5 – Laser Fusion Experiments and Analysis	5-i
Section 6 – Diagnostic Technologies	6-i
Section 7 – Solid State Laser Technology	7-i

Section 5

*Laser
Fusion
Experiments
and
Analysis*

SECTION 5

CONTENTS

5.1	Introduction	5-1
5.2	Time-Resolved Suprathermal X Rays	5-2
5.3	Absorption and Stimulated Scattering of 1.06- μ m Light in Laser-Irradiated Gold Disk Experiments	5-5
5.3.1	Absorption	5-6
5.3.2	Stimulated Scattering	5-8
5.4	Studies of Closure Phenomena in Pinholes Irradiated by Nd Laser Pulses	5-16
5.5	Hyperion Experiments on Shiva	5-22
5.5.1	Introduction	5-22
5.5.2	Alignment	5-22
5.5.3	Start-Up Experiments	5-29
5.5.4	Hyperion Campaign	5-35

SECTION 5

LASER FUSION EXPERIMENTS AND ANALYSIS

5.1 Introduction

Despite heavy emphasis on activation of the Shiva target irradiation facility, we were still able to perform experiments on the Janus, Argus, and Shiva systems. Also, we were able to provide significant new insight and understanding of the physics required to implode targets to high densities.

We used the Janus laser system for experiments on the performance of spatial filter pinholes that are required for operating high power fusion laser systems. Clearly, as laser intensity loading on the edges of the pinhole exceeds plasma breakdown conditions, a plasma forms and propagates into the vacuum pinhole. This causes refraction and loss of transmission of the beam through the pinhole. By using the Janus laser and target chamber, we were able to irradiate pinholes of various materials and sizes with known intensities. Also, we were able to measure the rate of closure as a function of the loading on the pinhole. This series of experiments, described in §5.4, was critical to the staging of pinholes in the Argus and Shiva laser systems and in planning the layout of the Nova facility.

At the end of the spatial filter pinhole experiments, we took three months to finish the upgrade of the Janus system. This made its staging consistent with the latest understanding of the necessity for image relaying throughout the laser system. We completed the upgrade in May. At that time, because of manpower commitments to Argus and Shiva, the system was turned over to H Division for equation-of-state experiments.

Because of the commitment of personnel for activating the Shiva system, we operated Argus on a single-shift basis for the first six months of 1978 with only minimal preventive maintenance. In June, we were able to reestablish two shift operations and to establish a complete preventive maintenance program. We also restaged the Argus system to allow 2-kJ operation at 1 ns, which was required for the high density campaign.

In addition to the high density campaign, we used the Argus system to study the physics of absorption and stimulated scattering. Late in 1977, we

determined that stimulated Brillouin scattering could become very important in preventing laser energy from being absorbed by our fusion targets. In 1978, we continued our investigation of this area, primarily using high-Z materials for the targets. As a result of these experiments, we were able to formulate an approximate theory to allow us to calculate the effects of stimulated Brillouin scattering for our experimental conditions. Also, these high-Z disk experiments demonstrated the necessity for nonlocal thermodynamic equilibrium (non-LTE) physics to properly model the absorption and x-ray emission from the high-Z disk experiments. The experiments and analysis also demonstrated the requirement for inhibited thermal conduction. These disk experiments have thus significantly increased our understanding of the coupling of laser light to the target and the energy transport in the dense target plasma.

The activation period for Shiva extended from November 1977 through August 1978. During this period, we brought up the laser beam lines in groups, starting with one and then a group of four and then groups of five. As each group of beam lines was completed for operation into the target chamber, we performed a small number of exploding-pusher experiments designed to prove the quality of the laser system. These experiments consisted of a single-beam target irradiation, a 4-beam target irradiation, and 10- and 20-beam target irradiations. One 20-beam shot was performed on May 18, 1978, at the full power capability of the Shiva system: 27 TW were delivered in a 90-ps laser pulse. The exploding-pusher target produced a 6-keV ion temperature and 7×10^9 neutrons.

In September, we began our first target campaign with the completed Shiva system. A Hyperion series, conducted at the 15-to-20-TW level, produced a new record exploding-pusher neutron yield of 3×10^{10} . Hyperion was intended simply to increase the neutron record and at the same time continue to demonstrate our ability to properly focus 20 beams onto small laser fusion pellets.

In October, we shifted the emphasis and moved the high density implosion experiments from Argus to Shiva. By the middle of December, we had irradiated a number of different target designs and had achieved a neutron yield of 4×10^6 neutrons from a high density target design. Subsequent experiments in early 1979 confirmed that the fuel densities achieved in this target design were ≥ 50 times liquid density. The high density campaign on Argus and Shiva has generated significant new understanding of the requirements for high density implosions. We have also developed the diagnostic techniques to measure the high densities.

Authors

H. G. Ahlstrom
J. H. Nuckolls

5.2 Time-Resolved Suprathermal X Rays

In the 1977 Laser Program Annual Report,¹ we described time-resolved high energy x-ray spectra measurements obtained from laser-irradiated high-Z disk targets. By using the X-1 streak camera and a multichannel filter pack, we were able to obtain the first time-resolved direct observation of suprathermal x-ray tail behavior. Such behavior resulted from hot electron generation caused by collective processes.

Our measurements indicated that the suprathermal temperature θ_H has a temporal behavior that essentially follows the laser pulse of intensity I . These data imply a relation $\theta_H \sim I^n$, where $n \sim 1$ before the peak of the laser pulse and $n > 1$ after the peak. Because energy-loss time for a hot electron at ~ 10 keV is, classically, only a few picoseconds in the relevant spatially averaged plasma, it seems reasonable that the hot x-ray behavior should follow the laser pulse. The fact is that $n > 1$ is still unexplained. But we speculate that this may be due to enhanced Brillouin scattering, because it can cause laser intensity at critical to drop off more sharply in time than the temporal Gaussian of the incident pulse.²

We performed two important calibrations on the ultrafast X-1 x-ray streak camera.³ One was the

Fig. 5-1. Measured total response of X-1 x-ray streak camera.

characterization of the overall response of the streak camera in the energy range 4.5 to 98.4 keV. The other was the calibration of instrument streak speeds when the total sweep time was increased from 1 to 3 ns. The longer sweep time was necessary because many of the target shots were carried out using 1-ns FWHM pulses. Also, we obtained time-resolved suprathermal x-ray data from Argus disk experiments with target materials of different atomic number.

Measurements of streak camera total response were performed on a monoenergetic x-ray source (the L-Division Picker x-ray machine). We used well-characterized flux values at given x-ray energies from 4.5 to 98.4 keV to obtain film exposure through the streak camera. Figure 5-1 shows the total response of camera X-1. In this figure, relative sensitivity per keV is plotted as a function of x-ray energy $h\nu$. It is interesting to note that this curve is somewhat different than the theoretical response curve for a gold photocathode,⁴ which has been used for previous data reduction. The differences are: (1) the gold L-edges ~ 12 to 14 keV are not observed and (2) the drop in sensitivity between ~ 6 to 30 keV is a stronger function of photon

energy; i.e., the sensitivity is proportional to $(h\nu)^{-n}$, where $n \approx 2.5$ in the present case compared with $n \approx 1.6$ for an Au photocathode.⁴ We have not yet tried to investigate the cause of the discrepancy, but we have simply used this measured total response as the basis for further data reduction. We speculate that cathode surface contamination may be the cause of the discrepancy.

We calibrated streak speeds on the monojoule facility, using the following method:

- The switched-out pulse from the monojoule facility was directed into an air-gap Fabry-Perot etalon with reflectivities of 50 and 100%.

- The x rays were generated by a train of 1.06- μm pulses of monotonically decreasing intensity. These pulses, separated by the double transit time of the etalon, were incident upon a stainless steel strip target.

- Figure 5-2 shows a typical result of a calibration streak record. Because the transit time is fixed, and the distance between streaks of the film can be measured, the streak speed can be obtained.

By varying the delay on the streak camera, one can move the exposure pattern across the entire tube image area. Thus the sweep speeds over the whole range of the image area (diameter ~ 4 cm) can be obtained. Figure 5-3 shows the measured inverse sweep speed (ps/mm) as a function of position on the streak camera image area. It is quite obvious that the streak speed is not constant and uniform throughout the whole sweep range. We have incorporated this calibration curve into the unfolding procedure. The instrument dynamic range has also been obtained by this calibration. From Fig. 5-2, we see that the dynamic range is $\sim 10^3$.

Time-resolved suprathreshold x rays from Argus disk experiments were measured with the x-ray streak camera. The disks were typically ~ 500 - μm diam and about 20-to-30- μm thick. We used targets made of four different materials (gold, tantalum, molybdenum, and zinc). All targets were irradiated by nominal 1-ns (FWHM) pulses with nominal peak intensities of 3×10^{15} W/cm². We used the 11-channel filter pack.¹

Fig. 5-2. Streak record and corresponding microdensitometer trace used for instrument sweep speed and dynamic range calibration.

Fig. 5-3. Calibrated inverse sweep speed as function of sweep position on image area for 3-na total-sweep mode.

The streak records obtained for the Au and Ta disks are quite similar to the Au-disk results reported earlier.^{1,2} Streak records of Ta disks and Mo disks are quite different in energy channels above ~10 keV, i.e., the range where suprathermals become important.¹ An example is shown in Fig. 5-4. Note that in the channels above 10 keV, the relative x-ray intensity obtained from the Ta disk is a factor of 3 to 5 higher than that of the Mo disk, whereas the relative x-ray intensities in energy channels below 10 keV, in the thermal spectrum, are almost the same. This is caused by the Z-dependence of the target material, as can be seen from the equation given by Krue,⁵

$$\left(\frac{Z}{79}\right) 5 \times 10^{11} E_{\text{HOT}} = F, \quad (1)$$

where Z is the atomic number of the target material, E_{HOT} is the energy that went into hot electrons in joules, and F is the fluence in keV/keV at θ_{HOT} . For the example shown here, θ_{HOT} is 27 keV for the Mo disk ($Z = 42$) and 45 keV for the Ta disk ($Z = 73$),⁶ and the fluences are 6×10^{11} keV/keV for the Mo disk and 2×10^{12} keV/keV for the Ta disk. This gives $E_{\text{HOT(Mo)}} = 2.26$ J and $E_{\text{HOT(Ta)}} = 4.33$ J. The fraction of incident laser energy converted into

hot electrons is thus ~0.5% for Mo and 1% for Ta. For Zn disks, no measurements with the streak camera were made. However, FFLEX measurements indicate that the fluences at energies above 10 keV are quite low.⁶ Thus the x-ray streak camera would not have been sensitive to obtain suprathermal signals in any case.

The disk experiments using materials of different atomic number have provided us with the first set of time-resolved suprathermal data where the effect of target material atomic weight becomes obvious.

References

1. P. Lee and M. Rosen, *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), pp. 6-17 to 6-21.
2. P. H. Y. Lee and M. D. Rosen, "Time-Resolved High-Energy X-Ray Spectra of Laser-Irradiated Targets," *Phys. Rev. Lett.* **42**, 236 (1979).
3. D. T. Attwood, L. W. Coleman, J. T. Larsen, and E. K. Storm, "Time-Resolved X-Ray Spectral Studies of Laser-Compressed Targets," *Phys. Rev. Lett.* **37**, 499 (1976).
4. B. L. Henke, J. A. Smith, and D. T. Attwood, "0.1-10-keV X-Ray-Induced Electron Emissions from Solids—Models and Secondary Electron Measurements," *J. Appl. Phys.* **48**, 1852 (1977).
5. W. Krue, Lawrence Livermore Laboratory, Livermore, Calif., private communication (December 1978).
6. B. Pruett, Lawrence Livermore Laboratory, Livermore, Calif., data obtained from FFLEX measurements (November 15, 1978).

Author

P. H. Y. Lee

Fig. 5-4. Characteristic time-resolved suprathermal x-ray signals for targets of different Z . Targets were irradiated by 1-ns FWHM pulses with intensities of 3×10^{15} W/cm 2 .

5.3 Absorption and Stimulated Scattering of 1.06- μ m Light in Laser-Irradiated Gold Disk Experiments

For low- Z targets irradiated at 1.06- μ m with short pulses (100 ps) at moderately high intensities (10^{15} W/cm 2), it has been found that collective processes dominate the absorption process.^{7,8} Inverse bremsstrahlung, the classical absorption mechanism, seems to have played only a minor role

in these experiments. This is unfortunate, because inverse bremsstrahlung has the potential of leading to very high absorptions, whereas collective processes have led to absorptions only in the 30 (± 10)% range.^{7,9,10} The latter have created suprathermal electrons that can preheat and degrade the performance of a laser fusion target.¹¹⁻¹³ The inverse bremsstrahlung absorption coefficient is proportional to the mean ionization Z and inversely proportional to $T_e^{3/2}$. Because of this, high- Z targets irradiated at low intensity with long laser pulses most efficiently absorb the light. The

long irradiation time allows a long region of underdense plasma to form and provides the time necessary for local thermodynamic equilibrium (LTE) among the ionization states to be achieved.

Here we present basic data on absorption and stimulated scattering for high-Z disks irradiated by one beam of the Argus laser with long-pulse irradiation (200 to 1000 ps). These experiments were also discussed in §6.7 of the 1977 Annual Report.¹⁴ In particular, the x-ray spectrum, fraction of energy radiated, and angular dependence were covered, as well as some of the absorption and stimulated scattering results. For continuity there is necessarily some overlap in the material presented here. The light intensity was varied from 7×10^{13} to 5×10^{15} W/cm² by changing the laser energy from 50 to 500 J and the irradiated spot diameter from 150 to 450 μ m. The targets were gold disks, 10-to-20- μ m thick and 500- μ m diam, placed in the converging part of the beam focused by an f/2.6 lens (11.0° marginal ray angle). The measured absorptions were much less than what would be expected if there were no heat flux inhibition and no stimulated scattering. The backscattered light was predominately red-shifted even for normal incidence, and the mean red shift increased when the disk was tilted. We discuss first the absorption and then the spectral measurements.

5.3.1 Absorption

The absorption fraction is usually determined directly by an array of plasma calorimeters⁸ that measures the x ray and particle energy and indirectly by an array of silicon photodiodes (all with 100-Å bandpass interference filters) that maps the distribution of sidescattered light.

The plasma calorimeters have two equal-sensitivity receivers. One is covered by a glass window to stop particles and absorb x rays; thus, it responds only to the light energy. The other receiver is bare and responds to all three forms of energy impinging on it. Thermoelectric modules, which measure the temperature differentials of the receivers with respect to a common heat sink, are connected in opposition with appropriate compensating circuits. This automatically subtracts out the light contribution to the signal. The aluminum receivers are backed by copper for fast thermalization. The aluminum reflects most of the incident light and sputters less than most other materials under ion impact.

We calibrated the photodiodes to several percent relative accuracy and 10% absolute accuracy. Heavy metal holders and lead glass windows provided shielding against x rays. A blast shield over each diode was necessary to prevent the detector calibration factor from changing with time due to either a reflective coating being deposited on the neutral density filter or to pitting of the filter.

On separate laser shots, a nearly totally enclosing 1.06- μ m light calorimeter (the box calorimeter) performed the same task as the photodiodes, only in a spatially continuous manner. The box calorimeter provided a highly accurate measurement of the absorbed energy for two reasons. First, it was calibrated to 1% accuracy. Second, the box calorimeter, together with the laser calorimeters measuring light backreflected and transmitted together through the two target chamber lenses, covered 96% of a 4π solid angle. An inner glass box, thermally isolated from the rest of the calorimeter, prevented x rays and particles from reaching the absorbing glass receivers.

The array of 40 photodiodes was mounted on two "theta-arch" rings placed close to being either in or out of the plane of polarization, as shown in Fig. 5-5. The photodiodes measured the sidescattered light distribution for $22.5^\circ < \theta < 157.5^\circ$ in increments of 7.5° . Approximately diagonally opposite to these two photodiode rings, we placed two rings of plasma calorimeters. We specified detector positions in a spherical coordinate system in which the two f/2.6 lenses were at the poles $\theta = 0$ and 180° . The upward direction defined the azimuth $\phi \approx 0^\circ$, and both beams were linearly polarized at $\phi_E \approx 104.8^\circ$.

Table 5-1 describes the absorption results for irradiations that were Gaussian in time with an FWHM of 1 ns. The numbers quoted are the more accurate box calorimeter results and have about a

Table 5-1. Absorption for irradiations that were Gaussian in time.

Intensity, W/cm ² (J)	3×10^{15} (450)	3×10^{14} (450)	3×10^4 (45)
Normal incidence (%)	36	50	54
45° incidence (%)	33	42	—

10% error associated with them: thus a 50% absorption might be 45 to 55%. The auxiliary measurements made by the discrete PIN diodes and plasma calorimeters agree with the box calorimeter measurements to within the respective uncertainties. We irradiated targets in two configurations: normal incidence and with the disk tilted 45° to the incident laser beam.

We see that absorption drops with increasing intensity, as expected. Figure 5-6 shows how inverse bremsstrahlung absorption varies with intensity for several values of L and the parameter $\epsilon Z \ln \Lambda$. The absorbed flux is assumed to be a fraction of the free-streaming electron heat flux value:

$$f_{\text{abs}} I_{\text{inc}} = \epsilon \sqrt{\frac{2kT}{m_e}} kT n_c, \quad (2)$$

where m_e is the electron mass and n_c is the critical

density of 9.85×10^{20} electrons/cm³. The fraction absorbed for light normally incident on a linear density ramp with the scale length L defined by $n_c = n_c(x/L)$ is

$$f_{\text{abs}} = 1 - \exp \left[\frac{-32}{15} k_o L \frac{\nu_{\text{cr}}}{\omega_o} \right], \quad (3)$$

where

$$\frac{\nu_{\text{cr}}}{\omega_o} = \frac{\bar{Z}}{N_D} \frac{k n \Lambda}{11.3}. \quad (4)$$

Here N_D is the number of electrons in a sphere with a radius equal to the electron Debye length $\lambda_{De} = (kT_e/4\pi n_e e^2)^{1/2}$ in cgs units. The Debye electron

length at critical density is more simply expressed by

$$\lambda_{De} = \frac{\lambda_0}{2\pi} \sqrt{\frac{kT_e}{m_e c^2}}, \quad (5)$$

where λ_0 is the vacuum wavelength of $1.064 \mu\text{m}$. The flux-limited electron temperature θ_e can be expressed as

$$\theta_e = \left[\frac{1}{\sqrt{2}} \frac{f_{abs}}{\epsilon} \left(\frac{v_{osc}}{c} \right)^2 \right]^{2/3} m_e c^2, \quad (6)$$

where $(v_{osc}/c)^2 = 1(W/cm^2)/(1.208 \times 10^{18} W/cm^2)$ for $\lambda_0 = 1.064 \mu\text{m}$. We find that L must be $\sim 10 \mu\text{m}$ to be consistent with the experiment. For L to be so much smaller than $c\tau$, the heat flux inhibition must be severe. Also notice that absorption decreases little when the target is rotated 45° . Most of the absorption must occur at densities less than the turning density of $0.5 n_c$. Inverse bremsstrahlung absorption is clearly indicated, because absorption increases with pulse length and decreases with intensity.

Two-dimensional Lagrangian hydrodynamics simulations, with LTE ionization physics and classical electron transport, predict very efficient absorption (close to 100%), by means of inverse bremsstrahlung, for low intensity, 1-ns experiments.

We find that the inclusion of inhibited electron thermal conduction is crucial. Transport inhibition causes steepened temperature and density profiles near the critical surface and produces an electron temperature of several keV in the underdense corona. This in turn makes the inclusion of non-LTE ionization physics crucial as well. We must correctly compute the level populations of the high- Z atoms moving rapidly through a steep density gradient into the corona. With the inclusion of these two features, the reduction in L , $T_e^{3/2}$, and Z brings the calculated absorptions down to the measured values. Also, the simulations produce an x-ray spectrum remarkably close to that experimentally observed.

The inclusion of conduction inhibition and of non-LTE physics in the simulations is also essential in reproducing other experimental data, such as coronal electron temperature, the amount of x rays radiated by the disk, and the thickness of the x-ray emission region.

5.3.2 Stimulated Scattering

In these experiments, there is strong evidence that stimulated side- and back-scatter occur. This denies some of the light access to the density region $n_e > n_c/4$. Thus, little of this light is absorbed. The evidence lies in the facts that backscattered light always shows a clear red shift and that much more light is always scattered out of the plane of polarization than in it.

To give some feeling of when stimulated scattering will occur, we first discuss its growth in a

homogeneous plasma. Let $\tilde{A}_f$, $\tilde{A}_b$ be the complex vector potentials of the forward (incident) and backward (reflected) light waves and let n_e be the complex electron density. Each physical variable equals the real part of the product of its complex amplitude with a harmonic factor of the form $\exp(i\mathbf{k} \cdot \mathbf{x} - i\omega t)$. In the steady state, the coupled-mode equations take the form:

$$\frac{\partial \tilde{A}_f}{\partial X} = -i\alpha \tilde{A}_b \left(\frac{\tilde{n}_e}{n_0} \right), \quad (7)$$

$$\frac{\partial \tilde{A}_b}{\partial X} = +i\beta \tilde{A}_f \left(\frac{\tilde{n}_e}{n_0} \right), \quad (8)$$

$$\frac{\tilde{n}_e}{n_0} = \gamma \tilde{A}_f \tilde{A}_b^*, \quad (9)$$

where

$$\alpha \approx \beta \approx \frac{\omega_0}{4c} \left(\frac{n_{e0}}{n_{cr}} \right) \sqrt{1 - \frac{n_{e0}}{n_{cr}}}. \quad (10)$$

The slow-varying approximation has been made in which the fast time and space dependence is removed and only first-order partial derivatives in the amplitude are kept. The ion wave is assumed to be strongly enough damped so that its amplitude follows the driving term. With the phase conventions chosen, it is the negative imaginary part of γ that contributes to the growth of the reflected light wave:

$$\frac{\partial}{\partial(-x)} |A_b|^2 = +i\beta(\tilde{\gamma} - \tilde{\gamma}^*) |A_b|^2 |A_f|^2. \quad (11)$$

By solving the collisionless Boltzmann equations for the electrons and various ion species, together with Poisson's equation, we find that

$$\begin{aligned} \frac{\tilde{n}_e(\omega^*, k^*)}{n_0} = & - \left\{ 1 - k_{De}^2 \left[k^2 - \sum_j k_{Dj}^2 \left(1 - 2C_j \int_0^{C_j} e^{z^2 - C_j^2} dz \right. \right. \right. \right. \\ & \left. \left. \left. + i\sqrt{\pi} C_j e^{-C_j^2} \right) \right] \right\} \cdot \left(\epsilon / \sqrt{2} m_e c v_{te} \right)^2 \tilde{A}_f \tilde{A}_b^*, \quad (12) \end{aligned}$$

where A_f , A_b are the vector potentials of the forward and backward traveling light waves; k_{De} , k_{Dj} are the electron and j th ion species Debye wave numbers; and $C_j = \omega / \sqrt{2} k_B v_{ij}$, where v_{ij} is the j th ion species thermal velocity.

We define

$$\gamma = \tilde{D}(\omega^*, k^*) \left(\frac{\epsilon}{\sqrt{2} m_e c v_{te}} \right)^2. \quad (13)$$

The resonance function $D(\omega^*, k^*)$ has the value $-i\omega^* / \nu_{iL}$ at resonance, where ω^* is the angular frequency of the ion-acoustic wave and ν_{iL} is the ion-Landau damping rate. Off resonance, $D(\omega^*, k^*)$, has approximately a Lorentzian line-shape, as can be seen from Fig. 5-7, where its real and imaginary parts are plotted vs ω^* for a deuterium plasma and $k^* = \sqrt{2}k$ (corresponding to stimulated backscatter at $n_e = 0.5 n_0$). Ion temperature is the varying parameter between the curves. If we look just at the imaginary part, we see that it is negative, as required for gain. We also see that the peak negative value both decreases and shifts to higher frequency as the ion temperature increases from 200 to 450 eV in increments of 50 eV. The frequency shift is expected because the sound speed is proportional to $\sqrt{ZT_e + 3T_i}$. The width of the peak becomes very broad as the damping becomes large. Thus, even if the plasma were homogeneous and stationary, we would still expect the reflected light to have a broad frequency spectrum whose width was comparable to the shift. In Fig. 5-8, we plot the maximum value of $-\text{Im } D(\omega^*, k^*)$ as ion temperature varies for several values of electron temperatures. This is again for a deuterium plasma in which the 1.06- μm light is reflected at half-critical density. We warn that this

Fig. 5-7. Dependence of coupling constant γ on T_i and ω_p for direct backscatter of $1.064\text{-}\mu$ light in a D^+ plasma with $T_e = 1\text{ keV}$. $\Delta T_i = 50\text{ eV}$ between curves.

linear theory for Maxwellian velocity distributions may be far from reality. Particle code simulations show the formation of a hot-ion tail in the distribution; they also show highly nonlinear Landau damping and wave-crashing phenomena.

The reflected light wave sees a gain given by

$$\frac{\partial I_b}{\partial (-x/\lambda_0)} = \Lambda I_b I_f, \quad (14)$$

where I_f and I_b are the intensities of the forward and backward traveling light waves, respectively. The coefficient Λ is given by

$$\Lambda = \frac{n_{eo}/n_{cr}}{\left(1 - \frac{n_{eo}}{n_{cr}}\right)} \left(\frac{r_o \lambda_o^2}{c} \frac{1}{m_e c^2}\right) \left(\frac{m_e c^2}{k T_e}\right) \cdot [-\text{Im } \tilde{D}(\omega^*, k^*)] \quad (15)$$

Stimulated scattering is most effective when electron temperature is low, electron density is high, and the wavelength of the incident light is long.

Although energy transferred to the ions is not significant from the standpoint of absorption, it may still be able to heat the ions to a temperature where Landau damping is severe. Realize that the low ion velocity implies the ions stay in one region for a long time. Particularly for short pulse-length experiments, where irradiance on a small spot is high, one finds that this self-consistent ion heating limits reflectivity to a low value. If we know the number of intensity e-folding lengths $x = \Lambda \Lambda I_f$ and the initial noise level B , a transcendental equation may be solved to obtain the reflectivity R . However, this value for the reflectivity implies an ion temperature that, in turn, determines the Landau damping used to compute x . Together these two equations imply a self-consistent ion temperature and reflectivity, given by

$$\frac{B}{R} = \frac{1 - R}{\exp [x (1 - R)] - R} \quad (16)$$

and

$$T_i (\text{keV}) = \left(\frac{R I_f}{3.5 \times 10^{15} \text{ W/cm}^2} \right) \frac{\bar{Z}}{\mathcal{M}} \sqrt{\frac{1 - n_{eo}}{n_{cr}}} \quad (17)$$

Here, B is the initial level ($\sim 10^{-5}$) from which the reflected light wave grows, R is the fraction of the light energy reflected, $\bar{Z}$ is the mean ionization, and $\mathcal{M}$ is the Mach number of the flow.

Figure 5-9 shows the spectra of the light backscattered through the lens for two shots at each of the two intensities 3×10^{14} and $3 \times 10^{15} \text{ W/cm}^2$. One shot at each intensity is for normal incidence,

while the other is for a tilt angle of 45° . The ion acoustic wave has the dispersion relation $\omega^* = c_s k^* + \vec{u} \cdot \vec{k}^*$. Here, $\vec{u}$ is the matter velocity and c_s is the sound speed given by $\sqrt{(ZT_e + 3T_i)/Am_n}$, where T_e and T_i are the average electron and ion temperatures, respectively, Z is the mean ionization state, A is the nucleon number, and m_n is the mean nucleon mass. The Brillouin red shift is reduced by the Doppler blue shift of the outward moving matter. Since that matter blows off fairly normal to the disk's face, the spectrum for the 45° tilted disk should and does show a larger red shift. From the different shifts at the 0 and 45° tilt angles, we have two equations and two unknowns:

$$f(0^\circ) = f_B - \cos 0^\circ f_D. \quad (18)$$

$$f(45^\circ) = f_B - \cos 45^\circ f_D. \quad (19)$$

We use the mean red shift of the entire spectrum (the centroid) to obtain the values $f(0^\circ)$ and $f(45^\circ)$. We also assume that matter velocity, electron temperature, mean ionization state, and electron density where the scattering occurs do not change significantly when the disk is tilted. Since the inferred temperature depends on the square of the Brillouin red shift f_B , it should only be believed to within about a factor of two. Assuming a reasonable value for $\bar{Z}$ (based on simulations), and taking $n_e = \frac{1}{2} n_c$ and $ZT_e \gg T_i$, we obtain the following results:

For $3 \times 10^{14} \text{ W/cm}^2$ irradiation ($Z = 51$), the coronal electron temperature is $5(\pm 3) \text{ keV}$; for $3 \times 10^{15} \text{ W/cm}^2$ ($Z = 58$), the temperature is $20(\pm 10) \text{ keV}$. The discussion in §6.7 of the 1977 Annual Report¹⁴ shows how large differences in the coronal temperature of the simulations come about when inhibition is or is not included from the modeling. When it is included, the values of T_e are roughly 4 keV ($3 \times 10^{14} \text{ W/cm}^2$) and 16 keV ($3 \times 10^{15} \text{ W/cm}^2$). These values are close to the $5(\pm 3)$ and $20(\pm 10) \text{ keV}$ values just quoted as being consistent with the observed red shifts. However, when thermal conduction is classical, the energy is transported into the overdense region rather than being bottled up at critical and below (the corona). The code's predictions for T_e are then quite low: 1 keV ($3 \times 10^{14} \text{ W/cm}^2$) and 4 keV ($3 \times 10^{15} \text{ W/cm}^2$), values that are even outside the large error bars of the data!

The factor-of-4 rise in temperature with an increase of 10 in intensity is thus seen both experimentally and in the simulations (either model). This suggests a $T_e \sim I^{0.6}$ scaling. There are other data supporting this scaling.

Figure 5-10(a) shows the time-resolved spectrum for a disk tilted by 52° and irradiated at an in-

tensity of $3.2 \times 10^{15} \text{ W/cm}^2$ with a 203-ps FWHM pulse focused to a $161\text{-}\mu\text{m}$ -diam spot. The time and wavelength resolutions are 13 ps and $3 \text{ \AA}$, respectively. These resolutions are determined by the uncertainty relation $\Delta f \Delta t \geq 1$. Time-smearing results because there is a transit-time difference $n(\gamma_0/c)$ for light diffracted in the n th order from two adjacent grating rulings.

If N rulings are uniformly illuminated, the time and frequency resolutions are nN/f and $f/(nN)$. The number N is determined by an adjustable slit placed some distance behind the entrance slit. The mean red shift $\Delta f(t)$ (Fig. 5-9) is largest at the probable peak of the pulse, and the 315-ps interval between the half-maximum times is substantially greater than the 203-ps interval between the laser pulse half-power times. Defining n by $ZT_e \propto I^n$, we see that $n = (\tau_{\text{laser}}/\tau_{\text{spectrum}})^2$, where τ_{spectrum} is the time between half-maximum red shifts and τ_{laser} is the laser pulse FWHM. We find $n = 0.6$, supporting the 0.6 scaling once again.

Another interesting feature of the data in Fig. 5-8 is that even at normal incidence almost all the light is red-shifted. As the simulations show the

(a)

Shot No. 38051907
Gold disk tilted by 52°
 $3 \times 10^{15} \text{ W/cm}^2$, 226 J in 203 ps

Mean spectral shift in angstroms

(b)

Spectra for
two time windows

Time dependence of power
of backreflected light

(c)

Angle measured from specular direction, deg

Gold disk tilted 45°
456 J incident in 1010 ps
 $3 \times 10^{15} \text{ W/cm}^2$
 $\sim 28\%$ absorbed

Fig. 5-10. Scattered light distribution from a disk tilted at 45° . In (a), the time-resolved spectrum for a tilted disk target irradiated at high intensity is almost entirely red-shifted at all times. The peak shift occurs near the peak of the pulse. In (b), the spectrum always has about the same shape except for a wavelength scaling factor. The backreflection appears to saturate near the center of the pulse. In (c), the specular and backreflected peaks are easily distinguished in the long-pulse experiments.

critical surface motion to be slow and usually outward, this near-total detected red shift seems to indicate that Brillouin backscatter is quite effective. However, the $f/2.6$ lens angle subtends a half-angle of only 11° , representing a rather small solid angle. Does Brillouin backscatter have a broader angle of return than that? The answer seems to be yes. Figure 5-10 shows a scattered light distribution from a disk tilted $3 \times 10^{15} \text{ W/cm}^2$ at 45° . Besides the specular peak at 90° , there is clearly a Brillouin backscatter peak from 0 to 30° , not just 0 to 11° . Operationally, then, we will define light scattered from 0 to 30° as backscattered.

Table 5-2 simply gives the fraction of light scattered into the $f/2.6$ lens, which, from the discussion above, is mostly due to Brillouin processes. To estimate the amount of stimulated scatter into broader angles, we invoke the fact that for a signature of such scatter much more light is scattered out of the plane of polarization than into it. Figure 5-11 shows this asymmetry for intensities 3×10^{14} and $3 \times 10^{15} \text{ W/cm}^2$. Subtracting the in-plane values from the out-of-plane values and integrating over the solid angle gives a crude estimate of the amount of Brillouin scattering over and above specular reflection and refraction. While resonance absorption also produces such an asymmetry, it is usually much less drastic. Adding the values obtained from 15 to 30° from Fig. 5-11 to the values of Table 5-2 gives an estimate for the

Table 5-2. Light backscattered into $f/2.6$ lens.

Intensity, W/cm^2 (J)	3×10^{15} (450)	3×10^{14} (450)
Normal incidence (%)	12	9
45° incidence (%)	9	3

backscatter; the remaining values from 30° on up give an estimate for the sidescatter. The results are:

For $3 \times 10^{14} \text{ W/cm}^2$, backscatter is $13 \pm 5\%$ and sidescatter $16 \pm 5\%$, for a total stimulated scattering fraction of $29 \pm 10\%$; while for $3 \times 10^{15} \text{ W/cm}^2$, backscatter and sidescatter fractions are each $20 \pm 6\%$ for a total of $40 \pm 12\%$. Recalling the 45° disk experiment of Fig. 5-10, we see that the unambiguous Brillouin backscatter fraction was roughly 25% , which agrees with the $20 \pm 6\%$ estimate for the normal-incidence disk.

While the simulation code does not have the ability at present to treat stimulated scattering processes, we can estimate the amount of Brillouin backscatter it would have produced in the following way. Particle simulations and simple models estimate the amount of backscattered light as a function of a figure of merit X that involves the intensity, temperature, and density scale length:

$$\begin{aligned}
 x &= \left(\frac{v_{osc}}{v_t} \right)^2 \int_{Z(n=n_c)}^{Z(n=0.1 n_c)} \frac{n(Z)dZ}{n_c \lambda_o} \\
 &= \frac{4 \times 10^{-2} I (10^{14} \text{ W/cm}^2)}{T (\text{keV})} \int_{Z(n=n_c)}^{Z(n=0.1 n_c)} \frac{n(Z)dZ}{n_c \lambda_o} \quad (20)
 \end{aligned}$$

This is shown in Fig. 5-12. The figure of merit is evaluated from the code-generated profiles at the peak of the pulse.

We can evaluate X using the calculated values for the scale length and electron temperature. We find that for $3 \times 10^{14} \text{ W/cm}^2$, the modeling that includes the inhibition yields a backscatter fraction of $14 \pm 7\%$ while the noninhibited run gives $40 \pm 20\%$. For $3 \times 10^{15} \text{ W/cm}^2$, inhibited transport modeling predicts $20 \pm 10\%$ while noninhibited modeling predicts $40 \pm 20\%$.

Although the Brillouin reflectivities based on the inhibited transport model are closer to the inferred experimental reflectivities, too much should not be made of this fact. Our inferred experimental values could be low, for instance, because inverse bremsstrahlung absorbs some of the light as it goes into the plasma and as it is scattered out. Some of the light scattered in the plane of polarization could also be due to Brillouin scattering, which would also cause our estimates to be low.

With these rough estimates of the total scattering (back and side) now inferred from experiment (30% at $3 \times 10^{14} \text{ W/cm}^2$ and 40% at $3 \times 10^{15} \text{ W/cm}^2$), we find that the code predictions for total absorption (corrected for the scattering and its associated error bars) match the experimentally measured absorptions only if the inhibited modeling is used. The classical conduction model, with its lower corona temperature and shallower gradients, predicts too high an absorption by means of inverse bremsstrahlung and falls outside the error bars of the data.

Thus, we have shown how experimentally inferred coronal temperatures, when compared with simulations, support the assumption of inhibited conduction. The net red shift in all the experiments points to subsonic Mach numbers, another signature of transport inhibited below its classical

value. The flow must be subsonic, because a net red shift was observed even for normal incidence, when the dispersion relation becomes $\omega^* = c_s - uk^*$, where $u > 0$ if the matter moves outward.

Before leaving this subsection, we note that there are situations in which the sidescatter does not occur. From Fig. 5-11, we might conclude that sidescatter is independent of intensity(!) since the asymmetries are so identical. Apparently, the longer sidescattering scale length along the face of the disk for the $3 \times 10^{14} \text{ W/cm}^2$ shot (spot size $450 \mu\text{m}$) compensated for its lower intensity vis-a-vis the $3 \times 10^{15} \text{ W/cm}^2$ shot, which was at the same energy and pulse width, 450 J/1 ns , but with a $150\text{-}\mu\text{m}$ -diam spot size. Thus the scattering was similar. However, Fig. 5-13 shows a comparison of two shots at $3 \times 10^{14} \text{ W/cm}^2$: the first the usual 450 J on a $450\text{-}\mu\text{m}$ spot; the second, 45 J on a $150\text{-}\mu\text{m}$ spot. Here there was no larger intensity to compensate for the smaller spot (and scale length), so the sidescatter did not build up. Thus there is almost no asymmetry in the scattered light.

References

7. R. A. Haas, W. C. Mead, W. L. Krueger, D. W. Phillion, H. N. Kornblum, J. D. Lindl, D. MacQuigg, V. C. Rupert, and K. G. Tirsell, "Irradiation of Parylene Disks with a $1.06\text{-}\mu\text{m}$ Laser," *Phys. Fluids* **20**, 332 (1977).
8. J. S. Pearlman, J. J. Thomson, and C. E. Max, "Polarization-Dependent Absorption of Laser Radiation Incident on Dense-Plasma Planar Targets," *Phys. Rev. Lett.* **38**, 1397 (1977).

Fig. 5.4. Comparison of the spectra of the 471-J, 450- μm spot diam laser and the 48-J, 161- μm spot diam laser. The 'out of plane' and 'in plane' labels refer to the polarization of the laser beam.

9. R. P. Godwin, P. Sachsenmaier, and R. Sigel, "Angle-Dependent Reflectance of Laser-Produced Plasmas," *Phys. Rev. Lett.* **39**, 1198 (1977).
10. K. R. Manes, V. C. Rupert, J. M. Auerbach, P. Lee, and J. E. Swain, "Polarization and Angular Dependence of 1.06- μm Laser-Light Absorption by Planar Plasmas," *Phys. Rev. Lett.* **39**, 281 (1977).
11. K. Estabrook and W. L. Kruer, "Properties of Resonantly Heated Electron Distributions," *Phys. Rev. Lett.* **40**, 42 (1978).
12. P. Kolodner and E. Yablonovitch, "Proof of the Resonant Acceleration Mechanism for Fast Electrons in Gaseous Targets," *Phys. Rev. Lett.* **37**, 1754 (1976).
13. J. E. Balmer and T. P. Donaldson, "Resonance Absorption of 1.06- μm Laser Radiation in Laser-Generated Plasma," *Phys. Rev. Lett.* **39**, 1084 (1977).
14. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978).

Authors

D. W. Phillion
M. D. Rosen

5.4 Studies of Closure Phenomena in Pinholes Irradiated by Nd Laser Pulses

High-energy Nd glass lasers such as the Argus¹⁵ and Shiva systems have focused terawatts of power on targets of submillimeter extent by using spatial filtering and image relaying^{16,17} of the beam through the amplifier chain. Spatial filtering removes small-scale fluctuations in the beam that

would otherwise focus into hot spots and destroy optical materials and coatings. The nonuniformities in the beam would also lead to beam breakup at focus, resulting in a significant portion of the beam diffracting around the target.

Initial laser fusion experiments used pulses typically of 100-ps FWHM. For these short pulses, spatial filters with $f/10$ optics and 300- μm pinholes had energy transmissions of 98% or greater. As emphasis shifted to long-pulse (1 ns and greater) fusion experiments, the transmissions of the spatial filters degraded significantly. We measured transmissions of 20 to 30%. Transmission loss because of plasma closure of the pinholes had thus manifested itself as a critical parameter in the design of glass laser systems.

To provide a detailed data base for optimum spatial filter design, we performed a set of experiments at the Janus laser facility to determine the principal parameters of pinhole plasma closure. The experiments were conducted to determine the mechanism of transmission loss in a spatial filter configuration, dependence of the loss on pinhole geometry and material, pinhole periphery intensity loading, and effective closure velocity. We irradiated 300-to-500- μm -diam pinholes of various materials and thicknesses by using 20-to-100-J, 300-ps FWHM, 106- μm laser pulses. Calorimetry measurements yielded data on pinhole energy transmission and on intensity loading at the periphery of the pinhole. Ultrafast streak

Fig. 5-14. Experimental setup for transmission measurements.

photography measurements indicated effective closure velocities of 2×10^7 to 5×10^7 cm/s. Scattered light measurements showed transmission loss through a typical spatial filter configuration to be primarily refractive in nature.

Figure 5-14 illustrates the setup for the first three studies. We placed pinholes at the common focus of two $f/10$ lenses mounted in the Janus target chamber, which provided a vacuum environment. Beam diameter incident on the filter input lens was 80 mm. Laser calorimeters measured incident and backreflected light. An array of photodiodes was mounted out to 35° from the beam axis for measuring light forwardscattered and backscattered out of the acceptance angle of the input and output lenses. The light transmitted through the output lens went to three diagnostics: a laser calorimeter to measure transmitted energy, a streak camera to record the temporal shape of the transmitted light imaged slightly out of the plane of the pinhole, and a multiple-image camera used for the pinhole-loading measurement.

Spatial filter transmission loss caused by plasma closure is either reflective or refractive in nature. In the former case, the laser light is reflected off plasma in the pinhole at the critical density value of 10^{21} cm $^{-3}$ for $1.06\text{-}\mu\text{m}$ light. In the latter case, the subcritical density plasma acts like a positive lens and causes the beam traversing the pinhole to diverge from focus at an angle exceeding that of the $f/10$ input lens. This can be seen from the fact that n , the index of refraction of the plasma, is given by

$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}, \quad (21)$$

where ω_p is the plasma frequency and ω is the light frequency. Because ω_p^2 varies directly as the electron density, n is smallest at the pinhole periphery. This smallness factor gives the pinhole region the same phase retardation characteristics as those for a positive lens.

Figure 5-15 presents a typical scattered-light distribution. Such distribution clearly shows minimal backscatter and significant forwardscatter out of the acceptance angle of the output lens, thus indicating transmission loss to be primarily refractive in nature. Energy transmission through the spatial filter as a function of material and geometry is shown in Figs. 5-16(a) and 5-16(b). Figure 5-16(a) shows an independence of transmission to pinhole material and incident energy for 300-ps pulses and 300- μm -diam pinholes. This implies that the blowoff velocity of the plasma is relatively insensitive to atomic weight. The range of energies used

in these experiments was not sufficient to determine the effect of pulse energy. Figure 5-16(b) shows the strong dependence of transmission on pinhole diameter. Twenty-to-forty-percent transmission loss definitely occurs with 300- μm pinholes, but losses are negligible at 500 μm with the 300-ps FWHM pulses used here. We discuss focusing and intensity distribution in detail below.

Pearlman and Anthes¹⁸ reported closure studies of pinholes irradiated by 10-ns pulses. With 300- μm pinholes, they did not observe closure for at least 3 ns after the start of the pulse. However, they irradiated the pinhole with an f/4.3 lens and collected the transmitted light with an f/2 lens. Because the latter has a much larger acceptance angle than the former, it is easy to see why closure was not observed earlier in their experiment. The refraction angle of the light did not exceed the acceptance angle of the f/2 lens until the plasma densities became much larger than in the case required for irradiating and collecting lenses of the same f number. This appears to be another confirmation of the refractive nature of closure. Hence, the use of identical lenses in spatial filters makes them especially susceptible to refractive losses caused by plasma in the pinholes.

To measure the intensity distribution on the pinhole to prescribe a threshold loading for plasma formation, we used the following setup. The pinhole was replaced by a 300- μm -diam gold disk positioned at the common focus of the two f/10

lenses. We placed a 50% beam splitter next to the f/10 output lens. Half the energy transmitted about the pinhole was directed to a sensitive laser calorimeter. The other half was directed to a multiple-image camera, which was positioned to image the plane of the disk. In this manner, we measured the beam energy incident on the plane surrounding the pinhole. Figure 5-17 presents a typical energy loading based on densitometry of the camera film. Based on these measurements, we deduced threshold intensity for significant plasma formation to be $\sim 10^{12}$ W/cm². Peripheral pinhole

loading below 10^{11} W/cm² produced no closure effects. This threshold value agrees with Ref. 18.

The transmission experiment indicated a weak dependence of transmission loss on material and energy loading and a strong dependence on diameter. This result implied that the rate of closure is approximately constant. We determined this rate of closure by using Lawrence Livermore Laboratory's ultrafast optical streak camera. In the first measurement, we imaged the plane of the 300- μ m pinhole in the $f/10$ spatial filter configuration on the slit of the streak camera. Then we defocused the camera to give a slightly larger beam spot size. When a 300- μ m pinhole was irradiated with 20 to 100 J in 300 ps, the streak record of the transmitted light appeared as in Fig. 5-18. We interpreted the breakup of the streak as the onset of closure. With the pinhole removed from the $f/10$ lens common focus, the streak remained solid for the entire pulse duration. This indicated that the breakup was indeed a signature of closure. We used the time of onset of this breakup with respect to this pulse to estimate a closure velocity by dividing the radius of the pinhole (150 μ m) by this onset time. This gave values in the range:

$$V_{\text{closure}} = 2 \times 10^7 - 5 \times 10^7 \text{ cm/s} \quad (22)$$

A determination of the plasma density surface that moves with this velocity would require detailed measurements using interferometric techniques.^{19,20}

The second experiment for measurement of closure velocity used the setup in Fig. 5-19. In contrast with the spatial filter configuration, this setup used two $f/1$ lenses, for which a thick pinhole is aligned beyond the focus of the irradiating beam. We used this thick pinhole to maximize refraction effects because the angle of refraction through the plasma varies directly with path length through the plasma. The collecting $f/1$ lens and a second convex lens are used to image the central plane of the pinhole onto the slit of the optical streak camera. Upon irradiation, plasma expands into the pinhole. The result is a reduction in beam size at the central plane because

the long plasma region ahead of this plane causes the rays to converge inward. A circular beam block, positioned after the $f/1$ collecting lens, allows only an annulus of light to reach the streak camera slit. The primary purpose of this beam block is to limit the light reaching the slit of the streak camera. An excess of light would result in blooming of the streak tube and loss of temporal and spatial resolution. In the absence of closure, the camera would produce an image showing the streaks of two points on the annulus as straight lines. With closure, the streaks would move toward each other as the beam size at the central pinhole plane shrinks. When the plasma is sufficiently dense, the beam size shrinks to the point where the light is refracted totally into the beam block; thus the streak stops abruptly.

We did not observe the above in our experiments because the duration of the streak was the same as that of the incident pulse. The streak also disappeared if the critical density layer moved sufficiently out from the pinhole periphery to reflect back all rays that normally passed around the beam block.

Figure 5-20 shows the converging effect for a case in which a 1-mm-thick by 300- μm -diam pinhole began closing upon irradiation by a 60-J, 300-ps FWHM pulse. At the bottom of the streak, the gap between the two streak lines is 300 μm , which corresponds to the initial clear radius of the pinhole. Dividing the radius of the pinhole by the time at which these two lines are extrapolated to intersect yields a closure velocity of 3×10^7 cm/s.

This closure velocity agrees with ion velocity measurements from Nd laser-irradiated disk targets. Anthes et al.²¹ report asymptotic blowoff velocities of 5×10^7 cm/s from Nd laser-irradiated thick planar targets. Slater et al.²² report ion velocities of a few times 10^7 cm/s from targets irradiated by 1.06- and 0.532- μm light at intensities of 10^{15} W/cm².

The experimental value for closure velocity and the interferometric data of Ref. 20 can be used to construct a model for the refractive mechanism of closure. The results will be demonstrated to be in good agreement with the scattered-light distribution of Fig. 5-15. Reference 20 presented measured density profiles of disks irradiated at intensities of 10^{13} W/cm². From the radial distribution of these profiles, one can infer that the plasma densities at the surfaces of the pinholes are between one-tenth

Fig. 5-20. Streak record for determining closure velocity.

and one-half the critical value for 1.06- μm light ($N_c = 10^{21}$ cm⁻³).

The plasma in the pinhole will be modeled by a cylindrical region that has a uniform density in the axial direction and a parabolic density profile in the radial direction. The axial extent of the plasma X_0 is taken as twice the closure velocity times the FWHM of the laser pulse. For these experiments, this gives the value

$$X_0 \cong 200 \mu\text{m} . \quad (23)$$

Let R be the pinhole radius, r the radial coordinate, and N the plasma density. Then the parabolic density profile is

$$\frac{N(Z)}{N_c} = \alpha + (f - \alpha)Z^2 , \quad (24)$$

where $Z = r/R$, α is the ratio of plasma density at $Z = 0$ to the critical value, and f is the ratio of plasma density at the pinhole surface to critical. α and f are defined for these experiments by the relations

$$\begin{aligned} 0.1 &\leq f \leq 0.5 . \\ 0 &\leq \alpha \leq f . \end{aligned} \quad (25)$$

The refraction θ angle for a ray entering the plasma at a given distance from the axis r_0 is calculated by integrating the differential equation for ray propagation²³ in a refractive medium. For the profile assumed above, one has

$$\theta(r_0) = \int_0^{x_0/R} \frac{\ell}{N} \frac{dN}{dZ} d\ell, \quad (26)$$

where $\ell = x/R$ in which x is the axial coordinate along the plasma.

Equation (26) is integrated numerically because Z is a function of ℓ along the ray trajectory. All rays are assumed to enter the plasma at the focus where the rays are parallel to the axis. Figure 5-21 shows results for $X_0 = 200 \mu\text{m}$, $R = 150 \mu\text{m}$, $\alpha = 0$, and $f = 0.5$.

Using this calculated refraction angle distribution and the spatial energy profile of the laser focal spot, one can calculate a scattered light distribution. Let E be the pulse energy (J), σ be the half width (μm) of the beam focal spot that is assumed Gaussian in shape, and F the functional relationship between r_0 and θ determined from Eq. (26):

$$r_0 = F(\theta). \quad (27)$$

Then the refracted light distribution in joules/stera-dian is

$$P(\theta) = \frac{F F'}{\sin \theta} \frac{E}{\pi a^2} e^{-F^2/a^2},$$

where

$$a = \sigma / \sqrt{\ln 2}, \quad F' = \frac{dF}{d\theta}. \quad (28)$$

Figure 5-22 shows the refracted light distribution for a laser pulse with a FWHM (2σ) of $50 \mu\text{m}$, an energy of 100 J, and the refraction angle curve of Fig. 5-21. The results closely follow the data of Fig. 5-15, verifying the dominant role of refraction in pinhole closure.

In conclusion, these experiments have shown pinhole closure to be a significant factor in spatial filter performance when the pinhole radius divided by 3×10^7 cm/s is a significant fraction of the pulse length. Refractive mechanisms have been shown to be the dominant source of transmission loss. Spatial filter designs using large pinholes and large f-number optics to bring pinhole peripheral loadings below 10^{11} W/cm² can eliminate the adverse effects of closure.

References

15. D. R. Speck, W. W. Simmons, J. T. Hunt, M. J. Boyle, F. Ruiner, E. K. Storm, and C. D. Swift, *Performance of Argus as a Laser Fusion Facility*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-79816 (1977).
16. W. W. Simmons, J. A. Glaze, and J. B. Trenholme, "Solid State Laser Amplifier Chain Staging with Sequential Spatial Filtering," *J. Quant. Electron.* QE-11 30D, (1975).
17. J. T. Hunt, J. A. Glaze, W. W. Simmons, and T. A. Renard, *Suppression of Self-Focusing Through Low Pass Spatial Filtering and Relay Imaging*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-79904 (1977).
18. J. S. Pearlman and J. P. Anthes, "Closure of Pinholes Under Intense Laser Radiation," *Appl. Opt.* 16, 2328 (1977).
19. D. T. Attwood, "Ultraviolet Probing of Laser Produced Plasmas with Picosecond Pulses," in *Proc. 12th Intern. Congress High Speed Photography* (Society of Photo-Optical and Instrumentation Engineers, Toronto, Canada, 1976); also published as a preprint by Lawrence Livermore Laboratory, Livermore, Calif., UCRL-77744 (1976).
20. J. M. Auerbach, D. T. Attwood, P. H. Y. Lee, and D. W. Sweeney, *2660 Å Holographic Interferometry of Laser Produced Plasmas from Tilted Disk Targets*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-79775 (1977).
21. J. P. Anthes, M. A. Gusinon, and M. Keithmatzen, "Experimental Observation and Numerical Simulation of Laser-Driven Ablation," *Phys. Rev. Lett.* 41, 1300 (1978).
22. D. C. Slater, R. L. Berger, and J. F. McGrath, "Fast Ions and Hot Electrons", *Bull. Am. Phys. Soc.* 23, 767 (1978).
23. M. Born and E. Wolf, *Principles of Optics* (Pergamon Press, New York, 1970).

Authors

J. M. Auerbach
N. C. Holmes
J. T. Hunt
G. J. Linford

Major Contributors

H. G. Ahlstrom
E. S. Bliss

5.5 Hyperion Experiments on Shiva

5.5.1 Introduction

Like other approaches to producing controlled thermonuclear reactions, efficient inertial confinement fusion depends on the realization of a sufficient volume of hot, dense DT plasma. In its assault on "fusion hill," the Lawrence Livermore Laboratory (LLL) laser-fusion program has launched two salients. The first of these, historically, has held $n\tau$ between 10^{11} and 10^{12} and has improved yield efficiency by increasing temperature. These exploding-pusher studies have been carried out by each LLL facility in turn as shown on the bottom branch of Fig. 5-23. During the Hyperion campaign, we have used Shiva to reach higher exploding pusher yields, but it is clear that ultimate success depends on the achievement of high enough fuel ρr to trap α particles. Exploding-pusher studies have provided a testing ground for laser system and target diagnostic performance. As indicated in Fig. 5-24, Shiva has joined Argus in implosion experiments on the path to higher ρ in November. This section reviews the "start-up" and "Hyperion" experiments performed with Shiva.

5.5.2 Alignment

The Shiva laser system, shown in Fig. 5-25, occupies a 300-ft-long bay section of a 400-ft-long building. The 20 output, or δ , amplifiers in the foreground have a free aperture of just over 20 cm. Views of Shiva's target area appear in Figs. 5-26 to 5-28. From the bridge crane 80 ft up, the upper cluster of ten PFC (pointing, focusing, and centering)/RBD's (return-beam-diagnostics) as well as the ten IBD's (incident-beam diagnostics) are clearly visible in Fig. 5-26. The 10 upper and 10 lower beams enter the target chamber shown in Fig. 5-27 in nested pentagonal clusters. Some of the target diagnostic devices, particularly the energy balance modules (the black cylinders) that measure absorbed 1.06- μ m energy, are arrayed about the vacuum vessel. From below, Fig. 5-28 shows the lower lens cluster, with the lower target alignment viewer in the center of the converging beams. Each of Shiva's beam lines opposes another whose number differs by 10 and is diagnosed by IBD and RBD packages as shown in Fig. 5-29. The end result is that the target is illuminated with the geometry indicated in Fig. 5-30. Each beam strikes the target plasma in p-polarization to maximize absorption.

(Continued on page 5-29)

Fig. 5-25. Shiva laser system, which occupies a 300-ft-long bay in a 400-ft-long building. The 20 output amplifiers in the foreground have a free aperture of just over 20 cm.

Fig. 5-26. Shiva target area, showing upper cluster of 10 pointing, focusing, centering (PFC)/return-beam diagnostics (RBD) as well as 10 incident-beam diagnostics (IBD).

Fig. 5-27. Shiva target chamber, showing 10 upper and 10 lower beams entering in nested pentagonal clusters.

Fig. 5-28. Shiva target chamber, showing lower lens cluster with lower target-alignment viewer in center of converging beams.

Fig. 5-30. Shiva target-illumination geometry. Each beam strikes the target plasma in p-polarization to maximize absorption.

Precise alignment of the 20 laser beams on a target located within the viewing angles of all diagnostic systems requires the proper functioning of an elaborate alignment system. To begin, the target diagnostics must be aligned to the chamber center. A 5-mm surrogate target is placed there, using the "5-eye" target alignment viewers shown in Fig. 5-31. The surrogate target periphery is positioned relative to fixed 5-mm-diam reticles in the two viewers using the outer four microscope objectives (Fig. 5-32).

Next in the sequence, the PFC system aligns and focuses each of Shiva's 20 beams on this reflecting sphere. Once referenced to the surrogate target's center, the lens drives are commanded to translate the 20 beams into the shot configuration. With the target located using the center eyes of the two viewers (Fig. 5-33), we use the RBD/PFC systems to verify that each beam strikes the target in the precalculated fashion.

5.5.3 Start-Up Experiments

While the Shiva facility was being prepared for target studies, several opportunities were provided to test parts of the system. The first of these came shortly after Shiva's first beam was aligned. With this beam, Shiva delivered 1.4 TW to an 180- μ m-diam ball-on-plate target. The neutron counters showed approximately 4×10^5 DT neutrons, diagnostic timing was established, and the automatic data collection system functioned correctly (Fig. 5-34). As soon as four beams were ready, we attempted another target irradiation. This time 2.5 TW reached the 180- μ m diameter ball-on-plate target and the neutron counters reported approximately 10^7 neutrons. Once again, the automatic data collection system functioned correctly, with two results: Shiva's neutron time-of-flight (TOF) spectrometer was timed by the x-ray flash; and energy balance data were taken from 18 modules arrayed on the target chamber.

Early in April (Fig. 5-35), the lower 10 beams were aligned on the ball-on-plate target shown in Fig. 5-36. Resulting x-ray microscope and α -zone-plate camera images, Figs. 5-37 and 5-38, respectively, show the fuel trapped in a piston-like compression between the imploding front hemisphere and the massive plate. Plasma calorimetry revealed that this ball-on-plate target absorbed $\sim 33\%$ of the incident 1.06- μ m energy. A yield of 3×10^8 DT neutrons was recorded. The blow-off angular distribution for this target, shown in Fig. 5-39, is characteristic of the distributions measured with disk targets irradiated on one side.

The last of these start-up experiments, which took place in May (Fig. 5-35), involved directing the pulses from all 20 arms onto the target shown in Fig. 5-40. Irradiated by 26 TW, the target ball imploded and burned, reaching an average fuel ion temperature of 5.9 ± 1.2 keV and yielding 7.3×10^9

Fig. 5-33. Target located using the center eyes of the two viewers. We can now use the RBD/PFC systems to verify that each beam strikes the target in a precalculated fashion.

Beam No. 10, 1.4 TW on 180- μ m ball-on-plate:

- Neutron counters showed $\sim 4 \times 10^5$ neutrons.
- Automatic data collection system functioned correctly.
- Timing of diagnostics established.

Beams No. 1 through No. 4, 2.5 TW on 180- μ m ball-on-plate:

- Neutron counters showed $\sim 10^7$ neutrons.
- Neutron time-of-flight facility timed by x-ray flash.
- Automatic data collection system functioned correctly.
- Energy balance data taken from 18 modules arrayed on the target chamber.

Fig. 5-34. Target shot results of start-up experiments to test parts of drive system. We used one beam for the first target location and four beams for the second.

Ten-Arm Shot, 4/7/78:

- 13 TW on a 174- μ m ball-on-plate.
- "Piston-like" compression.
- 3×10^8 DT neutrons produced.

Twenty-Arm Shot, 5/18/78:

- 27 TW on a 204- μ m ball-on-plate.
- 6 ± 1 -keV ion temperature measured.
- 7.3×10^8 neutrons produced.

Fig. 5-35. Further preliminary target shot results, this time with a 10-beam shot then a 20-beam shot.

Fig. 5-36. Ball-on-plate target, set up for the 10-beam shot made in early April.

Fig. 5-37. X-ray microscope image of target after 10-beam shot. This shows the fuel trapped in a piston-like compression between the imploding front hemisphere and the massive plate.

Fig. 5-40. Ball-on-plate target, set up for the 20-beam shot made in May.

DT neutrons. The x-ray microscope image produced by this event is reproduced in Fig. 5-41. Specific absorbed-energy densities of more than 0.6 J/ng ensured a uniformly emitting target surface.

As in the 10-arm shot, the disk was added to prevent laser system damage and, because it cooled the equatorial region of the target, it actually reduced target yield as much as a factor of 10.

The α -zone-plate image shown in Fig. 5-42 provided further evidence of a cool equatorial band. Two zone-plate cameras, which viewed this implosion from widely separated angles, showed the same shape for the burning fuel. The difference between equatorial and polar pusher implosion velocities resulted in an oblate kidney-bean-shaped burn region. We obtained the ion temperature from the neutron TOF spectrum shown in Fig. 5-43, and we measured the absorbed energy using plasma and optical calorimetry. The blow-off plasma distribution observed for this target geometry is displayed in Fig. 5-44.

5.5.4 Hyperion Campaign

By late September, Shiva was prepared for its first series of exploding-pusher irradiations. Sufficient confidence had been built up in the alignment system to permit the removal of the protective disks around the target balls. We irradiated each microshell with a symmetrical beam geometry. Following the shot, the measured beam energies were input to LITAR (§6.1.16), which calculated the intensity distribution at the target surface. Since the angles of incidence and the polarizations of each beam were known, an estimate for the absorbed power density could be made as shown on the left in Fig. 5-45. Calculated absorption for this geometry was 28%; however, experimental results indicated an absorbed energy of 22% determined by optical and plasma calorimetry. The blow-off plasma distribution for this ball target was typical and is displayed in Fig. 5-46. This particular target was a 322- μm microsphere with a 2- μm wall thickness filled with 2 mg/cm³ of equimolar DT. It was irradiated by an 18.5-TW laser pulse of 90-ps FWHM and yielded $8.6 \pm 1.1 \times 10^9$ neutrons with an ion temperature of 3.2 ± 0.8 keV inferred from neutron TOF measurements.

Although this experiment did not produce the highest yield or the highest ion temperature, it is representative of that series of exploding pusher implosions. We did a two-dimensional (axisymmetric) calculation on this experiment, using a symmetrized but realistic radial laser beam profile from the LITAR computer code (§6.16). This profile is shown in Fig. 5-47. Angle-dependent absorption

(Continued on page 5-40)

2.6×10^{13} W in 9.5×10^{-11} s on target
 7.3×10^9 neutrons produced, 6 ± 1 keV ion temp

Measured x-ray image

Fig. 5-41. X-ray microscope image of target after 20-beam shot, which was Shiva's first using 20 of its arms. The disk, added to prevent laser system damage, cooled the equatorial region of the target and reduced target yield as much as a factor of ten.

Fig. 5-42. Alpha-zone-plate image of imploding target shown in Fig. 5-41. This view shows further evidence of a cool equatorial band.

The data shown above were
 obtained from the test
 program. The detector indicated an
 energy distribution as shown.

Calculated absorption

Polar x-ray microscope image

Fig. 5-45. Target ball irradiated with a symmetrical-beam geometry. This polar micrograph shows one of the first in a series of exploding-pusher irradiations, an effort that began in late September. By this time, the protective disks had been removed from the target balls.

Fig. 5-46. Blow-off plasma distribution for target ball shown in Fig. 5-45.

Fig. 5-47. Radial laser beam profile for target ball of Fig. 5-45, derived from LITAN computer code.

was used in the ray tracing of the incident laser light with a modified p-polarization absorption profile. The physics model included thermal conduction inhibition by the two-stream instability and self-generated thermoelectric magnetic fields. We placed laser-heated suprathermal electrons in an instantaneous equilibrium distribution whose characteristic temperature is given by

$$\theta_{\text{hot}} \approx \theta_{\text{AV}} + 3 \times 10^{-6} (I_L \lambda_L^2)^{0.425}, \quad (29)$$

where θ_{AV} is the average electron temperature at the critical density and I_L and λ_L are the laser intensity and wavelength (in μm),²⁴ respectively. At the peak of the laser pulse the temperature is about 20 keV.

Representative plots of the Lagrangian mesh are shown in Figs. 5-48 and 5-49. The distortion from the initial spherical shape becomes apparent by the time the peak of the pulse is reached. Non-symmetric illumination and absorption are evident with that portion of the shell being most violently exploded adjacent to the region of high absorption. Figure 5-49 is the mesh at the time of peak neutron productions, which occurs about 275 ps after the peak of the pulse. Clearly, the imprint of the efficient absorption regions is reflected in the compressed shape, that of an oblate spheroid. The calculation gives a neutron yield of 7.6×10^9 for an overall absorption of 20%.

In addition to reproducing the measured neutron yield and absorbed energy, the target simulation provided a calculated peak ion temperature of 3.14 keV. Time-dependent, fuel-averaged quantities are shown in Fig. 5-50. The electron temperature tracks the laser pulse because of the slight coupling between the more energetic suprathermal electrons, which penetrate into the fuel, and the background electrons. A peak ion temperature of about 3.1 keV is achieved at 275 ps, while the density peaks about 50 ps later. Figure 5-51 shows the nonuniformity of the ion temperature in the compressed fuel at peak burn rate. The yield comes from a small portion of the fuel, which was strongly heated by the rapid compression of the target poles.

Our code has the capability of reproducing both thermal and suprathermal x-ray images. Figure 5-52 shows the calculated and experimental images in a 0.81-keV window at 1.9 keV, with the

view normal to the laser axis. The x-ray emission is characteristic of the exploding-pusher target. The shell is heated rapidly by the short duration laser pulse and experiences almost no hydrodynamic motion. A second burst of x rays is emitted as the pusher stagnates against the compressed fuel. This intense pulse is the signature of the conversion of the inward-directed kinetic energy into thermal energy of the fuel and adjacent glass mass. X rays in this image are almost entirely caused by free-bound radiation from the nearly completely stripped silicon atoms.

Figure 5-53 compares the calculated and experimental images using x rays in the energy range of 17 to 30 keV. These energetic photons are created by the bremsstrahlung interaction of the suprathermal electrons as they collide with the ions of the glass shell. Because the suprathermal electrons are present only during the laser pulse, they effectively sample the density distribution of the pusher. The comparison shows good agreement, with a clear indication of the most intense regions of suprathermalization.

Faraday cups showed an ion peak around 4×10^8 cm/s. During the 100 ps of the laser pulse, these ions moved approximately 400 μm , creating a region of underdense plasma of similar dimensions. Because the average irradiation intensity was of the order of 10^{15} W/cm², with higher flux in regions of beam overlap, the threshold for onset of Brillouin scattering was exceeded.²⁵ Compared with pretest computations, the observed absorption implies that approximately 80% of the incident light reached the critical surface. The balance of 20% cannot, however, be entirely ascribed to Brillouin backscatter, since only 10% of the incident light was recovered in the focusing lenses. Brillouin sidescatter could be significant. But because of the overall radial polarization of the beam clusters, this would not be evident in the data from PIN diodes or light calorimeters (no infrared spectrometers were installed on Shiva).

A common feature of all Shiva Hyperion target irradiations was the clear demonstration of strongly inhibited electron conduction toward the ball equator.²⁶ Indeed, the x-ray microscope located in the center of the upper beam cluster shows the five-fold symmetry of the irradiation pattern (Fig. 5-45) rather than a smoothed-out emission region. The side-viewing microscope (Fig. 5-52) also shows that very little energy was conducted to the equatorial

Fig. 5-48. Representative plot of Lagrangian mesh for target ball of Fig. 5-45. Distortion from the initial spherical shape becomes apparent by the time the pulse peak is reached.

Fig. 5-49. Representative plot of Lagrangian mesh for target ball of Fig. 5-45, which shows the mesh at the time of peak neutron production. The imprint of the efficient absorption regions is reflected in the compressed shape, that of an oblate spheroid.

Fig. 5-50. Time-dependent fuel-averaged quantities for target ball of Fig. 5-45. Electron temperature tracks with the laser pulse because of the slight coupling between the more energetic suprathermal electrons and the background electrons.

Fig. 5-51. Fuel-pusher interface for target ball of Fig. 5-45. This shows the nonuniformity of ion temperature in compressed fuel at peak burn rate.

Fig. 5-52. Experimental (left view) and calculated x-ray images for target ball of Fig. 5-45. X-ray emission is characteristic of the exploding pusher target.

Fig. 5-53. Comparison of (a) experimental and (b) calculated images for target ball of Fig. 5-45, using x-rays in the energy range of 17 to 30 keV. This shows good agreement, with a clear indication of the most intense regions of suprathermalization.

region of the targets, where the high angle of incidence of the beams resulted in low absorption. The same micrographs show that the poles of the balls (along the beam cluster axis) were punched inward although the irradiation strategy provided for a lower incident energy at these points (Fig. 5-45) and the x-ray emission from the poles was maximum on axis. This implies that the on-axis dip in irradiation was not sufficient to offset the cylindrical symmetry of these experiments. This effect resulted in good electron conduction near the poles and an inward velocity multiplication on axis. The toroidal shape of the compressed region is visible in the zone-plate α image (Fig. 5-54).²⁷

Comparison of x-ray micrographs and zone-plate x-ray data shows the same general features of the emission region. The FWHM of the central region emission decreases with increasing energy and shows the two-peak feature along the beam axis associated with the inward shell motion. The punched-in nose appears as a single peak in the highest energy zone-plate image (17 to 30 keV). As indicated in Fig. 5-54, most of the thermonuclear burn occurs in the compressed region between the two disks of hot pusher material.

Thermal electron temperatures of the order of 1 to 3 keV can be inferred from the x-ray spectrometer data. The zone-plate images show the corresponding emission coming mainly from the stagnation region of the glass shell. On the other hand, the crystal spectrograph data show temperatures of the order of 700 eV for regions of maximum line emission (near the initial shell position).

The zone-plate images show large emissions caused by suprathermal electrons from the corona (high-energy channel). Unfortunately, only two x-ray spectrometer channels cover this region, so the "hot electron" temperature cannot be exactly determined. Values of about 20 keV appear to roughly fit the data.

Another method of obtaining fast electron energy estimates is available. Indeed the locations of the Faraday cups on Shiva permit an unambiguous determination of the maximum ion velocity, which is of the order of 2×10^9 cm/s. This value is confirmed by the proton signal on the TOF spectrometer. Assuming an isothermal corona model as originally proposed by Crow, Auer, and Allen²⁸ and extensively used since then,^{29,30} fast electron energies of the order of 15 keV are implied. These energies agree with the x-ray spectrometer data and

with previous measurements of T_{HOT} as a function of laser intensity.³¹

We recorded neutron TOF spectra of sufficient quality to measure ion temperatures on most shots. In Fig. 5-55, we plot these data against the measured specific energy absorbed by the target ball in Fig. 5-49. For several years, simulation calculations have predicted this relationship for exploding-pushers. The simple exploding-pusher scaling arguments³² estimate DT ion temperature by equating the usefully absorbed energy with the thermal and kinetic energy residing in the fuel at peak compression. Because Shiva irradiated relatively massive targets with short pulses, the scaling laws contend that all the energy absorbed E was absorbed usefully. Under these conditions, a prediction for the average DT ion temperature may be made as follows:

$$\gamma E \cong 3/2 k (\beta N_p T_p + N_e T_e + N_f T_f) , \quad (30)$$

where γ = the fraction of usefully absorbed energy available as thermal energy at stagnation in the pusher and the fuel $\cong 0.1$; β = the fraction of the pusher mass that implodes $\cong 0.5$; N_p , N_e , N_f = total number of pusher ions, electrons, and fuel ions, respectively; and T_p , T_e , and T_f = pusher ion, electron, and fuel ion temperatures, respectively.

Following Ref. 32, assume that $T_e = T_p = 1/5 T_f$ and that $N_e = N_i + ZN_p$, where $Z \cong 9$ = the average charge state of the silicon dioxide pusher at peak burn. A relationship between usefully absorbed energy E , pusher mass M_p , fuel mass M_f , and DT ion temperature emerges:

$$T_f \text{ (keV)} \cong 13.9 \left\{ \frac{E/(M_p + M_f)}{1 + 9.5 (M_f/M_{fp})} \right\} \text{ (J/ng)} . \quad (31)$$

We used this expression to calculate the ion temperatures for each target irradiation, then plotted the calculations in Fig. 5-55. The temperature assumption used came from a specific simulation and is not true in general. The agreement apparent in Fig. 5-49 may be fortuitous but is empirically useful.

Figure 5-56 illustrates the influence of specific energy absorbed, and hence T_f , on neutron yield. In

this case, we calculated the neutron yield using Ref. 32's scaling arguments as follows:

$$N = n_D n_T V \Delta t \langle \sigma v \rangle$$

$$= 4.5 \times 10^5 \rho_0^2 C^{2/3} r^4 T_f^{-7/6} \exp(-19/T_f^{1/3}), \quad (32)$$

where ρ_0 = initial DT fill in mg/cm³, C = compression at 1.75 M_p/M_f, r = initial fuel radius in μ m, and T_f = fuel ion temperature in keV.

Because the neutron yield of a symmetrically heated exploding pusher target is dominated by the Maxwell-averaged DT cross section $\langle \sigma v \rangle$, which depends only on T_f , knowledge of T_f leads to a good estimate for N . In summary, the exploding-pusher targets irradiated recently by Shiva absorbed slightly more (23%) than those exposed to Argus (20%) but generally behaved similarly. As indicated in Fig. 5-56, the peak DT neutron yield recorded for these 15-to-20-TW irradiations was 2.7×10^{10} neutrons.

The Shiva target irradiation facility can now perform two 20-TW target shots per day. Exploding-pusher studies completed thus far show that these targets scale to higher powers without surprises. The ball-on-plate and ball-in-plate start-up experiments also illustrate the role of heating uniformity on exploding-pusher performance. Strong heating asymmetries affect the average value of fuel ion temperature only weakly, but DT yield drops sharply. The effective value of $n\tau$ is apparently reduced in nonuniformly heated target implosions.

In conclusion, these high power (17-to-19-TW short pulse; 90-to-100 ps) irradiations of glass microspheres did not exhibit any dramatically new results. The scaling determined from Janus and Argus shots adequately predicted ion temperature

and neutron yields. As previously observed, the x-ray emission characteristics are determined by the useful absorbed energy. Finally, an important result of these experiments was to demonstrate that the anticipated enhancement in absorption resulting from radial polarization is offset by scattering processes that will have to be more carefully accounted for in future computations. As shown in §4.6, these scattering processes become increasingly important in longer pulse irradiations.

References

24. K. Estabrook and W. Kruer, "Properties of Resonantly Heated Electron Distributions," *Phys. Rev. Lett.* **40**, 42 (1978).
25. D. Phillion, W. Kruer, and V. Rupert, "Brillouin Scatter in Laser-Produced Plasmas," *Phys. Rev. Lett.* **39**, 1521 (1977).
26. J. Larsen, J. Thomson, and C. Max, *Absorption and Conduction in Spherical Targets*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-78467 (1976).
27. N. M. Ceglio (§6.7).
28. J. Crow, P. Auer, and J. Allen, "The Expansion of a Plasma into a Vacuum," *J. Plasma Phys.* **14**, 65 (1975).
29. E. M. Campbell, in *Proc. 6th Intern. Conf. Plasma Phys. and Controlled Nucl. Fusion, Berchtesgaden, Germany, 1976* (International Atomic Energy Agency, Vienna, Austria, 1976).
30. E. Lindman, Los Alamos Scientific Laboratory, Los Alamos, N. Mex., LA-UR72-100 (1972).
31. K. Manes, H. Ahlstrom, R. Haas, and J. Holzrichter, "Light-Plasma Interaction Studies with High-Power Glass Laser," *J. Opt. Soc. Am.* **67**, 717 (1977).
32. E. Storm, "A Simple Model for Exploding-Pusher Targets," in *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), pp. 6-38.

Authors

K. R. Manes
J. T. Larsen

Major Contributors

V. C. Rupert
J. M. Auerbach
N. C. Holmes
D. W. Phillion
N. M. Ceglio

Section 6

SECTION 6

DIAGNOSTIC TECHNOLOGIES

6.1	Introduction	6-1
6.2	Soft X-Ray Streak Camera Development and Application	6-2
6.3	Filtered Photoelectric Diode Measurements	6-5
6.4	Filter-Fluorescer Spectrometer for High-Energy X-Ray Diagnostics	6-8
6.5	Reflector-Diffractor Spectrograph for Sub-keV X-Ray Measurements	6-12
6.6	Kirkpatrick-Baez X-Ray Microscope Optimization and Development	6-14
6.6.1	Fundamental Optical Constraints	6-15
6.6.2	System Constraints	6-15
6.6.3	Fabrication and Measurement Constraints	6-15
6.6.4	Optimization	6-16
6.7	Wolter Axisymmetric X-Ray Microscope Development	6-23
6.7.1	Manufacture	6-23
6.7.2	Characterization	6-24
6.7.3	Preparation for Application of ASXRM's	6-25
6.8	X-Ray Imaging Calibration Facility	6-27
6.9	Fresnel Zone Structures for Advanced X-Ray Microscopy	6-30
6.9.1	Multispectral X-Ray and Alpha-Particle Zone Plate Camera	6-30
6.9.2	Fresnel Microstructures as X-Ray Optical Elements	6-30
6.10	X-Ray Probing Diagnostics For High Density Implosion Experiments	6-38
6.11	Optical Preheat Diagnostic	6-40
6.12	Neutron Activation Diagnostics for High Density Targets	6-45
6.12.1	Collector	6-45
6.12.2	Detector	6-46
	Efficiency	6-47
	Background	6-48
6.12.3	Shiva Rabbit System	6-51
6.13	Neutron Yield By Lead (Pb) Activation	6-53
6.14	Applications of Charge-Coupled Devices	6-54
6.14.1.	Streak Camera System	6-54
6.14.2.	CCD Photon Camera	6-56
6.14.3.	CRT/CCD Oscilloscope	6-57

6.15	Optical Streak Cameras	6-59
6.15.1	Dynamic Range vs Slit Width	6-61
6.15.2	Dynamic Range vs Input Pulse Width	6-61
6.16	Fiber Optic System for Multiple Beam Diagnostics with a Streak Camera	6-62
6.17	Windowless X-Ray Detector with 50-ps Response	6-64
6.18	Laser Irradiation on Target (LITAR) Code	6-66
6.19	Shiva Target Diagnostic Mapping	6-67
6.20	TACAI Upgrade for Argus	6-70

SECTION 6

DIAGNOSTIC TECHNOLOGIES

6.1 Introduction

One of the primary responsibilities of the Fusion Experiments Program is to vigorously support the development and implementation of diagnostic hardware and software. The following subsections, which are summarized below, discuss in detail our work and accomplishments during the year.

We continue to place heavy emphasis on x-ray diagnostics in our experiments program. We implemented the soft (sub-keV), 15-ps-resolution streak camera and obtained data at the Monojoule and Argus laser facilities. We designed, built, calibrated, and implemented improved and expanded versions of our photodiode-based, sub-keV filter spectrometers on Argus and Shiva. There, we also measured high-energy (supra-keV) x-ray fluence with newly designed, engineered, and calibrated filter-fluorescer spectrometers.

High-resolution crystal diffraction spectrometry in the keV x-ray regime is difficult because a flux of higher-energy x rays can create background noise and overlap of higher-order diffraction patterns. The overlap problem seriously inhibits our ability to record and interpret the desired spectrum. To eliminate it, we designed a crystal spectrograph with a grazing-incidence reflector as the first element. The high-energy cutoff of the mirror reflectivity eliminates the higher order overlap. This configuration also allows for good shielding to suppress the background adequately.

Imaging the sources of x-ray emission from laser-irradiated targets is an important diagnostic tool for understanding the interaction and implosion processes. We discuss:

- X-ray microscopes of the Kirkpatrick-Baez (cylindrical-mirror-pair) grazing-incidence-reflection type, the "workhorses" of x-ray imaging. Also, we present the effects of design parameters, tolerances, and manufacturing perturbations on the performance of these microscopes.

- Several of our advances in extending the use of Fresnel structures for imaging applications. We extended the energy range and combined mul-

tispecies and energy imaging capabilities in a single camera.

- New work leading toward the development of zone-plate, x-ray lensing elements.

- The concept of x-ray probing as a technique for diagnosing compressed target configurations.

To obtain accurate neutron yield measurements on low-yield (10^4 to 10^6) targets, we built and used Pb-activation detector systems on Argus and Shiva. We also implemented a neutron-activation diagnostics scheme designed to directly measure the ($\rho\Delta R$) of compressed targets during the short pulse of neutron production. This technique works by collecting and counting a measured fraction of the glass target ball that has been activated by nuclear reactions with 14-MeV neutrons from the reacting DT fuel. We should be able to deduce the density of the compressed DT fuel from this measurement.

We also report:

- New results on quantifying the performance of ultrafast streak cameras in various configurations for different experimental applications.

- Advances in the implementation of charge-coupled device (CCD) arrays as active readout elements for ultrafast streak cameras, high-bandwidth oscilloscopes, and optical imaging applications.

- A sensitive, high-time-resolution, filter radiometer that uses an ultrafast streak camera, with response in the visible spectrum, for measuring low preheat levels in disk target experiments.

- A multichannel optical system with high-bandwidth fiber optics for recording layer pulse-intensity profiles at the outputs of all 20 Shiva beams, using only two streak cameras.

We are upgrading the Target Acquisition, Control, and Instrumentation (TACAI) software system on Argus to make it the same as the version on Shiva. This upgrading will enhance commonality of operations, maintenance, and documentation.

With Shiva operating routinely for target experiments, we have begun to use the computing power provided by the Shiva control system to help plan experiments. We discuss two software packages. The first, LITAR, allows experimenters

to calculate the effects of focusing schemes on target-illumination geometry to select a final-focusing and beam-placement scheme for an experiment. The second code is a system for mapping the use and status of the 190 ports on the Shiva target chamber. Such mapping allows selection of locations for future diagnostics and avoids conflict or interference with already installed diagnostics.

Author

L. W. Coleman

6.2 Soft X-Ray Streak Camera Development and Application

In previous annual reports, we described the development and application of our 15-ps x-ray streak cameras.^{1,2} We have now extended our diagnostic capability for 15-ps-resolution streak photography into the sub-keV region of the x-ray spectrum. The lower limit of the 1- to 10-keV x-ray detection range, described in Ref. 2, stems from the attenuation of x rays below 1 keV by the 7.5- μ m-thick beryllium window of the x-ray streak tube. This beryllium window is both a vacuum barrier and the substrate for the x-ray photocathode. We changed the x-ray window material to a 0.25- μ m-thick carbon foil, which transmits x rays down to 100 eV with 35% efficiency. Figure 6-1 compares the sub-keV transmission efficiencies of 7.5- μ m-thick beryllium and 0.25- μ m-thick carbon.

The fragile nature of this carbon window requires that no appreciable pressure differential can exist across it, and that it must be easily replaceable. Therefore, we added a pumping system to maintain a vacuum on both sides of the carbon window independent of the target-chamber vacuum system.

To analyze and test standard gold x-ray photocathodes and new developmental photocathodes, we designed the new camera for easy interchange of the x-ray photocathode assemblies. Figure 6-2 is an example of data from a gold photocathode test recorded for a target illuminated by laser pulses that were uniformly spaced in time. The gold photocathode thickness ranges in steps from 130 to 3200 $\text{\AA}$ across the streak camera's aperture slit. Such data allow the determination of photocathode efficiency vs thickness, and they give characteristic camera operating parameters of sweep speed, dynamic range, and gain linearity.

We installed the first soft x-ray streak camera (SXRSC) on Argus to diagnose laser fusion targets (Fig. 6-3). The initial SXRSC experiments use three x-ray channels, each consisting of a grazing-incidence x-ray mirror and an absorber filter. Table 6-1 lists the mirror-filter combinations of the three channels. The absorber filters provide spectral definitions of the channels. The K- or L-absorption edges give a sharp high-energy cutoff. Increased absorption at low x-ray energy provides an effective low-energy limit.

Use of the x-ray mirrors at grazing incidence discriminates against those high-energy x-rays for which the absorber filter is transparent. Below a given critical energy for a given angle, the mirrors have a reflectivity coefficient near unity. Above this energy, reflected x-ray intensity decreases rapidly, making the mirrors effective low-pass filters.

Table 6-1. Parameters for the three x-ray channels on SXRSC.

Channel	Filter		E_{abs} , keV	Mirror	
	Material	Thickness, μ m		Material	Angle, deg
A	Carbon	2.0	0.284	Carbon	5
B	Vanadium	0.8	0.513	Nickel	5
C	Iron	0.9	0.708	Nickel	3

Photocathode: 0.25- μ m carbon-300- $\text{\AA}$ gold.

Fig. 6-2. Streak record of a stepped cathode test, showing the relative sensitivity of gold cathodes with thicknesses ranging from 130 Å to 3200 Å.

The calculated responses of the three x-ray channels, shown in Fig. 6-4, include the spectral response of the transmission photocathode, which is

assumed to be proportional to the transmission through the carbon window, and the x-ray energy deposited in the thin gold film. The channels have

Fig. 6-3. Soft x-ray streak camera, as mounted on the Argus target chamber.

Fig. 6-4. Calculated spectral responses for the three soft x-ray channels of SXRSC.

Fig. 6-5. Data from an Argus target shot. Left: Isointensity contours of the streak data; right: average streak record from the three channels.

peak responses at 200, 500, and 700 eV with a FWHM of 50, 90, and 110 eV, respectively, indicating an $E/\Delta E$ of 4 to 6.

Figure 6-5 shows x-ray streak records from a gold disk irradiated on Argus. The input laser energy is 470 J; pulse width is 950 ps, FWHM; peak power density is 3×10^{14} W/cm². Streak-camera data are recorded on film. The resultant image is then encoded into a 2-D digital array by a computer-controlled microdensitometer. Isointensity contours of the streak records are shown on the left in Fig. 6-5; average streak records for the three channels are shown on the right. The temporal widths of the x-ray emissions are slightly larger than the laser pulse width. The lowest-energy x-ray channel has a longer time response than do the high-energy channels. These general features are noticed on most laser target shots. All three channels register a precursor signal that is more than an order of magnitude less intense than the primary x-ray signal. This sensitivity demonstrates the advantage of the camera's wide dynamic range.

The SXRSC information complements the absolute fluence measurements by the Dante array in characterizing the low-energy x-ray emission. We are calibrating absolutely the SXRSC to enhance its utility.

References

1. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-74 (1975).
2. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-75 (1976).

Authors

G. L. Stradling
R. L. Kauffman

6.3 Filtered Photoelectric Diode Measurements

Measuring low-energy x-ray emission from laser irradiated targets has become increasingly important for understanding the physics of laser-target interactions. We use filtered, photoelectric diodes for x-ray measurements below 1.5 keV because such detector systems can be accurately and absolutely calibrated and are reasonably reliable.³ Moreover, these detector arrays provide adequate temporal and spectral (200 eV) resolution for most of our laser target experiments, and detector response is less than 200 ps. Temporal resolution of the system

Fig. 6-6. Experimental arrangement of 10 filtered, sub-keV x-ray diodes at the Argus laser facility. This type of diagnostic experiment is locally called a Dante system.

is limited by the response of available fast oscilloscopes to 200, 450, or 750 ps. We rely on complementary data from low-energy x-ray streak cameras for high time resolution (See §6.2) and on crystal spectrometer data for high energy resolution (See §6.5).

For measurements on Argus and Shiva we:

- Increased the number of channels. We enlarged our previous system³ from 5 to 10 channels.
- Installed more arrays. We installed 10-channel arrays on Argus and Shiva. Each laser facility will soon have three arrays at different angles, including one set of 10 and two sets of 5 detectors.
- Improved detector performance. We are using techniques to significantly decrease sensitivity variations between detectors of a given type.
- Improved filter performance. We added several, good, low-energy x-ray filters, bringing the total number of filter-detector combinations to 14.
- Provided basic data on laser-target interactions. We used one or two Dante arrays to provide

x-ray data during nearly all of the laser target investigations on Argus.

- Obtained experimental confirmation. To within experimental error, the total low-energy x-ray emission that we measure with a flat response detector has been in reasonable agreement (20%) with results obtained by integrating the Dante 10-channel spectra.

Figure 6-6 schematically shows the new Argus 10-channel Dante array. We enlarged our previous arrangement by adding five channels on the front assembly. Detector cathodes consisting of different metals and selected K- or L-edge filters were chosen to provide 200-eV energy resolution between 100 eV and 1.5 keV. Practical considerations such as long-term detector stability led us to a system consisting of three detector cathode types—Al, Cr, and Ni. Figure 6-7 shows absolute sensitivity measurements for these three types to better than 20% at the LLL X-ray Calibration and Standards Laboratory. By improving procedures for detector cleaning, handling, and surface finishing, we significantly decreased sensitivity variations among detectors of

a given type. Table 6-2 lists the characteristics of our most frequently used filtered x-ray diode array.

According to our transmission calibration data, the quality of the new filters that we have added (Cr, Co, Ni, and Cu) is very high. Iron is the only filter with a significant calibration uncertainty that results from the presence of iron oxide and the lack of available calibration energies in the critical region below the iron L-edges.

Using these instruments, we plan to conduct disk experiments to more accurately determine the low-energy x-ray emission as a function of:

- Target atomic number Z .
- Laser intensity.
- Laser incidence angle.
- X-ray emission angle.

Reference

3. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978) p. 3-61.

Author

K. G. Tirsell

Table 6-2. Characteristics of a filtered x-ray diode array.

Cathode type	Absorption edge	Filter ^a		Channel width, keV
		Thickness, mg/cm ²	Edge energy, keV	
1. Al	Carbon-K ^b Oxygen-K	0.15	0.28	110
2. Al	Vanadium-L	0.33	0.52	125
3. Al	Chromium-L	0.43	0.58	110
4. Al	Iron-L	0.31 (Fe) 0.06 (Fe ₂ O ₃)	0.71	270
5. Al	Cobalt-L	0.98	0.79	240
6. Al, Cr	Nickel-L	0.62	0.86	160
7. Cr	Copper-L	0.89	0.94	170
8. Cr, Ni	Zinc-L	1.0	1.03	180
9. Ni	Aluminum-K	2.5	1.56	470
10. Ni	Aluminum-K	5.0	1.56	250

^a A 10-g/cm² Polyene filter was also used for each channel.

^b Formvar (C₁₀H₁₆O₃) was used for this filter.

6.4 Filter-Fluorescer Spectrometer for High-Energy X-Ray Diagnostics

We designed a four-channel filter-fluorescer diagnostic and used it to measure x-ray spectra (>20 keV) from various targets irradiated with the Argus laser system. A complete description of the basic principles of the experiment and its advantages relative to the simple K-edge filter technique has been published previously.^{4,5}

We chose prefilter and fluorescer materials and thicknesses to provide a balance between response function shape, resolution, and the expected signal appropriate for the anticipated spectral shapes. A summary of the channel parameters for this experiment is given in Table 6-3, and a plot of the three

Table 6-3. Channel parameters for filter-fluorescer diagnostic.

Channel	Energy band, keV	Prefilter		Fluorescer		Fluoresced response scattered response	Band response total response	Flatness of response function in band ^a
		Material	Thickness, mils	Material	Thickness, mils			
1	20-29.2	Sn	2.7	Mo	1.0	6.2	0.47	1.20
2	46.8-61.3	Yb	6.0	Sm	1.0	14.3	0.38	1.10
3	80.7-115.6	U	15.0	Au	0.5	6.3	0.36	2.4
4	>115.6	U	15.0	U	1.0	—	—	—

^aRatio of maximum to minimum response within band.

response functions appears in Fig. 6-8. The fourth channel was normally used to indicate background levels.

Figure 6-9 is a schematic of the experimental arrangement. The magnets shown are 6 in. long and provide a field of 1200 G. For 1-MeV electrons, these conditions produce trajectories with a radius of curvature of less than 4 cm; thus, all electrons are cleared from the x-ray beam incident on the fluorescer foil. Detectors consist of 1- or 3-mm-thick NaI crystals used with Amperex XP2020 photomultipliers. These detectors were calibrated from 8 to 97 keV with a Picker x-ray machine and a series of filtered fluorescers. Data obtained from Argus laser shots were recorded on LeCroy 2249 integrators or Tektronix R7903 oscilloscopes.

We used this diagnostic to measure x-ray spectra produced by Argus laser shots with intensities of 3×10^{14} to 3×10^{16} W/cm² incident on gold disks. Results are shown in Fig. 6-10. For these conditions, x-ray intensity decreases with increasing photon energy, similar to bremsstrahlung spectra from Maxwellian electron distributions with $kT = 10$ to 35 keV or more. In fact, at the level of 3×10^{16} W/cm², the x-ray spectrum has flattened out so much that a calculation of temperature is meaningless because of the experimental error associated with this prototype system.

Fig. 6-10. X-ray spectra from laser-irradiated Au disk.

We installed complete 10-channel filter-fluorescer systems on both the Argus and Shiva target chambers.^{5,6} These systems will operate in the photon energy range between 1 and 100 keV, as indicated by channel response functions shown in Fig. 6-11. Each system has 10 additional straight-through channels that include 5 K-edge filters for

Fig. 6-11. Channel response functions of the filter-fluorescer.

Fig. 6-12. Shiva Nova x-ray diagnostics — filter fluorescer experiment.

measuring very low intensity x-ray spectra and 5 different thickness Pb filters for measuring energies above 100 keV. Figure 6-12 shows the mechanical arrangement of the filter-fluorescer and straight-

through channels, and Table 6-4 gives our preliminary choice of foils and detectors. Figure 6-13 is a schematic of the recording electronics. We began taking data with these systems early in 1979.

Table 6-4. X-ray spectrometer channels.

Channel	Filter,		Fluorescer,		Postfilter, μm	Detector, mm	
	μm	keV	μm	keV			
1	1.5 Zr	2.2	0.75 Al	1.6	—	0.25 NEIII	PM
2	2.0 Sm	3.9	13 Cl	2.8	—	0.25 NEIII	PM
3	13 Fe	7.1	5 Ti	5.0	2.5 Ti	2.5 NEIII	PM
4	20 Zn	9.7	5 Fe	7.1	2.5 Fe	2.5 NEIII	PM
5	50 Se	12.7	8 Zn	9.7	2.5 Zn	2.5 NEIII	PM
6	75 Mo	20.0	8 Y	17.0	5 Y	2.5 NEIII	PM
7	380 Dy	53.8	25 Sm	46.9	25 Sm	1.0 NaI	PM
8	250 W	69.5	50 Yb	61.3	50 Yb	1.0 NaI	PM
9	380 U	116	50 Pb	88.0	25 Au	3.0 NaI	PM
10	810 Pb	Bkgd	50 Pb		25 Au	3.0 NaI	PM

	Filter (1)	Filter (2)	Filter (3),		Detector, mm	
			μm	keV		
11	Zr	Al	75 Mo	20.0	2.5 NEIII	PM
12	Sm	Cl	380 Dy	53.8	1.0 NaI	PM
13	Fe	Ti	210 W	69.5	1.0 NaI	PM
14	Zn	Fe	380 U	116	3.0 NaI	PM
15	Se	Zn	810 Pb	Bkgd	3.0 NaI	PM

	Filters, g/cm^2 Pb	Energy range, keV	Detector, mm CsI
16	0.4	90-300	0.5
17	1.0	100-400	0.5
18	2.0	150-500	0.5
19	4.0	200-600	0.5
20	12.0	>400	0.5

References

4. H. N. Kornblum, B. L. Pruett, K. G. Tirsell, and V. W. Slivinsky, *Filter Fluorescer Experiment on the Argus Laser*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-81471.
5. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), p. 3-64.
6. B. L. Pruett, K. G. Tirsell, H. N. Kornblum, S. S. Glaros, D. E. Campbell, and V. W. Slivinsky, *A Ten Channel Filter-Fluorescer Spectrometer*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-81477.

Author

H. N. Kornblum

Major Contributors

B. L. Pruett
K. G. Tirsell
V. W. Slivinsky
J. M. Auerbach

6.5 Reflector-Diffractor Spectrograph for Sub-keV X-Ray Measurements

Second- and third-order diffractions from radiation above 1 keV can obscure the response of a crystal spectrograph to x rays below 1 keV. We built

Fig. 6-14. Diagram of the reflector-fraction spectrograph.

a spectrograph for target diagnosis that uses a germanium mirror as a low-pass filter and allows a curved rubidium acid phthalate (RAP) crystal to be illuminated only by sub-keV radiation (Figs. 6-14 and 6-15). The crystal energy coverage is 500 eV to 1 keV, and the spectra are recorded on special vacuum uv Kodak-type 101-01 film. A tantalum entrance aperture collimates the incoming x rays, and a 0.75- μm -thick aluminum window prevents exposure of the film by light.

Fig. 6-15. Spectrograph geometry, showing x rays striking the germanium mirror at an angle of 1.75° . Only sub-keV x rays are reflected onto the RAP crystal, which Bragg-diffracts them onto the film.

Germanium was chosen for the mirror material because L-absorption edges help produce a sharp i-keV energy cutoff for x rays incident at 1.75° . To confirm this choice, we measured the reflectivity of a germanium mirror using the L-division x-ray calibration facility. Results are displayed in Fig. 6-16. Because RAP integral reflectivity for second- to fourth-order diffractions is 10 to 50 times lower

Fig. 6-16. Reflectivity of germanium at 1.5 , 1.75 , 2.0 , and 2.25° .

than for first-order diffractions, there is additional discrimination against higher-order diffractions.

The overall sensitivity of the instrument (Fig. 6-17) at 59 cm from the laser target is the product of window transmission, mirror reflectivity, crystal integral reflectivity, and instrument geometrical sensitivity.

We demonstrated instrument operation using radiation from aluminum and nickel Henke-tube anodes. Figure 6-18 shows the 1.487-keV K_{α} line of Al and its second-order diffraction measured with and without the germanium mirror in place. From such spectra, we conclude that the instrument can exclude confusing high-order diffractions from its measurement of a sub-keV spectrum.

Author

S. M. Lane

Major Contributors

L. N. Koppel

S. G. Glaros

V. W. Slivinsky

J. Auerbach

6.6 Kirkpatrick-Baez X-Ray Microscope Optimization and Development

We have routinely used Kirkpatrick-Baez x-ray microscopes (KBXRM's) in Shiva target irradiation experiments (Fig. 6-19). Figure 6-20 shows an image from the first 26-TW Shiva experiment. The KBXRM's have again proved their worth by providing information in a 2-D visual format, which frequently clarifies target behavior that could only be inferred with difficulty and uncertainty from the data of other diagnostics.

KBXRM data have helped us to understand better:

- Coupling of the energy in the laser beams to the target.
- Energy transport within the target.
- Compression of the fuel.

Because of the demonstrated value of x-ray microscopy to the program, we devoted a significant effort to developing and improving KBXRM's.

We conducted a theoretical study of four-channel KBXRM's to define performance limits that can be attained without compromising the usefulness of the instruments. As part of this study, we developed a strategy for building these x-ray microscopes as simply and cheaply as possible. Our major goal was to develop a four-channel KBXRM design that is easy to align reliably, and has high resolution, large solid angle, and broad spectral coverage among the four channels.

Fig. 6-19. Schematic of simple four-channel x-ray microscope.

To satisfy these requirements, we developed a detailed set of constraints, which fall into three categories:

- Fundamental optical constraints.
- System constraints.
- Fabrication and measurement constraints.

6.6.1 Fundamental Optical Constraints

KBXRMS's are subject to geometrical aberrations that limit the resolution and field of view.⁷⁻¹² The two most important aberrations are spherical aberration and obliquity of field. Spherical aberration, which increases with mirror width, can be reduced by the proper design of mirror surface figures, but fabrication becomes more difficult.

Obliquity of field, which is inherent to the operation of KBXRMS's, is unaffected by modifications of mirror surface figure. It can be corrected by using additional mirror pairs or by using carefully sized and aligned apertures. However, both methods of correction are expensive or difficult.

6.6.2 System Constraints

Although each channel is a separate x-ray microscope, we require that the field of view of each channel have nearly total overlap with those of the

other channels. The fields of view must be large enough to accommodate an entire laser fusion target (~ 1 mm) with reasonable resolution (5 to $10 \mu\text{m}$). A somewhat smaller field of view must have sufficient resolution to distinguish the finest anticipated features, ~ 1 to $3 \mu\text{m}$. The microscopes must also have an object distance long enough to avoid blast damage, and a magnification high enough to produce images of useful size, compatible with the recording medium. The energy channels must give broad energy coverage without leaving large gaps or overlapping.

6.6.3 Fabrication and Measurement Constraints

Typical KBXRMS cylindrical mirrors, with the required object distances, differ from optical flats by only about $0.5 \mu\text{m}$. The best metrology is limited to approximately $0.025 \mu\text{m}$. Hence, the radius of curvature and focal length of the mirror are known to only 5%, which is a variation larger than the depth of field. To obtain identical focal lengths for all four channels, each channel must have either mirrors that were polished simultaneously, or mechanical adjustment of each mirror so that focal length can be individually adjusted. We prefer the

Fig. 6-20. X-ray microscopic image — first 26-TW Shiva target experiment.

former procedure because it is simple, cheap, and reliable.

Surface roughness, which causes scattering of the x rays and degradation of the images, is another fabrication constraint. A roughness of less than $\sim 10 \text{ \AA}$ rms is desired and can be achieved on only a limited number of substrate materials. If other reflector materials are required, they must be applied to the polished substrate surface in thin coatings.

6.6.4 Optimization

We drew many interrelated conclusions that are internally consistent. No attempt is made to derive them here; they are merely stated:

- Cost and reliability dictate that obliquity of field not be corrected. Similarly, acylindrical mirror figures are too costly to use to correct spherical aberration. Resolution goes up, but the field of view is reduced below useful limits.

- To reduce cost and guarantee identical fields of view for each channel, the four mirrors must all be identical in size, shape material, and radius of curvature. They must also be polished simultaneously.

- Mirror surfaces can then be coated with materials of different density to yield different energy cutoffs and channel energies.

- The most satisfactory substrate material is vitreous carbon, which is stable, amorphous, and

takes a 10-Å surface finish. It also has the lowest density of any practical mirror material; hence, uncoated, it can serve as the lowest-energy channel. Very thin coatings can be used without danger of getting spurious reflections from a substrate material denser than the coating. An outline of the design strategy is shown in Fig. 6-21.

Optimization proceeds by minimizing the equivalent resolvable spot size in the object plane. The on-axis spot size is determined by diffraction, which decreases with increasing mirror width, and spherical aberration, which increases with increasing mirror width. The spot size is minimum at a mirror width where the two contributions are nearly equal. This condition was first derived by Prince⁸

and later in more detail by Dyson.⁹ The geometry under consideration is shown in Fig. 6-22. The geometrical spot size from spherical aberration is

$$S_G \cong \frac{3}{8} \frac{\epsilon W^2}{R} \frac{M-1}{M} \quad (1)$$

and the diffraction spot size is

$$S_D \cong 0.886 \frac{d_o \lambda}{W \sin(i)} \cong 1.10 \times 10^{-6} \frac{d_o}{W i E} \text{ (mm)} , \quad (2)$$

where

- W = mirror full width, mm
- R = mirror radius of curvature, mm
- M = magnification
- d_o = object distance, mm
- i = grazing incidence angle, radians
- E = average photon energy, keV
- λ = average photon wavelength, Å
- ϵ = numerical constant between 0.33 and 0.52.

The angle of incidence i is related to the mirror high-energy cutoff and to the average photon energy E of that channel by

$$i = 0.019 \frac{\sqrt{\rho}}{E_c} = 0.019 \frac{\beta \sqrt{\rho}}{E} \text{ (radians)} , \quad (3)$$

where ρ is the reflector density, and β is the ratio of the channel's average photon energy to the mirror cutoff energy, typically between 0.6 and 0.9. Additional formulas required are the KBXRM focal-length formula

$$f = \frac{R}{2} \sin(i) \cong \frac{Ri}{2} \quad (4)$$

and the thin-lens formula

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{Md_o} = \frac{M+1}{Md_o} . \quad (5)$$

Using Eqs. (3) to (5) to eliminate R , i , and f from Eqs. (1) and (2), and assuming that the total spot size S_o is given by

$$S_o^2 = S_G^2 + S_D^2, \quad (6)$$

then, S_o can be minimized with respect to W_o . Solving

$$\left. \frac{dS_o}{dW} \right|_{W=W_o} = 0$$

yields

$$S_D = \sqrt{2} S_G \quad (7)$$

at W_o . This, in turn, yields

$$\begin{aligned} S_o &= \sqrt{3} S_G = \sqrt{\frac{3}{2}} S_D \\ &= 3.14 \times 10^{-4} \left[\frac{\epsilon d_o}{\beta \sqrt{\rho} E} \left(\frac{M^2 - 1}{M^2} \right) \right]^{1/3} \text{ (mm)} \end{aligned} \quad (8)$$

and

$$W_o = 0.225 \left[\frac{d_o^2 E}{\epsilon \beta^2 \rho} \left(\frac{M^2}{M^2 - 1} \right) \right]^{1/3} \text{ (mm)}. \quad (9)$$

These are the optimum resolution and mirror width for an individual channel. As stated above, the angle is held constant for all four channels. Therefore, Eq. (3) relates channel energy and reflector density as

$$\frac{\sqrt{\rho_n}}{E_n} = \frac{\sqrt{\rho_m}}{E_m}, \quad (10)$$

where the subscripts indicate channel numbers from 1 (lowest energy) to 4 (highest energy). The ratio of

maximum to minimum channel energies is related to the maximum and minimum possible reflector densities ($\rho_1 = 1.54 \text{ g/cm}^3$ for vitreous carbon, and $\rho_4 = 22.4 \text{ g/cm}^3$ for iridium) by

$$\frac{E_4}{E_1} = \sqrt{\frac{\rho_4}{\rho_1}} \approx 3.8.$$

Intermediate density reflectors are used for intermediate energy channels.

Using Eq. (10) and evaluating Eqs. (8) and (9) for each microscope channel in terms of channel four, we found that each channel has a different optimum resolution and width (narrower mirrors and better resolution at higher energies). However, we decided that it would be simpler and less costly to make all mirrors the same width. Therefore, we found an optimum width for all four channels as follows. If W_{on} and S_{on} are the optimum mirror width and resolution for channel n , respectively, then the resolution of channel n for mirror widths other than W_{on} is

$$S_n(W) = \frac{S_{on}}{\sqrt{3}} \sqrt{2 \left(\frac{W_{on}}{W} \right)^2 + \left(\frac{W}{W_{on}} \right)^4}. \quad (11)$$

The best compromise mirror width W is that which degrades the resolution of each channel the least (fractionally) from its individual channel optimum resolution. This condition occurs approximately when

$$\frac{S_1(\bar{W})}{S_{o1}} = \frac{S_4(\bar{W})}{S_{o4}}. \quad (12)$$

Using Eqs. (8) through (12), we can show that

$$\frac{\bar{W}}{W_{o4}} = \left[\frac{2(R^{-1/3} - 1)}{(1 - R^{2/3})} \right]^{1/6} \approx 1.23, \quad (13)$$

where

$$r = \left(\frac{\rho_1}{\rho_4} \right) = \left(\frac{E_1}{E_4} \right)^2$$

and we assume $r = 0.0688$. Using Eqs. (8) to (11) and Eq. (13), we find the final optimized resolution for each channel S_n :

$$\bar{S}_n = \left[\frac{1 + 0.578 \left(\frac{E_4}{E_n} \right)^2}{1.578} \right]^{1/2} \quad (14)$$

$$\bar{S}_4 = 3.44 \times 10^{-4} \left[\frac{e d_o}{\beta \sqrt{\rho_4} E_4} \left(\frac{M^2 - 1}{M^2} \right) \right]^{1/3} \text{ (mm)} . \quad (15)$$

W is

$$\bar{W} = 0.277 \left[\frac{d_o^2 E_4}{\beta^2 \epsilon \rho_4} \left(\frac{M^2}{M^2 - 1} \right) \right]^{1/3} \text{ (mm)} . \quad (16)$$

The solid angle of each channel is

$$\begin{aligned} \bar{\Omega} &= \left(\frac{\bar{W}_i}{d_o} \right)^2 \\ &= 2.78 \times 10^{-5} \left[\frac{\beta^2 \rho_4}{E^2 d_o^2 E_4} \left(\frac{M^2}{M^2 - 1} \right)^2 \right]^{1/3} \text{ (str)} . \end{aligned} \quad (17)$$

The mirror sagittal depth is

$$\begin{aligned} \bar{\sigma} = \frac{\bar{W}^2}{8R} &= 9.12 \times 10^{-5} \left[\frac{d_o}{\beta \epsilon^2 E_4 \sqrt{\rho_4}} \left(\frac{M^2}{M^2 - 1} \right)^2 \right]^{1/3} \\ &\quad \times \left(\frac{M+1}{M} \right) \text{ (mm)} . \end{aligned} \quad (18)$$

The depth of field $\bar{D}_o$ (approximately that focal shift which gives an object plane spot size of $\sqrt{2} \bar{S}_n$) is defined as

$$\begin{aligned} \bar{D}_o &= \pm \frac{3}{8} \bar{W} \frac{M^2 - 1}{M^2} \\ &= \pm 0.104 \left[\frac{d_o^2 E_4}{\beta^2 \epsilon \rho_4} \left(\frac{M^2 - 1}{M^2} \right)^2 \right]^{1/3} \text{ (mm)} . \end{aligned} \quad (19)$$

As the image point moves laterally away from the center of the field of view, the angle of incidence of the rays on the mirror changes. Consequently, the focal length $f = \frac{1}{2} R_i$ also changes. The image becomes defocused and the object plane spot size increases. If one defines the breadth of field B_o as the lateral distance from the center of the field where the focal length is shifted by $\pm \bar{D}_o$, then

$$\begin{aligned} \bar{B}_o &= \pm \frac{3}{4} \frac{\bar{W} d_o}{R} \frac{(M^2 - 1)}{(M + 1)^2} \\ &= \pm 1.97 \times 10^{-3} \left[\frac{\beta \sqrt{\rho_4} d_o^2}{\epsilon E_4^2} \left(\frac{M^2}{M^2 - 1} \right) \right]^{1/3} \\ &\quad \times \frac{M - 1}{M} \text{ (mm)} . \end{aligned} \quad (20)$$

Noting that the dependence on M is slight, we plot Eqs. (14) through (20) as Figs. 6-23 through 6-29 for typical parameters of x-ray microscopes in the Shiva and Nova facilities.

We next consider mounting the mirrors. The simplest and most reliable mounting method is to optically contact the mirrors against a glass spacer block that has faces parallel to within ± 5 to $10''$ and is slotted to pass the x-ray beams. One mirror touches each side of the spacer on faces parallel to the optical axis. The distance from the optical axis to the mirror surface and the object distance together determine the grazing angle. This arrangement provides accurate relative alignment of all the mirrors and, therefore, accurate superposition of the fields of view. The microscope can then be aligned as a unit.

Note that Eq. (19) indicates a depth of field only 0.375 the width of the mirrors and that one pair of mirrors is necessarily mounted in front of the other pair by at least a mirror width. If the spacer were the same width for both pairs of mirrors, one set would always be out of focus when the other was in focus. We solved this problem by making the

back spacer slightly wider than the front spacer, thereby slightly increasing the focal length of the back mirror pair. The front (-) and back (+) spacer thicknesses are given by

$$T_{\pm} = 2 i_0 \left\{ d_0 \left[1 + \left(\frac{M-2}{M} \right) \left(\frac{e}{2d_0} \right)^2 \right] \pm \frac{e}{2} \left[\left(\frac{2M-1}{M} \right) - \frac{1}{M} \left(\frac{e}{2d_0} \right)^2 \right] \right\} \quad (21)$$

where e is the separation distance of the front and back mirror center lines and has a minimum value of W , and i_0 is the nominal grazing angle. This technique of correcting the focus results in a slight difference in magnification as measured in the two orthogonal planes that include the microscope optical axis. However, the error is slight—between 1 and 5%.

Two types of Shiva KBXRM's have been designed according to the above optimization strategy. The first is a 1.6- to 5-keV four-channel x-ray microscope. The second is a 0.25- to 1.1-keV soft x-ray microscope.

References

7. P. Kirkpatrick and A. V. Baez, "Formation of Optical Images by X-rays," *J. Opt. Soc.* 38, 766 (1948).
8. E. Prince, "The Resolving Power of an X-ray Microscope," *J. Appl. Phys.* 21, 690 (1950).
9. J. Dyson, "Optics of the Focusing X-ray Microscope," *Proc. Phys. Soc. Lond.* B65, 580 (1952).
10. P. Kirkpatrick and H. H. Patee Jr., "X-ray Microscopy," in *Handbuch der Physik*, S. Flugge, Ed. (Springer-Verlag, Berlin, 1957) Vol. 30, p. 326.

11. J. F. Megee, D. R. Hesser, and J. W. Milton, "X-ray Reflection Optics (Recent Developments)," in *Fifth International Congress on X-ray Optics and Microanalysis*, G. Mollenstadt and K. H. Gankler, Eds. (Springer-Verlag, New York, 1969), p. 11.
12. J. F. Megee and J. W. Burrows, "A Total Transverse Aberration Function for Grazing Incidence Optics," in *Proc. of Soc. of Photo-Optical Instr. Eng.*, K. C. Chase and G. W. Kuswa, Eds. (1977) Vol. 106, p. 107.

Author

R. H. Price

Major Contributor

M. J. Boyle

6.7 Wolter Axisymmetric X-Ray Microscope Development

Development of an axisymmetric x-ray microscope (ASXRM), see Fig. 6-30, proceeded slowly during 1978 because of other demands on resources. Nevertheless, there were some significant developments, which we report here.

6.7.1 Manufacture

One 22X (22 times magnification) ASXRM (22X, mod II), which had been diamond-turned in

Fig. 6-30. Axisymmetric x-ray microscope (9X mirror) with hyperboloid-ellipsoid grazing incidence reflecting surfaces.

1977, was polished and completed at LLL. Subsequent metrology showed that the mirror became distorted when it was removed from the chuck and potting. To eliminate such problems, we devised a new mounting system to hold the mirror on the diamond turning machine (Fig. 6-31).

To avoid other potential problems discovered during metrology, the steel substrates will be lapped to an optical finish before electroless nickel plating, final diamond turning, and figuring.

To produce better final surface finishes and to allow figure correction, we automated the axisymmetric mirror polishing machine. The new digital control system will be brought into use in stages during 1979.

We began a systematic study of ways to improve the polishing process for ASXRM's in hopes of improving the surface finish that can be produced on complex curved surfaces.

We are studying new substrate materials that have improved macroscopic and microscopic dimensional stability, as well as improved machinability.

Production began on 12 ASXRM substrates for the new 22X design. We plan to finish six microscopes during 1979.

Two 22X mirrors and two diamond-turned 22X substrates are to be provided to AWRE-NPL, in England, under the Triad Program, which began in 1978. NPL will polish two mirror substrates and will measure and characterize all of the finished mirrors. Two mirrors will eventually be returned to LLL.

Two diamond-turned substrates will be supplied to Visidyne, Inc., for final figuring and polishing under the ASXRM development contract with LLL. The remaining mirrors will be finished at LLL.

6.7.2 Characterization

We evaluated three ASXRM's (one 9X and two 22X), using a combination of measurements from the Moore measuring machine, Clevite profilometer, and Indi-Round. Absolute measurements of ASXRM figures were made to within several microinches; relative measurements of figure contours were to within $\sim 0.5 \mu\text{in.}$ ($125 \text{ \AA}$).

Four azimuthal scans about the optical axis are made with the Indi-Round. One scan is made at each end of the hyperboloid and ellipsoid surfaces. The absolute angular location during the scans is

measured relative to a fixed point on the mirror substrate. Next, four scans of the hyperboloid-ellipsoid surfaces are made with the Clevite profilometer, at $\phi = 0, 90, 180$ and 270° , parallel to the optical axis. Finally, with the Moore measuring machine, we measure the absolute internal radius of the mirror surface as a function of distance from the mirror end.

Data from the measurements are combined using a computer code to find the hyperboloid-ellipsoid surface that most closely matches the data. The code then outputs the exact optical constants of the new ASXRM. The measurements can be combined using the best-fit figure as a skeleton to yield the total figure down to the finest level of structure. We are developing a code to do the final synthesis of the data and a code to interpolate the surface figure between the measured points. The output of these codes will be used with the RATRAC ray-tracing code, developed at Visidyne, Inc., for detailed studies of the imaging properties of the finished ASXRM's.

To date, the most damaging surface distortions have been out-of-roundness, arising from distortion while the mirror was mounted for machining, and surface ripples with azimuthal symmetry, which appear to be remnants of machining marks. The new diamond-turning mounting fixtures should correct the out-of-roundness, but there are at least two possible sources of the surface ripples. One is that they may simply be unpolished tool marks left during the final diamond-turning process, and we are studying an improved polishing process that might solve this problem. However, the surface ripples

may result from coarse machining marks left on the substrate before nickel plating, which "print through" the plating. In this case, we must lap the machining marks off the steel substrate before nickel plating, which we will do to future ASXRM's as a precaution.

An optical slope scanning device that can measure to $0.1''$ and $125 \text{ \AA}$ accuracy on a surface region $50 \text{ }\mu\text{m}$ in diameter was developed at Random Device, Inc., a Visidyne, Inc., subcontractor. The probe beam can then be scanned over the entire surface of an ASXRM. The slope scanner appears to be amenable to further improvement in accuracy. Table 6-5 shows the present levels to which we can measure ASXRM tolerances.

To test the capabilities of the optical slope scanner, we used it to measure the ASXRM 22X, mod II, which previously had been completely measured at LLL. The slope scanner is absolutely calibrated, and the calibration method is completely independent and different from that used on the LLL measuring devices. Measured on the slope scanner, detailed surface structures matched those measured at LLL, even at the $125\text{-}\text{\AA}$ level. The scale factors matched within 2 to 3%. We believe that the slope scanner establishes a new state of the art as a noncontact optical measuring technique.

6.7.3 Preparation for Application of ASXRM's

We have almost completed the characterization and calibration procedure for ASXRM's. Following the full metrology procedure described above, the microscope is calibrated at the x-ray imaging

Table 6-5. Comparison of the ASXRM's tolerance magnitude and the consistency of the Random Devices, Inc., optical slope scanner measurements.

Tolerance description	Tolerance magnitude	Consistency of scanner measurement
Roundness ($R_{\max} - R_{\min}$)	$0.5 \text{ }\mu\text{m}$	$0.015 \text{ }\mu\text{m}$
$\frac{dR}{d\theta}$ (maximum slope error about a circumference)	$0.8 \text{ }\mu\text{m/cm}$	$0.2 \text{ }\mu\text{m/cm}$
$\Delta R(\theta)$ (variation of ΔR with θ ; that is, $\Delta R_{\max} - \Delta R_{\min}$)	$0.033 \text{ }\mu\text{m}$	$0.015 \text{ }\mu\text{m}$
$\Delta S(X)$ (deviation of the actual surface profile from the ideal profile in planes containing the optical axis)	$0.011 \text{ }\mu\text{m}$	$0.011 \text{ }\mu\text{m}$
$\frac{dS}{dX}$ (departure of the actual local slope from the ideal local slope in planes containing the optical axis)	$0.022 \text{ }\mu\text{m/cm}$	$0.26 \text{ }\mu\text{m/cm}$ ($0.018 \text{ }\mu\text{m/cm}$) ^a

^aValue after laser stabilization.

Fig. 6-32. ASXRM (22X, mod I) mirror cell with optical alignment lens.

calibration facility described in §6.8. We recently measured the ASXRM 22X, mod I resolution to better than $5 \mu\text{m}$ FWHM. Complete characterization of an ASXRM mirror consists of:

- Metrology of the mirror.
- Spatial calibration.
- Spectral calibration.

Alignment techniques for ASXRM's on the target chamber, which involve adjusting the tilt of the mirror to $\pm 20''$ to minimize off-axis aberrations, are also in an advanced state of development. Lateral translation of the ASXRM's, accurate to better than $\pm 5 \mu\text{m}$ in the object plane, and focus adjustment to $\sim \pm 10 \mu\text{m}$ are also necessary.

We can easily adjust tilt with the single reflection focus, from the ellipsoid, of a point light source placed at the object point. Typically, the light source is an optical fiber mounted on the target manipulator and placed at the target chamber center. The image of the point source is a ring with a dot in the center. The dot moves, relative to the ring, with the mirror tilt. Symmetry considerations require that when the dot is centered in the ring, the mirror tilt is zero. An error of $\pm 20''$ is easily detected.

For lateral adjustment, we move the image plane location, not the microscope. This procedure allows the accuracy of adjustment to be coarser by a factor of the magnification of the x-ray microscope. Initially, the image plane is centered on the microscope optical axis using the point light source that is used for the tilt adjustment.

To align on a target, we mount a glass lens, with a focal length identical to that of the ASXRM, in the center of the ASXRM so that their optical axes and principal planes coincide (Fig. 6-32). The target can then be viewed in visible light and its image moved to the proper place by translating the image plane and detector system (streak camera, film, etc.). In practice, a separate visible-light camera and removable right-angle mirror are attached to the image plane translator so that alignment can be done without removing the x-ray detector system.

To make the focal adjustment, we use the x-ray point source.^{13,14} Alternatively, we can aperture the acceptance annulus of the ASXRM to a small pie-shaped slice that increases the depth of field and makes focus much less critical; however, this technique reduces solid angle. No further shot-to-shot adjustments are required after initial focal measurements. We are also considering other focusing schemes.

References

13. R. H. Price, M. J. Boyle, and S. S. Glaros, *A Miniature X-Ray Point Source for Alignment and Calibration of X-Ray Optics*, Lawrence Livermore Laboratory, Livermore Calif., UCRL-79777 (1977).
14. R. H. Price, M. J. Boyle, and S. S. Glaros, "Point X-Ray Source," *Rev. of Sci. Instr.* (accepted for publication).

Author

R. H. Price

Major Contributor

M. J. Boyle

Fig. 6-33. X-ray imaging calibration facility, showing x-ray microscope positioner and Palmer tube x-ray source.

6.8 X-Ray Imaging Calibration Facility

The x-ray imaging calibration facility (Fig. 6-33) is located in the Building 381 Argus High Bay and makes use of the 3-ft-thick concrete slab on which the Argus laser is built. The optical table and support structures are rigidly attached to the concrete slab for maximum stability, which is required for micrometer-resolution exposures.

The lab contains:

- Several types of x-ray sources suitable for imaging applications.
- A computer-based multichannel analyzer system.
- A windowless Si(Li) detector.
- A Shiva style x-ray microscope positioner (Fig. 6-34) that fits all existing and planned x-ray microscopes.
- A vacuum system whose pumps are free of organic compounds, to maintain the extremely

clean vacuum conditions required for grazing incidence x-ray optics.

We emphasize commonality and interchangeability among system components so that different optics can be calibrated with a minimum of setup time.

We can attach the x-ray sources interchangeably to the Shiva x-ray microscope positioner without changing object distances. The first x-ray source—a 3-kW, watercooled Palmer tube, with interchangeable anode materials—is used to backlight various x-ray test patterns. We mount the test patterns on small interchangeable carriers that fit into a fixture between the Shiva XRMS positioner and the Palmer tube. The carriers realign to better than $\pm 13 \mu\text{m}$ laterally and $\pm 4 \mu\text{m}$ along the optical axis. We use a 25- μm pinhole, backlit with a He-Ne laser, for initial alignment of the x-ray optics. A 20×20 element array of 2- μm pinholes is the most useful test pattern. The pinhole

Fig. 6-34. Shiva style x-ray microscope positioner.

Fig. 6-35. Enlarged x-ray micrograph of 2- μ m pinhole point spread array, taken with the ASXRM (22X, mod I).

center-to-center spacing is 50 μm , and the array is made of 5- μm -thick gold.

We use the 400-pinhole array, called a point spread array, to measure point spread functions simultaneously over the whole lateral field of view of an x-ray microscope. A point spread function is the distribution of radiation produced in the image plane when an infinitely small source of radiation is placed in the object plane. The quality of an optical element can be determined from its point spread function. Therefore, several pictures taken at different focal settings can completely characterize the imaging properties of an x-ray microscope.

We are developing a computer code to reduce the images taken of the point spread array and to plot the resolution over the field of view. The shape of the point spread functions will also be determined for possible use in unfolding x-ray micrographs of target experiments.

We used this system to calibrate axisymmetric x-ray microscope 22X, mod I. Figure 6-35 shows an enlargement of one of the point-spread-array x-ray micrographs taken with the 22X, mod I. Figure 6-36, a densitometer scan across one of the points, shows an FWHM of less than 4 μm when corrected for the pinhole size contribution.

Other x-ray sources include:

- Two types of point x-ray source with very sharp x-ray emitting tungsten needles.^{15,16}
- A small scanning electron microscope whose beam can be used to produce submicrometer x-ray emission regions.
- A British NPL electron-beam source with 2- μm -diameter spot size, which is extremely bright. The x-ray sources with small point emission regions will prove useful in studying the detailed shape of point spread functions and as a nearly isotropic source for measuring spectral transmission functions.

To determine spectral transmission functions, we measure the source spectrum with the multichannel analyzer and the windowless Si(Li) detector. The spectrum transmitted by the optic is then measured and divided by the source spectrum to yield the spectral transmission function.

References

15. R. H. Price, M. J. Boyle, and S. S. Glaros, *A Miniature X-Ray Point Source For Alignment and Calibration of X-Ray Optics*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-79777 (1977).

16. R. H. Price, M. J. Boyle, and S. S. Glaros, *Point X-Ray Source*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-81643 (1978).

Author

R. H. Price

6.9 Fresnel Zone Structures for Advanced X-Ray Microscopy

We use micro-Fresnel zone plates as coded apertures¹⁷⁻¹⁹ and are developing them as x-ray lensing elements²⁰ for the microscopy of laser fusion targets. Although micro-Fresnel zone structures are common to both coded-imaging and x-ray-lensing applications, the structures differ in scale, fabrication technique, and use in the two different applications. Table 6-6 compares the zone structures used in coded imaging with those used as x-ray optical elements.

6.9.1 Multispectral X-Ray and Alpha-Particle Zone Plate Camera

We have used zone plate cameras, employing coded imaging techniques, to image the alpha-particle and x-ray emissions from laser fusion targets.^{21,22} Recently, we made thick ($\leq 30\text{ }\mu\text{m}$) gold zone plates that provide high-contrast coded images of suprathreshold x-ray emissions. These zone plate apertures have extended our x-ray coded imaging capability up to $\sim 40\text{ keV}$. We combined the thick coded apertures with an appropriately designed multilayer filter/film pack (Fig. 6-37) to gain multispectral imaging capability. In the first layer, an image of the alpha-particle emission is recorded in the cellulose nitrate track detector. X-ray images of successively higher energy channels are recorded in subsequent layers.

One zone plate camera can simultaneously produce images of the thermonuclear burn region, the thermal x-ray emission, and the suprathreshold

x-ray emission from a laser fusion target. This capability is illustrated with zone plate camera data from a recent ball target shot in the Shiva facility. A $325\text{-}\mu\text{m}$ -diameter microsphere target underwent a 17-TW, two-sided illumination. Laser pulse width was 90 ps FWHM, and target neutron yield was 5×10^9 . One zone plate camera, viewing the target in the horizontal plane normal to the directions of the incident laser beams, simultaneously recorded images of the thermonuclear alpha emission, the thermal (4- to 7-keV) x-ray emission, and suprathreshold (17- to 30-keV) x-ray emission. These images are shown in Figs. 6-38, 6-39, and 6-40, respectively. Image resolution is $\sim 15\text{ }\mu\text{m}$.

One advantage of the multispectral camera is its ability to overlay images in different energy bands to provide insight into target dynamics. Figure 6-41, an overlay of the thermonuclear burn and thermal x-ray image data, illustrates fuel compression within the glass pusher material.

6.9.2 Fresnel Microstructures as X-Ray Optical Elements

The LLL Diagnostic Development Group is collaborating with the Research Laboratory of Electronics at the Massachusetts Institute of Technology to design, fabricate, and use Fresnel microstructures (zone plates, phase plates, and blazed phase plates) as x-ray lensing elements. Table 6-7 lists parameters and imaging capabilities for a prototype zone plate now being tested for resolution. A scanning electron micrograph of it is shown

(continued on page 6-36)

Table 6-6. Fresnel zone structure characterization.

	For coded imaging	For x-ray optics
Types of structures	Zone plates	Zone plates, phase plates, blazed phase plates
Minimum line widths	2.5-15 μm	0.1-0.5 μm
Thickness	2-50 μm	0.75-2 μm
Materials	Gold	Gold for zone plates Varied for phase plates
Diameters	1-20 mm	0.25-2 mm
Fabrication technique	Mechanical pattern generation and uv lithography	Scanning electron beam pattern generation and x-ray lithography
Imaging characteristics	No x-ray diffraction Short target distance (about 1 cm)	X-ray diffraction dominant mechanism Long target distance (about 1 m)

Fig. 6-37. Typical multilayer filter/film pack — zone plate camera.

Fig. 6-29. Two-dimensional plot of thermal (4- to 7-keV) x-ray emission.

Fig. 6-48. Two-dimensional plot of superthermal (17- to 30-keV) x-ray emission.

Table 6-7. Prototype zone plate parameters.

Minimum zone width	3200 Å
Number of zones	500
Diameter	0.632 mm
Material, thickness	1.5 μ m, gold
Support structure	Free standing (strut supported); also supported on 0.5- μ m thick polyimide membrane

Anticipated imaging capabilities (under test)

Resolution	$\approx 0.4 \mu$ m
Bandwidth	$\frac{\Delta\lambda}{\lambda} \approx 2 \times 10^{-3}$
Spectral range	100 eV-6 keV

(a) Alpha-image line-out scan position.

(b) Thermal x-ray line-out scan position

(c) Overlay of thermal x-ray and alpha-image line-outs.

Fig. 6-41. Overlay of thermal x-ray and alpha image line-outs through target center. Note that most, but not all, of TN beam occurs in the compressed region between the two disks of hot powder material. Arrows in (c) designate original ball diameter.

in Fig. 6-42. We expect such structures to provide high-resolution, narrow-band imaging for selected x-ray line emissions from laser fusion targets. We expect them to play a major role in LLL's program to develop an x-ray probing capability similar to that routinely available in the visible spectrum.

References

17. N. M. Ceglio, D. T. Attwood, and E. V. George, *J. Appl. Phys.* **48**, 1566 (1977).
18. N. M. Ceglio, *J. Appl. Phys.* **48**, 1563 (1977).
19. N. M. Ceglio, *Proc. of Photo Optical Instru. Engineering*, Vol. 106, p. 55.
20. N. M. Ceglio and H. J. Smith, Lawrence Livermore Laboratory, Livermore, Calif., UCRL 79966.
21. N. M. Ceglio et al., *Annual Report Articles* (1976 and 1977).
22. N. M. Ceglio and L. W. Coleman, *Phys. Rev. Lett.* **39**, 20 (1977).

Author

N. M. Ceglio

Fig. 6-42(b). Detail of scanning electron micrograph — prototype zone plate.

6.10 X-Ray Probing Diagnostics For High Density Implosion Experiments

Diagnostic needs have changed greatly as the emphasis has moved to ablatively driven targets from exploding pusher targets. The use of x-ray images to study pusher dynamics and the final compression state has especially changed. With exploding pushers, the fuel-pusher interface is hot, producing copious x rays, and the pusher is sufficiently transparent that these x-rays escape and provide a convenient source for x-ray imaging. With ablative implosions, particularly in the early stages of development, we trade temperature for density in target designs, and diagnostics suffer. X-ray self-emission is reduced and opacity is increased.

One technique for diagnosing ablatively driven targets requires diagnostic x rays from a hot auxiliary target, sometimes called a backlighter. Figure 6-43 shows a typical scheme in which a laser-irradiated disk produces probing x rays λ_x , some of which pass through the compressing target and imaging optics, represented in Fig. 6-43 by an x-ray pinhole. Images generally fall into two categories:

- Two-dimensional (2-D) flash radiography, in which the x-ray burst is temporally short enough to provide a stop-action photograph.
- Long-pulse streak photography with one-dimensional (1-D) imaging for space-time (r,t) studies of pusher dynamics.

The two techniques are complementary; one provides pusher dynamics history, the other 2-D implosion symmetry data.

Figure 6-43 shows a schematic space-time plot for an ablatively driven target. The dashed lines at early time emphasize our interest in identifying a clearly defined pusher-ablator interface by the appropriate choice of materials and x-ray probe energy, typically 2 to 5 keV for present target designs. Figure 6-44 shows some typical trade-off curves for plastic and beryllium ablators, on a thin glass mandrel, as a function of x-ray energy. These curves are for an uncompressed target, but they demonstrate radial transmission profiles that might be used to experimentally define the pusher-ablator interface.

The cold-opacity curves of Fig. 6-44 point out the interplay between ablator material, x-ray energy, and required resolution and dynamic range in the recording instrument. A dynamic range of

only a factor of ten would make this technique difficult to use even under ideal conditions. A dynamic range of 100 appears more appropriate. Figure 6-45 shows profiles for an idealized target, a 3-keV probe, and a 30- μm -thick Be ablator. Although the density profiles are unrealistic, the transmission profiles again demonstrate that a well-defined interface is discernible with appropriate dynamic range. These characteristics are seen to persist in more realistic simulations that include density profiles and instrument resolution, when proper ablator and x-ray energy are chosen.

To study significant aspects of target design physics, we plan to optimize a backlit ablative implosion in which the ablator and x-ray energy are selected to follow interface dynamics with large dynamic range. With $\text{CF}_{1.4}$ ablators the appropriate probing energy is in the 4 to 5-keV region and must be tailored to emphasize early or late ρr conditions. The price we pay for high-energy probing is reduced

x-ray flux and instrument sensitivity. Thus, we need a larger laser drive for the backlighter. We hope to avoid this by producing low-Z mandrels and ablators.

Author **Major Contributor**
D. T. Attwood **N. M. Ceglio**

6.11 Optical Preheat Diagnostic

Target preheat of only a few electron volts can significantly change the isentropic path along which fuel is compressed for high-density target designs. The blackbody radiation for temperatures of 0.5 to 2 eV peaks in the visible or uv region where air is transparent. By measuring the relative emission at two widely spaced wavelengths, we can infer a temperature. Temperatures much higher than 2 eV can also be measured, if the optical system and detector are absolutely calibrated.

The measurement technique consists of irradiating the front side of a sample—typically a thin disk placed over an opening in a large, thick titanium shield—and looking at the thermal emission from the back side. The shield prevents high-energy electrons from going around the target. An achromatic Galilean telescope images the back side of the sample onto an S-20 streak camera with a linear magnification of 11.3 (Fig. 6-46). A cube beam splitter creates two optical channels that look at precisely the same region of the target. Color filters allow the reflected beam channel to look just in the blue spectral region and the transmitted beam channel to look just in the orange. Any parametrically generated 2ω light would not get through either set of color filters.

To separate the prompt preheat signal from shock breakthrough at a later time, we needed a timing fiducial that was synchronous with the laser pulse. Therefore, we doubled a small fraction of the 1.06- μm laser beam and brought it to a streak

camera slit with a fiber optic bundle. The lack of any response of the S-20 photocathode in the infrared imposed the complication of frequency doubling. The three channels (blue, orange, and green fiducial) have been synchronized to within 50 ps by irradiating a gold strip target, using the shortest obtainable laser pulse duration of 200 ps, and timing the 2ω light from the target with the fiducial.

Figure 6-47 gives absolute spectral responses for the two optical channels. These curves are the total response functions calculated from the transmission and reflection spectral responses of the elements in the optical system, together with the measured absolute spectral response of the S-20 photocathode. Centered at 420 nm, the blue channel has a spectral width of 780 Å FWHM and a peak response of 9.4 mA/W. Centered at about 660 nm, the orange channel has a spectral width of 640 Å

and a peak response of 6.8 mA/W. The shape of its long red tail is determined both by the KG-3 heat-absorbing filter, which is intended to block any 1.06-μm laser light before it can enter the optical system, and by the red tail of the S-20 photocathode response. An OG570 sharp-cutoff filter determines the short-wavelength response. The blue channel response is primarily governed by a BG-12 blue bandpass color filter. The response falls rapidly to zero in the ultraviolet, because of the multielement f/1.4 achromat that is used to relay the streak camera slit image onto the S-20 photocathode.

Imaging of the target allows us to look at only a small region in the center of the disk. Because this small region is nearly uniform in temperature, we need not worry about the effect of spatial averaging in computing a temperature. We can observe the actual structure of a shock, and we avoid the smearing

out caused by shock breakthrough at different times across the sample.

The S-20 streak record for a 25- μm -thick gold sample (Fig. 6-48) shows substantial heating of the back side at early times, caused by either a very fast shock or preheat from high-energy electrons and x rays. We placed the gold disk over a 460- μm -diameter opening in a 25- μm -thick titanium shield, 4 mm square. We focused the laser beam to a 163- μm -diameter spot with an $f/2.6$ lens (11.0° marginal ray angle). Energy on target was 772 J in a Gaussian pulse of 928 ps FWHM.

The maximum temperature is achieved in a few hundred picoseconds after the peak of the laser pulse; then the plasma cools rapidly. The blue channel fluence decreases faster than the orange channel fluence, which is the expected qualitative behavior. The dip at 700 ps results from old damage to the image intensifier that occurred when the streak camera was operated in the dc mode. The image intensifier gain is drastically reduced in a narrow region, a few millimeters high, along the entire width of the image intensifier. Much of the structure seen in the two plots is due to the high spatial frequency variation of the image intensifier gain.

By absolutely calibrating streak camera No. 3 and combining its gain with the spectral response of

the S-20 photocathode and the measured transmission and reflection curves of all the elements in the optical system, a temperature can be obtained directly from the film exposure. The P-11 step wedge on the film provides the absolute calibration necessary to convert the film density into the absolute film exposure in ergs/cm^2 . The EG&G flash sensitometer that exposes the step wedge is set at 10^{-4} s (the same length of time that the streak camera image intensifier is gated on), so reciprocity need not be assumed. Also, the Lytton microchannel plate has a P-11 phosphor, which matches the spectrum of light from the EG&G flash sensitometer.

The first steps in measuring the streak camera gain were to measure:

- Spectral response of the S-20 photocathode (42 mA/W at 5320 $\text{\AA}$).
- Streak speed (115 ps/mm with the X3 plug-in).
- Transverse magnification (1.25).

The output beam from the Argus oscillator was collimated at about 1-cm diameter, frequency-doubled in a KDP crystal, and then apertured by a precision 2.5-mm-diameter aperture, placed just ahead of a nominally 50-50% 45° splitter for the s-polarized, 5320- $\text{\AA}$ beam. The streak camera looked at the reflected beam while a calibrated PIN-6/LC photodiode looked at the transmitted beam. The photodiode detector included a 200- $\text{\AA}$ FWHM bandpass interference filter, centered at 5345 $\text{\AA}$, and a KG-3 infrared absorbing filter. This detector had been calibrated using the light from a quartz-iodine lamp filtered by a 100- $\text{\AA}$ FWHM bandpass interference filter centered at 5320 $\text{\AA}$. The 1.064- μm light was blocked before the splitter by two KG-3 filters and a BG-18 filter. Also, the S-20 photocathode is insensitive to light with a wavelength longer than 8000 $\text{\AA}$. The splitter was calibrated absolutely in place using a second calibrated photodiode detector in place of the streak camera. The reflected beam illuminating the streak camera slit was attenuated by a precision metal filter whose transmission at 532 nm was taken from the curve supplied by the manufacturer. The streak camera slit width was set at 100 μm , the same width used for almost all the experiments.

Two oscillator shots were obtained on Royal-X-Pt 7 (RXP) film. The images were then encoded using a microdensitometer and a 50- μm -square slit.

Fig. 6-48. Streak record for a 25- μ m gold sample irradiated at 3×10^{12} W/cm 2 . (a) Time vs position; (b) and (c), intensity vs time for blue and orange channels, respectively; (d) second harmonic fiducial.

To demonstrate that the calibration did not depend upon the film development, one negative was developed at the Shiva automatic processor (2.5 min, $\gamma \approx 1$), while the other was developed by Technical Photography (10 min DK-50, $\gamma \approx 2$).

The photodiode measures only the pulse energy. To obtain the peak power density, one must obtain the pulse width from the streak record and the area from the precision aperture. The peak surface current density (mA/cm 2) at the photocathode can then be obtained from the photocathode sen-

sitivity and this peak power density (after accounting for the 72.5% transmission at 5320 Å of the f/1.4 multielement achromat that relays the image of the mechanical slit plane onto the S-20 photocathode). We then integrate over the 100- μ m slit height (the long dimension is horizontal) to obtain the peak linear current density. The EG&G flash sensitometer and step wedge are both calibrated, so the flux in ergs/cm 2 is known for each of the 21 steps. By fitting a seventh or eighth degree polynomial through these steps, we can obtain the

relation between film density and the absolute exposure in ergs/cm^2 . We find the linear current density to be related to the exposure by

$$I (\text{mA/cm}) = \begin{Bmatrix} 0.0292 \\ 0.0272 \end{Bmatrix} E (\text{erg/cm}^2) (\text{measurement})$$

where the upper and lower numbers are for streak records with $\gamma = 2.134$ and 0.966 , respectively. It is more convenient to give the calibration in terms of a quantity called the fluence F , to distinguish it from the exposure E . Both have the same units of ergs/cm^2 . Fluence is defined as the integral of the exposure across the width of the image divided by the width of the image at the slit plane. Thus, the fluence will be larger than the exposure by the transverse magnification factor. Using the fluence gives a more accurate answer because it is an averaged quantity and the streak tube focussing is imperfect. The blurring is typically about $200 \mu\text{m}$ in the transverse direction, which is comparable to the image width in these experiments. In terms of the fluence, the linear current density is given by

$$I (\text{mA/cm}) = 0.023 F (\text{erg/cm}^2) .$$

That this number is reasonable can be seen by estimating the gain of the streak camera. The photoelectrons ejected from the S-20 photocathode gain 17 keV energy in the RCA C73435AG streak tube but lose 4 to 6 keV of this energy in the aluminizing layer before they enter the P-11 phosphor. The phosphor radiates 7 to 8% of the remaining energy. The Lytton microchannel plate has a gain G_{MCP} of 5120 at 800 V for a light source having a P-11 spectrum and RXP film. The fiberoptic coupler between the streak tube and the photocathode of the microchannel plate intensifier has a loss of about $T_{\text{FOC}} = 50\%$. The film exposure is given by

$$E (\text{erg/cm}^2) = 10^{-4} V (\text{kV}) I (\text{mA/cm}) \times \Phi G_{\text{MCP}} T_{\text{FOC}} \lambda (\text{ps/mm}) / M$$

where λ is the streak speed, V is the net accelerating potential of 12 kV, Φ is the radiative conversion ef-

ficiency of the phosphor (7.5%), and M is the transverse magnification factor. Putting in the numbers, we obtain

$$I (\text{mA/cm}) = 0.0472 E (\text{erg/cm}^2) (\text{estimate only}) .$$

The streak camera is actually 60% as sensitive as this estimate predicts.

The images for both channels are apertured by narrow slits transverse to the streak camera slit. The slit widths are $135 \mu\text{m}$ for the blue channel and $310 \mu\text{m}$ for the orange channel. Because the magnification of the optical system is 11.3 and the opening in the titanium shield is $460 \mu\text{m}$, the two crossed slits ($135 \times 100 \mu\text{m}$ for the blue channel and $310 \times 100 \mu\text{m}$ for the orange channel) define a very small rectangular region at the center of the sample that is viewed.

Figure 6-49 relates the linear current densities in each channel to the temperature for a blackbody emitter. The ratio of the blue-to-orange channel fluences F approaches zero as the temperature goes to zero, and it approaches an asymptotic value of 4.9 as the temperature goes to infinity. The asymptotic value for shot 39020111 is about 2.8,

Table 6-8. Temperatures based on the absolute calibration.

Shot and material	Blue channel fluence and linear current density	Orange channel fluence and linear current density	T _{blue} ^a eV	T _{orange} ^a eV
39020111	14 erg/cm ²	4.9 erg/cm ²	3.9	5.5
25-μm gold	0.34 mA/cm	0.12 mA/cm		
39020708	4.13 erg/cm ²	3.4 erg/cm ²	2.0	4.0
25-μm gold	0.11 mA/cm	0.081 mA/cm		
39020803	ND too great	5.9 erg/cm ²	—	6.3
2-μm gold		0.14 mA/cm		
39020806	8.0 erg/cm ²	3.7 erg/cm ²	2.7	4.3
14.5-μm Au	0.19 mA/cm	0.089 mA/cm		
39020812	18.6 erg/cm ²	8.1 erg/cm ²	4.8	8.2
2-μm gold	0.45 mA/cm	0.19 mA/cm		
39020812	36 erg/cm ²	16 erg/cm ²	8.0	16
2-μm gold	0.86 mA/cm	0.38 mA/cm		
39020914	190 erg/cm ²	80 erg/cm ²	37 ^a	74 ^a
2-μm gold	4.56 mA/cm	1.92 mA/cm		

^aSome saturation occurring.

considerably below the theoretical value. We do not yet understand why the asymptotic ratio is so far off.

Table 6-8 lists fluences for the disk shot sequence, together with the linear current densities inferred from the estimated streak camera gain and the corresponding temperatures obtained from Fig. 6-49. For comparison, we note that Dante 5-2 measured a temperature of 90 eV on shot 39020914. The optically inferred temperatures are invariably much lower than the Dante-measured temperatures. Because the targets are too thick for a substantial fraction of the radiation from the front side to make it through the target unabsorbed, the discrepancy can only be explained by assuming that the Dante system senses radiation from the titanium shield.

Author

D. W. Phillion

6.12 Neutron Activation Diagnostics for High Density Targets

We made considerable progress in developing the Rad Chem (neutron activation) diagnostic for measurement of pusher $\mu\Delta R$. To do this, we developed an extremely efficient debris collector ($\eta_c \lesssim 0.7$) and an efficient ($\eta_o \approx 0.4$), low-background

(0.4-cpm) nuclear detector. In this subsection, we discuss this work and also the development of an automatic retraction system at the Shiva laser facility.

6.12.1 Collector

The basic collector design consists of thin (10 to 20 μm) Ti or Ta foil that lines a thick-walled (2-mm-thick) aluminum cylinder.²³ The metallic foil serves as the collector, and the cylinder serves as both a mechanical support and a rabbit for transfer to the counting facility. We selected the collector foil based on activation and thermomechanical considerations. We determined collector efficiency with a ²⁴Na tracer, which we made by irradiating the glass microspheres with thermal neutrons.²³ The tracer is created in the ²³Na (*n*, γ) ²⁴Na reaction in which the ²³Na source atoms comprise about 5% of the pusher atoms.

Because so few ²⁸Al atoms are expected from high density targets at the Argus facility, we must collect a large fraction of the target debris. To do this, we use a modified collector (Fig. 6-50). The collector is mated to a hemispherical section, also lined with Ti or Ta foil, that contains and redirects target debris into the collector tube.

Energy considerations imply that the debris ions or atoms will not adhere to the collector foils at the initial contact. Their energy is too great for physical absorption ($E_{\max} \gtrsim 50$ eV) and too low for

lattice implantation ($E \lesssim 5$ to 10 keV).²⁴ Thus, because the debris ions or atoms do not accelerate further, several interactions with the surface are required before they are absorbed. Because we want minimal deposition on the hemisphere, we make its radius 2 cm. Then, for a nominal laser irradiation of 1000 J, the average loading on the surface is sufficient to raise the foil temperature above the vaporization limit.²⁵ In contrast, we expect little damage to the foil within the tube. For example, the axial loading on the collector for 1100 J incident on the target is shown in Fig. 6-51. We made three holes in the hemisphere: two for the two laser beams to pass through ($f/2.2$ focusing optics), one for target insertion. The holes subtend only 6% of 4π .

6.12.2 Detector

The nuclide of interest, ^{28}Al , decays by simultaneously emitting (within 10 ps) a β^- with 2.86-MeV end-point energy and a 1.78-MeV γ ray.²⁶ This isotope can be detected readily by β - γ coincidence techniques. We use a Rad Chem detector (Fig. 6-52), which consists of a NaI(Tl) scintillation crystal, 25.4 cm in diameter and 25.4 cm in length, for the γ -ray detection and a two-component cylindrical NE 102 β^- fluor with overall dimensions of 5.08 cm in diameter and 15.24 cm in length.²³ For maximum detection efficiency, the β^- fluor is positioned in a well inside the NaI(Tl) crystal.

The factors that determine the minimum observable count rate are detector efficiency and background. We present below results of experiments examining these factors.

Efficiency. We use coincidence counting of the ^{28}Al decay to absolutely calibrate the detector.²⁷ Consider a nuclide such as ^{28}Al that decays by β - γ emission. The activities measured by the β , γ , and coincidence system are given by

$$N_1 = C_1 \lambda N \quad (\beta^- \text{ detector})$$

$$N_2 = C_2 \lambda N \quad (\gamma \text{ detector})$$

$$N_3 = C_1 C_2 \lambda N + \tau N_1 N_2 \quad (\text{coincidence})$$

where

N_1, N_2, N_3 = measured β^- , γ , and coincidence count rates, respectively.

C_1 and C_2 = β^- and γ detector efficiencies, respectively.

λ = decay coefficient.

N = number of decaying atoms.

The term $\tau N_1 N_2$ represents accidental coincidence arising from the finite resolving time τ of the coincidence electronics. For the present system, the measured τ of 10^{-8} min results in a negligible contribution with the anticipated count rates.

We can calculate the overall efficiency η of the detector from the unknowns, C_1 , C_2 , and N and the three independent measurements of N_1 , N_2 , and N_3 . Rearranging the equations above,

$$\eta = C_1 C_2 = \frac{(N_3 - \tau N_1 N_2)^2}{N_1 N_2}$$

A ^{28}Al source for the calibration can be made from the only naturally occurring aluminum isotope, ^{27}Al , by the $^{27}\text{Al}(n, \gamma)^{28}\text{Al}$ neutron-capture reaction. To make a source of appropriate strength, we irradiated a 10^{-3} -g sample of 99.9995% ^{27}Al for 3 s in the slow rabbit facility of the LLL Light Water Test Reactor. The integral neutron flux at this location is $10^{12}/\text{cm}^2\text{-s}$ with a cadmium ratio of two.²⁸ At count time (usually 10 to 15 min after irradiation), we obtained ^{28}Al decay rates exceeding 10^6 dpm for the calibration experiments.

Figure 6-53 shows the γ -ray spectrum of a calibration source obtained with a 1024-channel pulse height analyzer. The ^{28}Al photopeak is clearly visible, and there are no other apparent peaks in the spectrum. The figure also shows the energy window of a single-channel analyzer that is normally used in the counting experiments. The large fraction of counts in the photopeak region was one reason for obtaining the large well detector. The predominant interaction of a 1.78-MeV photon with the crystal is

Compton scattering; hence, a large fraction of the photon energy may not be detected.²⁹ The large volume and well geometry increase the probability of multiple photon-crystal interactions; therefore, many 1.78-MeV photons eventually deposit all their energy in the crystal.

Figure 6-54 is a decay curve of ²⁸Al activity vs time ($t = 0$ at 15 min after sample irradiation) from a typical experiment. In each segment of the time axis, the lower-level β^- energy discriminator, and thus the detector efficiency, was set as shown. The γ system levels are fixed about the 1.78-MeV photopeak. As can be seen, a maximum efficiency of 40% is obtained (the round-off of the experimental decay curve near 10^6 cpm is due to dead-time effects arising from the high count rate). At these settings, the individual efficiency of γ is 43% and that of the β^- system is 95%, a value that demonstrates the effective 4π geometry of the plastic scintillator. Crystals of similar dimensions, but without a well, have efficiencies at this energy of

15 to 20% (with the detector subtending 2π at the source).³⁰ We expect a decrease in efficiency as the β^- lower discriminator is raised because the detector samples less of the β^- distribution.

Background. Efficiency and background are interrelated variables. However, because the minimum number of detectable atoms scales as $\sqrt{B}/\eta$, where B is the background, we concentrated on reducing the background while maintaining the maximum detector efficiency of 40%, as described above.³¹

There are three primary sources of background in nuclear detectors—cosmic rays, radioactivity, and accelerators and reactors.³¹ Extensive showers caused by the interaction of cosmic rays with the upper atmosphere are primarily responsible for the background levels in clean, well-shielded, large-volume detectors. At sea level, the shower consists of a central core (typical area ~ 1 m²) of energetic muons and nucleons surrounded by a diffuse electron-photon cascade (area ~ 500 m²). Most of the background results from the interactions of muons and nucleons with the detector shield and surroundings that produce:

- High-energy electrons.
- Bremsstrahlung photons.
- Annihilation radiation.
- Evaporation neutrons.

Inelastic collisions between high-energy neutrons and shield atoms may also result in unstable nuclei, which further contribute to the background.

Examples of natural and artificial radioactivity found in the detector, shield, and surroundings are ⁴⁰K, members of the ²³⁸U and ²³²Th decay series, and ⁶⁰Co. The first three isotopes have half-lives exceeding 10^9 yr and occur naturally. However, ⁶⁰Co has a 5.27-yr half-life and is a contaminant from contemporary steel manufacturing.

The background associated with reactors and accelerators stems from both direct radiation and induced radioactivity levels that depend on the operation of the machines and are time-dependent. An example of this type of background is ⁴¹Ar, produced by thermal neutron capture in nuclear reactors.

We used both passive and active shielding to reduce the background rates from these sources. Figure 6-55 is a schematic of the detector and shield arrangement. The detector is located in the Argus laser bay to take advantage of the 200 g/cm² of concrete floor, which greatly attenuates the nucleonic

Fig. 6-55. Schematic of background detector and shield arrangement.

component of cosmic rays on the shield.³¹ A gravitational rabbit system, described in Ref. 23, transports target debris from the chamber to the detector.

The main shield consists of 10.16 cm of Pb that completely encloses the detector. The shield primarily screens out γ rays from environmental radioactivity. The upper portion of the shield is lined with cadmium and copper to reduce the number of K x rays, emitted when high-energy particles strike the Pb shield, that reach the detector. The lower portion is unlined because the NaI(Tl) crystal effectively screens out the Pb x rays. The shield roof is equipped with an access port and door mechanism for sample insertion.

We added an active anticoincidence shield of Geiger Mueller (GM) tubes to screen radiation that cannot be effectively blocked by passive shielding. The deployment of these detectors and a block

diagram of the complete system are depicted in Figs. 6-55 and 6-56, respectively. In all, there are 32 argon-quenching gas-filled tubes, 81.3 cm long by 5 cm in diameter, and 18 tubes, 30.5 cm long by 2.54 cm in diameter. Because of the great difference in sensitivity to various radiations compared to either the plastic scintillator or the NaI(Tl) crystal, the GM tubes do not represent the best guard shield. However, the tubes and associated electronics were readily available. We are designing an anticoincidence system based on effectiveness, availability, and cost.

To quantify the background in the NaI(Tl) crystal, we measured the output of the spectrometer, placed within the Pb cave, with a 1024-channel pulse height analyzer. Figure 6-57 shows a sample spectrum and the channel (energy) window used for the 1.78-MeV ^{28}Al radiation. Several photopeaks allow us to identify the emitting

nuclides. Table 6-9, which lists both the energy and the source of the radiation, shows that much of the activity is from the natural isotopes discussed above. A γ -ray spectrum, taken with the 3-MW LLL reactor operating, exhibits an additional ^{41}Ar photopeak at 1.29 MeV. The net background rate of the NaI(Tl) detector in the ^{28}Al window from all the sources mentioned above is 60 cpm.

Table 6-9. Energy and source of radiation (photopeaks from Fig. 6-53).

Energy, MeV	Origin
0.486	^{222}Rn
1.47	^{40}K
1.56	^{232}Th
2.615	^{232}Th

With the β -fluor placed in the NaI(Tl) well crystal inside the Pb house, background rates typically range about 59 cpm. This value is for the detector run in the integral mode, that is, at maximum efficiency, with the energy window set at 0.05 to 3 MeV. The poor energy resolution of the NE102 makes it difficult to ascertain the source of the background.³² However, high-energy cosmic rays (secondary particles) and their interaction products with the Pb house are most likely a major source.

Despite massive shielding and guard detectors, our results show that background levels in both the γ and β^- systems far exceed the expected activity (1 cpm) from the activated pusher debris. To further reduce the background levels, we used coincidence counting of the β^- and γ radiation from the ^{28}Al decay. To determine the appropriate background levels, we made a series of 5-min counts (the counting time of the experiment) with the detectors in the Pb house and running in anticoincidence with the guard detectors. Figure 6-58 displays the data and a Poisson distribution with a mean value of 2.1 that agrees well with the data.

To determine the source of the coincidence background, we fed the output of the γ system into a pulse height analyzer (PHA) that we ran in coincidence with the plastic detector. Figure 6-59 is an example of the resulting spectrum. The absence of photopeaks indicates that natural radioactivity is not a problem. The only visible peak is that from positron annihilation at 0.511 MeV. The data are

representative of a high-energy continuous source, such as cosmic ray muons and photons from the electron-photon cascade with energy beyond 10 MeV. There is further evidence for high-energy particles: when the γ amplifier output is monitored on an oscilloscope, most pulses are saturated, i.e., energy deposition in the crystal is greater than an equivalent photon energy of 10 MeV.

The minimum number of counts, defined as three times the square root of the background rate, is 4.2. With a collection efficiency of 0.7, transfer time of 2.24 min (one half-life), detector efficiency of 0.4, and a counting period of 5 min, we infer a detection limit of 40 atoms. For a pusher μAR of 10^{-2} g/cm^2 , a neutron yield of 2×10^6 results.

6.12.3 Shiva Rabbit System

The minimum number of detectable atoms depends on how rapidly the collector can be transferred from the target chamber to the counting facility. Transfer could be done manually in about 60 s at the Argus facility, but the Shiva target facility requires an automatic retrieval system. Automation and the subsequent rapid collector removal allows for the possibility of examining isotopes with half-lives $\lesssim 60$ s.

The Shiva extraction system (Fig. 6-60) consists of:

- A rabbit lined with collector foil.

Fig. 6-60. Shiva extraction system.

- An air lock and turning chamber.
- A plastic transfer tube.

The rabbit is retracted into the air lock by a large stepping motor and chain drive. Pneumatic valves provide vacuum isolation and rapid venting. A controller, triggered by a fiber optics signal from one of the Shiva computers, directs the logic and command functions so that the following sequence of events occurs automatically:

- At the firing of the laser, the motor retracts the rabbit into the air lock.
- After the rabbit is positioned properly, the first valve closes and isolates the target chamber.
- The vent valve opens.
- The rabbit is retracted further, released, turned by the mechanical assembly, and then directed down the plastic tubing a distance of 13.84 m to the counting room.

The system can transfer the rabbit to the counting facility in 25 s. Upgrade of the mechanical assembly could reduce this time to 15 s.

References

23. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), §3.5.2.
24. P. D. Townsend, J. C. Kelly, N. E. W. Hartley, *Ion Implantation, Sputtering and Their Applications* (Academic Press, 1976).
25. R. E. Bolz and G. L. Tube, *Handbook of Tables For Applied Engineering Science* (CRC Press, 1976).
26. C. M. Lederer, J. M. Hollander, I. Perlman, *Table of Isotopes* (Wiley and Sons, 1967), 6th ed.
27. G. Friedlander, J. Kennedy, J. Miller, *Nuclear and Radiochemistry* (Wiley and Sons, 1964), 2nd ed.
28. W. J. Richards, *User's Guide Livermore Pool-Type Reactor*, Lawrence Livermore Laboratory, Livermore, Calif., M-051 Rev. 1 (1975).
29. K. Siegbahn, *Alpha, Beta, and Gamma Ray Spectroscopy* (North Holland Publishing Company, 1965), vol. 1.
30. R. L. Heath, *Scintillation Spectrometry* (Phillips Petro. Co., 1964), 2nd ed.
31. R. A. Dudley, *Measurement of Low Level Radioactivity*, ICRU Report 22 (1972).
32. *Nuclear Spectroscopy*, F. Auzenberg-Selove, Ed. (Academic Press, 1960), part A.

Author

E. M. Campbell

6.13 Neutron Yield By Lead (Pb) Activation

Target experiments require sensitive monitors of DT neutron yield that function well in a hostile x-ray environment. Our fluor detectors³³ function poorly for targets that have a low neutron yield and a high x-ray output. A low yield requires the detector to be placed close to the target; thus, the time between x-ray and 14-MeV neutron arrival is small. An intense x-ray pulse often overdrives the recording electronics, rendering interpretation of the low-level neutron signal arriving 25 ns later either difficult or impossible.

To provide better diagnostics for low-yield targets, we designed, built, and calibrated Pb-activation neutron detector systems. We use them in the Argus and Shiva laser facilities to diagnose target yields as low as 10^4 neutrons per shot. Characteristics that make the Pb activation technique³⁴ attractive include:

- Easy separation of the target x-ray burst from Pb decay gamma rays.
- High sensitivity.
- Large dynamic range.
- 1.6-MeV reaction threshold.
- 10% calibration accuracy.
- Ease of setup.

Figure 6-61 shows the Pb activation system and lists the activation and decay processes. DT

neutrons from an imploded target form ^{207m}Pb atoms by $^{208}\text{Pb}(n,2n)$ and $^{207}\text{Pb}(n,n')$ reactions in a 1.9-cm-thick Pb sheath that surrounds a 7.6-cm-long, 7.6-cm-diameter NaI(Tl) crystal. The crystal is optically coupled to a photomultiplier (PM) tube. The 1.06-MeV and 570-keV gamma rays from the 0.8-s half-life ^{207m}Pb atoms produce PM pulses that are amplified, discriminated, and recorded by a pulse-height analyzer operating in the multichannel scaling mode. The number of recorded pulses is proportional to the level of Pb activation, which, in turn, is proportional to the neutron yield from the target. After a preselected counting period, data are transferred to a computer system and analyzed.

The NaI(Tl) crystal provides high sensitivity and a well-defined photopeak for establishing the system operating point. Care must be used, however, because inorganic crystals can be activated by neutrons. In the pulsed mode of operation, we detect the 11.4-s half-life beta decay of ^{20}F atoms formed by $^{23}\text{Na}(n,\alpha)$ reactions in the NaI(Tl) crystal. We increase our detector sensitivity by including this decay process in the detector calibration and data analysis. Other reactions also take place; however, their cross sections and relative activity rates, which are caused by a subnanosecond neutron burst, make them negligible in our application.

Fig. 6-62. Lead system output. Data are for a 10^6 calibration shot on thirva. Initially, decay of the 0.5-s half-life ^{207}Pb atoms dominates the curve. After 5 s, the decay of ^{209}Pb atoms (11.4-s half-life) dominates the curve.

We mount the detector in a reentrant tube to get it as close as possible to the target. We select system gain and discriminator settings, using a radioactive ^{22}Na source mounted outside the vacuum chamber at the flange of the reentrant tube. Passage of 511-keV and 1.27-MeV source gamma rays through the PM tube into the NaI(Tl) crystal permits adjustment of all the electronics with the detector mounted on the vacuum chamber, without the need for entering the chamber.

The x-ray burst generates about 10^9 times more light intensity in the NaI(Tl) crystal than does an individual γ ray from lead decay. To minimize the effect of this light pulse on the PM tube, a gate circuit removes the PM high voltage 2 s before a shot, then restores it 70 ms after the shot.

We use copper activation techniques³⁵ as our primary diagnostic for neutron yields above 10^8 . To achieve a good Pb system calibration, we:

- Mount the Pb detector on the vacuum chamber.
- Irradiate a target that yields about 10^8 neutrons.

- Determine the yield by copper activation.
 - Calculate the Pb system neutron sensitivity in source neutrons per Pb detector count.
- The calibration under shot conditions includes effects of detector-target geometry, nearby scattering sources, and ^{20}F decay.

Figure 6-62 shows the Pb system output taken on a calibration shot. For yield calculations, we use the total number of Pb counts between 0.2 and 2.2 s after the shot. During the first 0.2 s, short half-life reaction products and the effects of the x-ray burst disappear before the counting starts. Then, we count for 2.5 ^{207}Pb half-lives. Sometimes, the target x-ray burst saturates the detector for up to several seconds after the shot. In such cases, detector calibration and target-yield calculations are based on the first 2-s time interval after the saturation effects disappear.

References

33. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-74 (1975), pp. 337-339.
34. Spencer and Jacobs, "Lead Activation Technique for High Energy Neutron Measurement," *IEEE Trans. on Nucl. Science*, Feb., 1965, pp. 407-414.
35. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50621-76 (1977), p. 3-105.

Author

R. A. Lerche

6.14 Applications of Charge-Coupled Devices

6.14.1 Streak Camera System

We made progress in developing a practical streak camera readout system that uses charge-coupled devices (CCD's). The CCD-equipped streak camera will be able to directly record a 2-D (space-time) electron streak image in a totally electronic manner. Data on the CCD are read out electronically and digitized by a video analog-to-digital (A/D) converter. A computer directly manipulates the resulting digitized data. Two main advantages accrue:

- One CCD sensor, within the streak-tube envelope, replaces the internal phosphor, the external image intensifier, and the recording film.

Fig. 6-63. General view of the S-1 photocathode CCD streak camera system.

- Direct computer processing of the CCD data bypasses the time-consuming steps of film retrieving, processing, and digitizing.

Previously, we totally characterized the RCA-52501 CCD for use as a streak-camera readout device, a 1.06- μm imager, and an oscilloscope readout.³⁶ We found that the RCA sensor can perform all the necessary functions of imaging and electron multiplication. Our major remaining problem was how to incorporate the CCD sensor in a streak-tube envelope with a usable S-1 photocathode. Here we report how we solved this problem.

Figure 6-63 shows the first LLL ultrafast S-1 streak camera equipped with a direct computer-interfaced CCD streak tube. The tube is a modified RCA-C73435 image-converter tube. We removed and replaced the back phosphor/fiber optics with an RCA-52501 CCD sensor that is back-thinned (10 μm) and e-beam back-illuminated. We then processed the CCD streak tube according to a new

S-1 photocathode processing schedule to avoid damaging the heat-sensitive CCD sensor.

The S-1 photocathode has excellent sensitivity—650 $\mu\text{A/W}$ at 1.06 μm —compared with the LLL acceptance criteria of 100 $\mu\text{A/W}$ and the minimum usable photocathode value of 10 $\mu\text{A/W}$. Figure 6-64 shows the S-1 CCD streak tube and the photocathode sensitivity vs wavelength.

Figure 6-65 illustrates the experimental setup for measuring the dynamic characteristics of the CCD-streak camera system. A 1.06- μm YAG pulsed laser generates a series of etalon pulses, each 50 ps in duration with 100 ps between pulses. The pulses illuminate the input slit of the CCD streak camera system. A Le Croy A/D converter digitizes the recorded time-amplitude-resolved 2-D CCD data at a TV-video (6-MHz) rate. The resulting data files are stored in a 80k-byte local RAM memory and are accessible to an LSI/11 computer via the CAMAC data highway.

Figure 6-65 also shows a linear plot of the data. Theoretically, if the etalon data were plotted as log of the intensity vs linear time, the data peaks would fit a straight line. The figure shows a straight-line fit for the data plotted on a semilog format. Table 6-10 summarizes the operating characteristics of the CCD streak camera.

6.14.2 CCD Photon Camera

A solid state sensor, such as a CCD, can provide valuable information in the time-integrated 2-D imaging of photons. Generally, all such silicon sensors are sensitive to low-energy photons between 1.2 and 0.4 μm . Within this range, absorption of one photon produces one electron-hole pair. The electron is captured by the nearest CCD well and later appears as an output signal. The CCD is also sensitive in the low-energy x-ray region, in which absorption of one x-ray photon between 1 and 10 keV may create many electron-hole pairs. Thus, the CCD signal is more intense.

The CCD camera can be used in either the TV or pulsed mode. In the TV mode, the video signal

can be used either for the alignment of a laser-optical system or an x-ray microscope. Two advantages accrue:

- Both the 1.06- μm and the x-ray imaging use the same sensor.
- Cooling the CCD permits time-integration of the low-intensity x-ray flux generally associated with DC x-ray microscope alignment systems.

After alignment, the CCD camera can be used in the pulsed mode, in which it records the time-integrated 2-D intensity profile of the photon flux. The only solid state sensor that will preserve the short-pulse (~ 50 -ps) reciprocity property is the RCA-52501 CCD imager. CCD reciprocity is defined as the ratio of the sensor output signal to the input photon energy. If reciprocity is preserved, the CCD output should depend only on the total input energy, not on the input pulse duration.

We are constructing a digital CCD photon camera system for direct interfacing with an LSI/11 microprocessor. The system will have a CCD camera head to record and digitize an incident photon image at the standard TV video rate. Output

Fig. 6-65. Block diagram of test setup for evaluating the CCD streak camera system. The result is plotted in both the linear-linear and semi-log format.

digital data will be stored in a local 80k-byte memory system that is interfaced with the "Q" bus of an LSI/11 computer. Before each laser shot, the main computer can determine if the camera is active and ready to take data. Immediately after the shot, it can:

- Determine if a given CCD camera has been triggered.
- Confirm the validity of the recorded data.
- Request transmission of data to the main computer for further analysis and processing.

6.14.3 CRT/CCD Oscilloscope

Used as an electron imager, a CCD can replace the output phosphor of the cathode ray tube (CRT) in an ultrafast oscilloscope. One CCD sensor will then perform imaging, signal intensification, and direct electrical readout of the recorded signal.

Figure 6-66 shows our first ultrafast CCD/CRT oscilloscope tube. It is basically a modified EG&G KR-23 CRT, in which the traveling-wave deflector has been redesigned to take advantage of the smaller scan area of the CCD target (~1 cm).

Table 6-10. Operating characteristics of the CCD-equipped streak camera.

Static spatial resolution	100 μm
Linear dynamic range	>100:1
Temporal resolution	20 ps
Photocathode sensitivity	690 μA/W
Electron energy	17 keV
Number of horizontal CCD cells	320 (temporal direction)
Number of vertical CCD cells	256 (spatial direction)
CCD cell dimensions	30 μm × 30 μm

Fig. 6-66. Modified EG&G KR-23 CRT equipped with an RCA CCD.

Fig. 6-67. Preliminary experimental characterization of CCD/CRT. (a) Frequency response of the system. (b) Digitized output of the CRT/CCD using a 1-GHz sine wave.

Table 6-11. CCD/CRT oscilloscope performance.

Deflection sensitivity	2V/cm (1 cm = full scale)
Dynamic range	>100:1
Bandwidth (-3 dB)	3.3 GHz
Spot size (this CRT only)	200 μm
Beam current (this CRT only)	1 μA
Beam energy	7 keV

The output phosphor screen was replaced by a back-thinned RCA-52501 CCD target. Figure 6-67 depicts a preliminary experimental characterization of the oscilloscope. Using a continuous sine-wave response technique, we found the -3dB point to be ~ 3.3 GHz. A digitized display of a 1-GHz sine wave is also shown. Table 6-11 summarizes the performance of this CCD/CRT oscilloscope.

Reference

36. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978) p. 3-45.

Authors

J. Cheng
G. R. Tripp

6.15 Optical Streak Cameras

The sensitivity loss of the S-1 photocathode at 1.06- μm wavelength remains a problem in RCA image-converter tubes for streak cameras.^{37,38} However, about half the tubes we received near the end of 1978 performed better than the earlier ones. Two S-1 tubes purchased some time ago from ITT continue to be stable at 1.06 μm . As a result, we are considering ITT as a second source.

Dynamic range studies on the LLL camera indicate that a nominal dynamic range of 2500:1 is easily achievable with 40-ps pulses.^{39,40} Figure 6-68 shows two typical dynamic-range plots for two different cameras (two different RCA image-converter tubes) but for the same ITT proximity-focused, microchannel, image intensifier. We used the same symbol to plot all data from the same laser pulse, i.e., from a single streak record. The curves show measured FWHM as a function of intensity for each camera. Two primary limitations to large dynamic range are revealed—large noise levels with both weak and intense signals and a general pulse-broadening with intense pulses.

Table 6-12 summarizes the dynamic range test results for several cameras. Except where noted, all tests used the ITT intensifier. Noise intensity (column 2) is for a location on the film away from any high intensity signal. Column 3 gives the intensity for the upper limit of the dynamic range, which we define as the intensity that produces a 10%

broadening of the FWHM of lower intensity pulses of the same etalon pulse train. The dynamic ranges are then the ratios of columns 3 to 2. Column 5 gives either a calculated or a best-estimate (~) effective intensifier gain, which is the actual increase in exposure on the film due to the intensification system. Reference 40 gives details on the significance of these gains.

The intensifier on camera 5 became gassy and we had to operate it considerably below 50% of rated gain, which explains its low dynamic range.

Cameras 8 and 11 were tested using the same intensifier (Fig. 6-68). They differ by 25% in dynamic range between the two image-converter tubes, and one has a larger noise level than does the other.

Some microchannel intensifiers can be run at 3 to 10X rated gain without serious damage if they are gated on only for short (100- μ s) periods. Cameras 12 and 16 were operated in this mode with a silicon, self-scanned Reticon array as the readout detector. This array is much less sensitive than film, and additional gain is required. To cover the full

Table 6-12. Results from dynamic range tests.

1	2	3	4	5	6
Camera	Noise intensity	10% broadening intensity	Dynamic range	Effective intensifier gain for RXP film	Comment (II = image intensifier)
5	2.85	1450	509	~300	II gassy and noisy (not ITT II)
8	2.39	6000	2510	1230	Used same II
11	1.42	4800	3380	1230	
12	1.42	12,000	8451	~10,000	II at 5.5 X rated gain
16	0.02V	>4V	>200	~6000	Reticon readout; II at 5 X rated gain
13	1.42	3910	2754	1850	ITT II
	3.27	1300	398	200	Varo 8606 II
	4.4 ^a	4200	938	330	EMI 9912 II
14	1.2	1300	1083	~2000	II at 1/2 rated gain
15	1.42	1600	1127	~1500	Subspec II
17	3.05	7400	2426	3000	Used ITT image-converter tube
12	—	—	5500	6500	Galileo II (see Ref. 40)

dynamic range of the Reticon array, we operated these cameras at approximately 5X rated gain (10^5 white-light gain).

We tested camera 13 with three different intensifiers.⁴⁰

The lower limit of the dynamic range is affected by the system noise, which is signal-dependent in both image converters and image intensifiers. Such signal-induced noise is greater in electrostatically and magnetically focused intensifiers than in proximity-focused intensifiers. It is also greater in image-converter tubes that use a fine-mesh grid (28 to 40 wires per mm), compared to those that use a coarse-wire or open-grid structure. At our invitation, ITT developed an electrostatically focused image-converter tube with an S-20 cathode. We used it in camera 17 and took the test data shown in Table 6-12. This tube has a fine mesh for the extraction grid, similar to streak tubes made by English Electric Valve, Instrument Technology, Ltd., and Hamamatsu T.V. Co., Ltd. The RCA tube uses a coarse (~5-mm separation) wire grid. The noise level for the ITT tube is about eight times higher than any other measurements near a high-amplitude signal.

We tested camera 12 twice, once with an ITT intensifier run at 5.5 times rated gain, and again with a Galileo intensifier, which had an S-20 cathode and a P-11 phosphor. The latter version is the system reported on in Ref. 37.

An attempt to standardize dynamic range measurements was made at the 13th International Congress on High Speed Photography.⁴¹ Dynamic range was defined there as the ratio of peak amplitudes of an upper and lower usable signal. Limits are determined by a 20% change in FWHM. The reference is a pulse near the middle of the dynamic range. We plan to re-evaluate the data presented here in terms of the new definition.

6.15.1 Dynamic Range vs Slit Width

With low-intensity input laser pulses and with the camera sweep not operating, the image width on the RCA image-converter phosphor remains at about 150 μm for 10- to 200- μm variations in input-slit width.⁴² Here, the slit was placed in direct contact with the external surface of the cathode window, instead of being imaged on the cathode with a lens, as was done for all other tests in this report.

Subsequently, we found similar results with imaged slits of from 2 to over 200 μm . The image of the slit was visible on the output phosphor during translation of the slit several hundred micrometers both above and below (in the sweep direction) the position for the above tests. This finding assured us that the electron beam was not being apertured by the streak tube electronics. Apparently, aberrations in the electron lens of the tube mask any changes in the slit width. The coarse grid wires, biased at +2600 V from the cathode, create a negative lens effect. This effect causes local tube magnification in the sweep direction to be about 0.2 near the slit image on the usable cathode area, though the transverse magnification is 1.5. Hence, even a 200- μm -wide slit should appear to be about 40 μm wide on the phosphor screen. However, aberrations in the focusing electron optics limit the minimum image width to 150 μm .

Next, we measured dynamic range for slit widths of 25, 50, 100, 200, and 300 μm . We decreased the current density at the cathode by decreasing the input intensity in direct proportion to the increase in slit width. We did this to keep the output intensity approximately the same for each slit tested. The dynamic range plots (not shown here) were much the same as those in Fig. 6-68. The noise level on the film was constant, and the saturation intensity levels were, respectively, 1700, 2800, 1700, 2000, and 2100 (in relative arbitrary units). These values are close enough to be considered the same within experimental accuracy. Hence, we conclude that dynamic range is independent of slit width from 25 to 300 μm . This conclusion raises the question of whether or not current density (or space charge) at the cathoded surface is the limiting factor for dynamic range in the RCA tube. We are now trying to answer this question.

6.15.2 Dynamic Range vs Input Pulse Width

Figure 6-69 shows our results for the dependence of dynamic range on input pulse width. Data from Friedman⁴³ are plotted along with a theoretical curve from Majumdar.⁴⁴ We also show data from camera 13 (for which we measured 220- and 40-ps-pulse dynamic ranges with an S-1 streak tube at 1.06- μm wavelength) and the sub-10-ps (below the camera temporal resolution limit) data with an S-20 streak tube at 605 nm. The intensifier was the same for all camera 13 measurements.

6.16 Fiber Optic System for Multiple Beam Diagnostics with a Streak Camera

For thorough diagnostic coverage of the 20-arm Shiva system, we must record the intensity-vs-time profile of the output of each laser arm on every shot. We designed and built a system to sample each laser beam at both the Incident-Beam-Diagnostic (IBD) and Return-Beam-Diagnostic (RBD) packages.⁴⁵ We do this by collecting the small fraction of laser pulse that is transmitted through turning mirrors in each package.

The pulse sample is split off from both the IBD and the RBD packages and steered into an adjacent relay housing. The housing consists of an assembly for mounting neutral-density filters that attenuate the beam, a focusing lens, and a fiber optics terminal (Fig. 6-70). The lens focuses the beam onto the carefully cleaved end of the 0.15-mm-diameter shielded fiber optics cable in the fiber optics terminal. The cable from each IBD or RBD is then routed through the Shiva space frame to a streak camera diagnostic station.

We made sure that each cable was of the correct length and individually timed so that all signals to a given streak camera arrived simultaneously. The output fibers from up to 12 cables are then grouped in a linear array along the slit plane of the streak camera (Fig. 6-71). Thus, an appropriately timed streak photograph of this multiple signal is a record of the temporal intensity profile of each of the sampled beams. We can record either IBD or RBD data on all 20 beams with just two streak cameras.

To ensure that the temporal resolution of the system is not degraded, the temporal dispersion of the optical fiber must be low. We tested various lengths of Corning Corguide No. 1053 graded index fiber at several wavelengths with the streak camera. Figure 6-72 shows dispersion vs length. We conclude that the dispersion resulting from the relatively short lengths (<10 m) of fiber optics cable needed to sample the 1.06- μm -wavelength light from the Shiva laser will not adversely affect this application.

Soon, we will eliminate film as the data recording medium. We plan to acquire data with a Hamamatsu Temporal Analyzer, which we will mount in place of the film pack and interface directly with an LS1/11 computer. Data will then be stored directly in computer memory for future access and timely analysis.

References

37. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977), p. 3-56.
38. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), p. 3-42.
39. S. W. Thomas and G. E. Phillips, *Dynamic Range Studies of the RCA Streak Tube in the LLL Streak Camera*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-81054 (1978).
40. G. E. Phillips and S. W. Thomas, *Recent Technical Developments and Intensification System Studies with the LLL Streak Camera*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-81053 (1978).
41. S. W. Thomas, Chairman, *Special Session on Streak Camera Dynamic Range Measurement*, 13th Int. Congress on High Speed Photography and Photonics (Tokyo, Japan, Aug. 20-25, 1978); Lawrence Livermore Laboratory, Livermore, Calif., UCRL-81704 (1978).
42. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-75 (1976), p. 399.
43. W. Friedman, S. Jackel, and W. Seka, "Dynamic Range and Spatial Resolution of Picosecond Streak Cameras," *SPIE* 97, 544.
44. S. Majumdar, "Dynamic Range of Picosecond Image Converter Streak Cameras," *SPIE* 97, 24.

Author

S. W. Thomas

Major Contributor

G. E. Phillips

Fig. 6-70. Schematic of fiber optic system for multiple beam diagnostics of IBD and RBD signals, using a streak camera.

Fig. 6-71. Hardware for fiber optic system for multiple beam diagnostics of IBD and RBD signals, using a streak camera.

Fig. 6-77 Temporal dispersion in Corning Corguide No. 1053 optical fiber.

Reference

45. F. Rienecker, M. Kobierecki, R. Ozarski, L. Seppala, K. Manes, and B. Merritt, *Shiva Optical Diagnostics*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-79776 (1977).

Author

J. W. Houghton

6.17 Windowless X-Ray Detector With 50-ps Response

We developed a windowless x-ray detector that has a calculated signal output rise time of 50 ps. The detector's radially bypassed anode structure minimizes anode inductance. The detector operates at a 5-kV anode-to-cathode potential; anode-to-cathode spacing is 1.2 mm; cathode area is 78 mm². A 50-mm outer mounting flange permits efficient array coverage using multiple detectors. Figure 6-73 is a cutaway view of the detector; specifications are listed in Table 6-13.

We designed the 50-ps-response detector to diagnose x rays in as near to real time as practical, using conventional oscilloscope recording techniques. The advent of the Thomson-CSF 4-GHz oscilloscope (rise time ~90 ps) motivated us to design a detector with comparable performance. The detector and 4-GHz oscilloscope will be connected by a short air-dielectric coaxial cable to diagnose x rays in the Argus and Shiva laser facilities.

We plan to use the Monojoule laser system to characterize the detector. This laser should provide an x-ray source with a temporal width of ~30 ps. Knowing the system's impulse response to this source, we will be able to deconvolve the data obtained in the Argus and Shiva target irradiation facilities.

Anode voltage is provided by means of a spring clip that contacts the front surface of the anode structure. A single high-voltage, vacuum feed-through connector provides high voltage to an array of detectors. A decoupling resistor between the connector and each anode prevents detector interactions. The anode is radially bypassed using chip ceramic capacitors. Two capacitors are wired in series to obtain the required voltage rating, and six such series sections are connected in parallel symmetrically around the anode periphery. The equivalent anode bypass value is 900 pF. The space-charge current limit is 45 A at 5 kV.

In the Dante systems of Shiva and Argus, the detector will provide extremely fast temporal response on selected energy channels. We developed a series of adapters for mounting the detector on the

Table 6-13. Specifications of 50-ps windowless x-ray detector.

Cathode structure impedance	50Ω
Rise time of calculated output signal	50 ps
Fall time of calculated output signal	65 ps
FWHM of calculated output signal	53 ps
Value of anode bypass capacitor	900 pF
Voltage rating of anode bypass capacitor	8 kV
Detector working voltage	5 kV
Space-charge current limit @ V _{AK} = 5 kV	45 A
Anode-cathode spacing	1.2 mm
Total cathode area	78 mm ²
Anode mesh material	Nickel
Anode mesh transmission	85%

Fig. 6-73. Cutaway view of 50-ps detector.

Dante package in place of the usual XRD-31 detector. These adapters include a high-voltage feed-through section for applying anode voltage to the detector. A vacuum of $\leq 5 \times 10^{-5}$ Torr must be established before the voltage is applied. We are now developing new mounting hardware to take advan-

tage of the reduced physical dimensions of this detector.

Author
D. E. Campbell

Major Contributors
W. Laird
T. Schwinn

6.18 Laser Irradiation on Target (LITAR) Code

To help evaluate focusing strategies for the Shiva laser system, we developed a computer code

that calculates and displays irradiation patterns for spherical and planar targets. This Laser Irradiation on Target (LITAR) code computes both the incident and absorbed intensities. The user can display results in tabular form, as a symbolic plot on the

line printer, or as a color display on a television monitor.

LITAR establishes a mesh in spherical coordinates between user-specified θ , ϕ limits at a specified target radius. LITAR sums the intensity from each beam at each mesh point, using the following series of transformations:

- Locates a mesh point on the target surface and transforms it into each lens coordinate system, in turn. Each focusing-lens mount provides positioning control in three orthogonal directions that are chosen as the axes of the lens coordinates.

- Translates the point in lens coordinates to cylindrical coordinates by user-specified offsets for the target under study.

- Computes local intensity and beam direction, using a user-specified superposition of Gauss-Laguerre functions.^{46,47} Components of the beam normal to the target surface and in the S and P polarizations are computed from the geometry.

- Sums the calculated incident and absorbed intensities for each beam at each mesh point on the target surface. The absorbed fraction is interpolated from short-pulse absorption data.⁴⁸ No attempt is made to calculate the interference patterns produced by overlapping beams.

Because Shiva target-irradiation strategies and target dimensions often change from shot to shot, LITAR has become an indispensable tool. Lens drive settings are chosen and checked using LITAR. After the shot, LITAR infers incident and absorbed intensity distributions on the target surface, using calorimetric data gathered on the shot.

Figure 6-74 shows inferred intensity distributions for a ball-in-plate target irradiation in which ~27 TW reached the target. The 10 beams in each cluster were arranged in ring patterns to improve energy deposition at the target equator and to avoid excessive heating of the target poles. Color changes imply a 40% intensity difference, and they graphically display the heating asymmetry of this target.

Absorption estimates made by LITAR compare well with energy balance measurements for sub-100-ps irradiations. As the pulse duration increases beyond 100 ps, however, stimulated scattering and other processes begin to dominate, and LITAR's estimates have been consistently high. We plan to add a more realistic absorption model to the code.

References

46. P. Renard and J. Hunt, *ARTEMIS: A Diffraction Model for Laser Light Propagation*, Lawrence Livermore Laboratory, Livermore, Calif., UCID-17381 (1977).
47. A. E. Siegman, *Introduction to Lasers and Masers* (McGraw-Hill Book Co., New York, 1971) p. 304.
48. K. Manes, V. Rupert, J. Auerbach, P. Lee, and J. Swain, "Polarization and Angular Dependence of 1.06- μ m Laser-Light Absorption by Planar Plasmas," *Phys. Rev. Lett.* **39**, 281 (1977).

Author

K. R. Manes

Major Contributor

F. D. Feiock

6.19 Shiva Target Diagnostic Mapping

The Shiva target chamber, a sphere 80 cm in radius, contains more than 200 ports and openings. Mounted on the ports are many diagnostics that, if not carefully installed, would interfere with each other's field of view and with the laser beams. To facilitate the planning of new diagnostics and maintain current records of the target chamber, we developed a computerized, target diagnostics, mapping system for the Shiva 11/70 computer.

For source data, the mapping software uses detailed diagnostic information maintained in the Shiva Diagnostics Data Base File, which is manually updated. This file contains the following primary information:

- Diagnostic name—a four-letter name code followed by a two-character sequence number or special designation. Name codes are presented in Table 6-14.

- Diagnostic category code. Diagnostics are subdivided into six categories: Laser Light; X-Ray; Neutron; Ion/Plasma; Alpha Particle; Target Alignment Equipment.

- Diagnostic color code. Each category of diagnostic is assigned a color for plotting on color TV displays.

- Diagnostic name symbol—a two-character code to identify diagnostics on computer-generated plots of the chamber configuration. Name symbols are presented in Table 6-14.

- Diagnostic coordinate and solid angle data. These consist of the diagnostics' spherical coordinates θ , ϕ and the solid-angle parameters $\Delta\theta$ and $\Delta\phi$. At the top of the target chamber, $\theta = 0^\circ$; along the axis of the target positioner, $\phi = 0^\circ$.

Table 6-14. Diagnostic labels and codes.

Name ^a	Description	Symbol	Color	Category code
LC21	LC-21 laser calorimeter	L1	Yellow	1
LC27	LC-27 plasma calorimeter	L7	Green	4
SLPD	Scattered-light photodiode	PD	Yellow	1
SLSC	Scattered-light streak camera	SS	Yellow	1
PLCA	Plasma calorimeter particle diagnostic	PC	Green	4
ICAL	Ion calorimeter particle diagnostic	IC	Green	4
XCAL	X-ray calorimeter	XC	Red	2
ATOF	α TOF ^b particle diagnostic	AT	Green	4
AZPC	α zone plate particle imaging	AZ	Purple	5
XRMS	X-ray microscope	XM	Red	2
FFLE	Filter fluorescer	FF	Red	2
XZPC	X-ray zone plate	XZ	Red	2
XRSC	X-ray streak camera	XS	Red	2
DANT	Dante	DA	Red	2
NTOF	Neutron TOF	NT	Blue	3
NCUA	Neutron yield (copper activation)	NC	Blue	3
NPBA	Sensitive neutron detector (Pb)	NP	Blue	3
RDCH	Neutron radiochemistry	RC	Blue	3
NOXA	Sensitive neutron detector (oxygen)	NX	Blue	3
NYLD	Neutron detector (scintillator)	NY	Blue	3
BCAL	Scattered-light box calorimeter	BX	Yellow	1
TAVI	Target alignment & viewing instrument	TV	White	6
TARP	Target positioner	TP	White	6
SNTY	Sentry	SY	White	6
XRAD	X-ray angular distribution	XA	Red	2
SVSH	X-ray spectrum (seven shooter)	7S	Red	2
SP25	X-ray spectrometer (2-5 keV)	SP	Red	2
PCAL	Pinhole box calorimeter	PC	Yellow	1
EBMD	Energy balance module	EB	Yellow	1
XPHC	X-ray pinhole camera	XP	Red	2
LC38	Sputtering calorimeter	L8	Green	4
LC39	Sputtering calorimeter	L9	Green	4
FCUP	Faraday cup	FC	Green	4

^aEach four-letter group is followed by a sequence number, i.e., NYLD01, XRMS10, etc.

^bTOF = time of flight.

● The name of the physicist or engineer responsible for the diagnostic. Using the coordinate and solid angle data, the computer program determines all sets of diagnostics with interfering fields of view. Polar presentations of the target chamber diagnostics are produced on both a VERSATEC plotter/printer and on a color TV screen.

Figure 6-75 is a sample plotter presentation. Each diagnostic is represented by an ellipse centered at the diagnostics spherical coordinates and having axes corresponding to $\Delta\theta$ and $\Delta\phi$. Each ellipse is labeled with the name code and an "x" if the diagnostic interferes with another. Note that, in the polar presentation, θ is the radial coordinate and ϕ

Fig. 6-75. Sample polar plot of target chamber diagnostic configuration.

is the azimuthal coordinate. Also, increments of arc length on a latitude parallel of the target chamber sphere are stretched relative to the arc length at $\theta = 20^\circ$ by

$$S_\theta = \frac{\theta}{20^\circ} S_{20^\circ}$$

Thus, ellipses corresponding to diagnostics near the south pole of the chamber appear quite stretched.

Figure 6-76 is an example of a color TV display. In addition to the diagnostic and beam ellipses, unused ports, blocked ports, and those for target chamber maintenance equipment are depicted with green, pink, and white crosses, respectively. The user can interact with this display to plan new diagnostics by plotting an ellipse having the solid angle characteristics of the proposed diagnostic. The blue ellipse at $\theta = 120^\circ$, $\phi = 180^\circ$, is the result of such an operation. In addition to the

Fig. 6-76. Color TV display of target chamber diagnostic configuration.

port listings, listings by diagnostic category, responsible physicist/engineer, or coordinates, are readily available.

Author

J. Auerbach

Major Contributors

J. Parker

C. Thomson

J. Greenwood

6.20 TACAI Upgrade for Argus

We upgraded the data acquisition capabilities of the Argus laser facility, which previously used the ADAS program.⁴⁹ Because of limitations in ADAS, we designed a better data acquisition system for the newer Shiva laser facility. Called Target, Acquisition, Control, and Instrumentation (TACAI), the system is in use on Shiva.⁵⁰ Now, it is also in use on Argus.

Use of TACAI on Argus increases its diagnostic capabilities and makes it compatible with the Shiva Control System.⁵¹ To accomplish the expansion, we installed two microcomputers—one to control hardware interactions among instruments, the other to control man-machine interactions. To make TACAI work on Argus, we needed timing and control signals to sequence the instrumentation. On Shiva, these signals are generated by a microcomputer that controls the laser system. Because the Argus system is not computer controlled, we built a generator to simulate the Shiva control system by creating signals from the manual controls.

There are two planned results of the Argus upgrade:

- To make the Argus system identical to the Shiva system, thereby consolidating both hardware and software support.

- To have one data base for the entire laser fusion program, thereby enabling experimenters to analyze data simultaneously with the same program. We anticipate a decreased turnaround time in data analysis.

References

49. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977), p. 2-181.
50. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), p. 3-90.
51. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), p. 2-22.

Author

J. T. Ozawa

SECTION 7

CONTENTS

7.1	Introduction	7-1
7.2	Components and Subsystems	7-3
7.2.1	Progress in Rectangular Disk Amplifiers	7-4
	RDA Prototype	7-4
	Reflector Geometries in the RDA Prototype	7-5
	34-cm Nova Prototype Amplifier	7-6
	Summary	7-7
7.2.2	Pulse Generation and Temporal Shaping	7-9
	Argus	7-9
	Shiva	7-9
	Nova	7-9
7.2.3	Regenerative Amplifiers	7-11
7.2.4	Compensated Pulsed Alternator	7-14
	2.5-MJ Compulsator Design	7-15
	Principles of Operation	7-15
	Application to Flashlamp Loads	7-17
	Compulsator Model	7-20
	Summary	7-20
7.2.5	Development of Plasma Shutter for Target Retroreflection-Laser Isolation	7-22
	Experimental Configuration	7-22
	Model	7-23
	Results	7-23
	Conclusions	7-26
7.2.6	Rod Amplifiers	7-26
7.2.7	Large-Aperture Pockels Cells for System Isolation	7-29
7.3	Optical Materials	7-34
7.3.1	Laser Glass Development	7-36
	Fluorophosphate Glasses	7-36
	Fluoroberyllate Glasses	7-45
	Tellurite Glasses	7-50
	Nd:Glass Laser Properties	7-53
	Fluorescence Sensitization	7-73
	Faraday Rotator Materials	7-76
7.3.2	Glass Physics	7-80
	Nonlinear Refractive Index	7-80
	Laser-Excited Fluorescence	7-82
7.3.3	Laser Damage Program	7-88
	Introduction	7-88
	Cause of Damage	7-89
	Recent Results	7-91
	Laser Damage Experiments	7-91
	Special Applications	7-94
	Facilities	7-95

7.4	Theory and Design Analysis	7-98
7.4.1	Propagation in Long Air Paths	7-99
7.4.2	A Statistical Analysis of Absorptive Laser Damage in Dielectric Thin Films	7-101
7.4.3	Intensity Loading of Pinholes in Vacuum Spatial Filters	7-106
7.4.4	Modeling for Design of Large Laser Systems	7-111
	Introduction	7-111
	Modeling Procedure	7-112
	Obscuration Noise	7-112
	Beam Statistics	7-112
	A Propagation Example	7-113
	Malaprop and Argus	7-117
7.4.5	Reflector Optimization Calculations	7-124

SECTION 7

SOLID STATE LASER TECHNOLOGY

7.1 Introduction

In 1978 our technology development program emphasized techniques that enhance the performance of both Nova and our operating laser systems, Argus and Shiva. The two major efforts were to improve materials and to improve components. We are commercializing laser glass, exploring durable optical coatings, and developing new components such as the plasma shutter and compensated pulsed alternator.

The enormous benefit of the new fluorophosphate laser glasses has been discussed in previous reports. This material is the basis of the Nova laser system. In 1978 we passed a major milestone in the glass development program, taking delivery of our first full-scale fluorophosphate laser disks and testing them in our Nova amplifier prototype (see Fig. 7-1).

We began a second major material development program to increase the damage thresholds of

Fig. 7-1. Nova amplifier prototype. This square amplifier pumping configuration achieves 2% pump efficiency.

>70% conversion of 1.06- μm light to 0.53- μm light, and we are beginning measurements to obtain damage thresholds at 0.53 μm and 0.26 μm . We feel it may be possible to convert the 1.06- μm light to 0.26 μm with an efficiency approaching 40%.

Several component innovations occurred which, in combination, resulted in substantial improvements for the Nova laser and are applicable to future laser systems. These innovations include the square amplifier pumping configuration (see Fig. 7-1) that achieves 2% pump efficiency, a plasma shutter that closes the spatial filter pinholes and isolates the Nova chain from target reflection, and a new low-cost potentially repetitive source of electrical power, called the compensated pulsed alternator. This device is being developed for us at the University of Texas, Austin. In addition, we continued our oscillator development program and have now demonstrated 15-ps oscillator pulses that are synchronized to within ± 5 ps of the master oscillator pulse for the chain input (see Fig. 7-2). This permits reliable stop-action viewing of plasma formation on fusion targets. To improve our oscillator switchout systems and overall chain timing, we developed a reliable high-voltage switching technology based on vacuum planar triodes. These tubes, when properly used, allow <1-ns timing jitter with 1- to 2-ns rise time driving 50- Ω Pockels cells.

Our theoretical design and analysis effort during the year focused on laser system design and related propagation problems. Conversion of Malaprop to a comprehensive system propagation and modeling code enabled us to address, quantitatively, a variety of problems: identification and characterization of the major source of spatial noise in large laser systems, assessment of far-field intensity distributions (i.e., at spatial filter pinholes), accurate assessment of the near-field growth of spatial modulation peaks, assessment of the nonlinear index effects of long air paths, and detailed verification of image relaying as an optimum spatial filter strategy for solid state laser chain design. This last achievement represents an important step in the systematics of laser design, permitting Shiva f/14 spatial filter simulation, Nova simulation, and future laser system simulation.

These broad-based technology programs have led us to expect substantial improvements in Nova's performance over our initial estimates, achieving >300 kJ long-pulse and 300 TW short-pulse. These laser innovations are being used on Argus and

Shiva, as they become available, to improve performance and reduce operating costs. They are also directly applicable to future fusion laser systems.

Authors

T. J. Gilmartin

J. F. Holrichter

7.2 Components and Subsystems

In this section we present highlights of the component development activities that occupied the Solid State Laser Group during 1978. All of these developments play prominent roles in planning and development of the Nova laser system. One—the compensated pulsed alternator—also seems sure to have a significant technological impact on the pulsed power community at large.

The rectangular disk amplifier (RDA) concept, wherein glass disks are face-pumped by two opposed arrays of flashlamps, originated in 1977 as a promising approach to more efficient optical pumping. Technological advances in laser glass, evolutionary trends toward longer pulse durations appropriate for laser fusion targets, and expanding capacitive energy storage requirements (for Nova in particular) then combined to put a dollar premium on the RDA's more efficient amplifier pumping (see §2 for a review of cost-effective laser design requirements). Our developmental work leading to a useful prototype amplifier, specifically at a 34-cm clear aperture, is described in §7.2.1.

In §7.2.2 and 7.2.3 we describe the results of ongoing developmental work on coherent pulse generation for solid state fusion applications. The relative merits and limitations of the several viable pulse-generating and pulse-shaping techniques are now quite clear (see last year's annual report), and we have begun to answer the remaining technological questions in the laboratory. We have demonstrated, for example, a simple pulse-shortening technique that decreases the FWHM temporal duration of a switched-out pulse from 100 to 60 ps and is eminently suitable for certain Shiva experiments. We have characterized an actively mode-locked Nd:YLF oscillator that operates at a center wavelength suitable for Nova, and we have fully characterized and optimized the regenerative pulse compression scheme described in last year's annual report. Implementation of the latter scheme

is planned for 1979 as part of an auxiliary diagnostic pulse system for Argus. During the coming year, also, we plan to implement several of these techniques online in the environment of large laser systems.

The compensated pulsed alternator¹ was conceived at the Center for Electromechanics, University of Texas, Austin, motivated partly by the desire to establish viable cost-effective alternatives to traditional capacitive energy storage. Studies carried out at Austin under funding from DLF/DOE and LLL led to a conceptual firming of this device; the university undertook design and construction of a scale model, which is now well along. Progress in this important project is described in §7.2.4.

Back reflection from the target constitutes a serious damage threat to large, expensive components in the laser amplifier chains. Historically we have protected our systems through Faraday isolation at or near the output end of each amplifier; however, the cost of this approach increases as the cube of the beam aperture. An alternative method, by which the focal plane of the final spatial filter is blocked by an overdense plasma before the target retroreflection arrives, has been extensively tested and appears to offer a very cost-effective solution for the Nova system. A detailed characterization of this plasma shutter is presented in §7.2.5.

During the year we significantly increased the reliability of the Shiva rod amplifiers by implementing several design modifications described in §7.2.6.

Finally, we made substantial progress in large Pockels cell development. Section 7.2.7 describes our exploratory developments in liquid electrode interfaces, grid electrodes, and "pusher" dielectric structures. These efforts are ultimately directed toward implementing Pockels cells with apertures greater than 10 cm. Hard-tube modulator circuits with less than 10-ns rise time have been shown to be reliable gate drivers for cells of smaller aperture; this technology seems readily adaptable to larger cells as well.

Reference

1. W. F. Weldon, M.-D. Driga, and H. H. Woodson, U.S. Department of Energy Patent Disclosure, Contract EG-77-S05-5594 (January 23, 1978).

Author

W. E. Martin

7.2.1 Progress in Rectangular Disk Amplifiers

The rectangular disk amplifier (RDA) was conceived in 1977 as a promising approach to more efficient optical pumping of solid state amplifiers. In the RDA (Fig. 7-3), flat arrays of flashlamps and their reflectors are placed above and below the laser disks. The side reflectors are flat sheets and, like the flashlamp reflectors, are silver-plated. Because flashlamp self-absorption is an especially significant factor in determining amplifier performance,^{2,3} the flashlamp light passes through the laser disks, in the RDA concept, before striking other flashlamps.

Simulation codes such as ZAP had predicted a significant increase in pumping efficiency for the RDA geometry. To explore this concept, a prototype RDA that could accept disks of up to 30-cm clear aperture was built and tested beginning in January 1978. This size was chosen for easy comparison with available data on round D amplifiers. Based on the success of this prototype, a 34-cm clear-aperture Nova prototype amplifier was built and tested with Nova fluorophosphate laser glass. Highlights of this test program are summarized in the following paragraphs.

RDA Prototype. We extensively tested the RDA prototype with ED-2 D-size disks (30 × 58 × 3.4 cm, 1.2% Nd) with EI-6/EI-4 edge cladding. To compare amplifier performance, we also tested the same disks in the circular-lamp-geometry D amplifier containing Pyrex shield glass. In all cases standard Shiva flashlamps were used: 1.5-cm bore, 112-cm arc length, and 300 Torr of xenon, driven in pairs from a 93-μF, 430-μH bank capable of charging the capacitors to 24 kV. The amplifier's small signal gain was measured as a function of bank energy by using a 1.064-μm Nd:YAG CW oscillator.⁴ The first tests on the RDA were performed with a lamp/reflector geometry containing 14 lamps per side, which closely matched the wraparound flashlamp reflector of the D amplifier. Figure 7-4 shows a segment of the RDA prototype and D-amplifier reflector assemblies. Figure 7-5 shows the measured small signal gain coefficient (which is proportional to the stored energy) vs bank energy for both amplifiers. The gains in amplifier efficiency using the RDA design can be seen by comparing the gain coefficients of the two amplifiers at a constant lamp-input energy. Relative pumping efficiency is easily compared by plotting efficiency (defined here as stored energy over bank energy) vs flashlamp

current density. Figure 7-6 shows the dramatic increase in efficiency obtained from a 28-lamp RDA compared with the 40-lamp D-amplifier geometry. (This improvement is greatest at low current densities.) Following these initial proof-of-concept experiments, we undertook an extensive program to explore the effects of reflector-flashlamp geometry on amplifier efficiency and performance.

Reflector Geometries in the RDA Prototype. Many flashlamp/reflector geometries were built and tested to explore various concepts of flashlamp pumping. Figure 7-7 shows two reflector geometries that exhibited advantages in performance over those in Fig. 7-5. The double-cusp reflector design⁵ is optimal in the sense that it prevents reabsorption by the flashlamp of its own light.

Fig. 7-5. Measured small signal gain coefficient vs bank energy for the 40-lamp round D-amplifier and the 28-lamp RDA prototype amplifier using the same ED-2 disks.

Fig. 7-6. Efficiency for a 28-lamp RDA compared with 40-lamp D-amplifier geometry. The increase in efficiency is dramatic, particularly at low current densities.

Figure 7-7(b) shows a modified single-cusp reflector used in later testing. This reflector is not radically different from the conventional reflector (Fig. 7-4) but has deeper cusps to shield adjacent lamps from each other.

Experiments were performed with several different geometries. Figure 7-8 summarizes the significant results. Gain coefficient vs bank energy is plotted here for four pumping geometries: (a) 28-lamp conventional reflectors, (b) 14-lamp double-cusp reflectors, (c) 14-lamp flat reflectors, and (d) a close-packed 34-lamp experiment with a single-cusped reflector assembly. Results confirm that flashlamp absorption adversely affects amplifier pumping efficiency, as clearly shown by comparing curve (b)—for 14-lamp double-cusp reflectors—with the other curves. However, large amplifiers must also realize enough stored energy in the disks for optimum system design performance. Curve (a), for example, may represent a more cost-effective amplifier than curve (b). Thus these experiments both point the way to greater amplifier efficiency and permit normalization of our flashlamp-glass pumping model.⁶ Based on these and on the RDA prototype experimental results, computer codes such as GAINPK⁷ are then used to predict amplifier performance, after which optimization codes can be used with confidence to establish a

baseline design for a 34-cm clear-aperture Nova prototype amplifier.

34-cm Nova Prototype Amplifier. Comprehensive testing of the RDA prototype speeded the fully engineered design and construction of a 34-cm clear-aperture Nova amplifier prototype, shown partly disassembled in Fig. 7-1. The first tests on this amplifier were performed in October 1978.

Initial testing of the Nova prototype amplifier used fluorophosphate disks $36 \times 64 \times 4.7$ cm in size containing $1.6 \cdot 10^{20}/\text{cm}^3$ Nd ions. The optical quality of the disks was very good. As before, 1.5×112 -cm flashlamps were used with a Shiva-style bank having $111 \mu\text{F}/450 \mu\text{H}$ per circuit. The flashlamp pulse width was $670 \mu\text{s}$ ($3\sqrt{\text{LC}}$). The reflector assemblies contained two 8-lamp double-cusp reflectors. First tests of the amplifier were performed without shield glass. The gaps between the reflectors and the side walls of the amplifier cavity, which would be filled by shield glass, were found to be extremely important in determining amplifier performance because the amplifier recirculates the pump light so many times that "leaks" in the pump cavity must be carefully closed. Covering the reflector gaps, which total 800 cm^2 in a cavity dimensioned 48 by 40 by 150 cm, in fact produced a 13% increase in amplifier efficiency.

Fig. 7-7. Reflector geometries with improved performance over the reflectors shown in Fig. 7-4. (a) RDA prototype reflector with 14 flashlamps (7 per side) and a nonconstrant feature. (b) 34-cm Nova amplifier reflector with 16 flashlamps (8 per side) and a single cusp. All numbers are in mm.

Figure 7-9 shows the measured gain coefficient as a function of bank energy (data points) as well as appropriate, normalized GAINPK simulations. From this simulation we can see that a bank energy of about 320 kJ is needed to reach a gain coefficient of 4.4 m^{-1} , corresponding to the desired small signal amplifier gain of 1.65. By comparison, an equivalent round 34-cm D amplifier would require at least 550 kJ to reach the same gain coefficient. Thus, the rectangular disk amplifier concept exhibits a striking improvement in efficiency.

Other reflector geometries were tested in the 34-cm cavity, including the eight-lamp single cusp shown in Fig. 7-7(b) and some 10-lamp double- and single-cusp reflectors similar to those in Fig. 7-7 but more tightly packed. We found no significant dif-

ferences in amplifier pump efficiency for the single- and double-cusp eight-lamp reflectors. The 10-lamp single-cusp reflector is more efficient than the 10-lamp double-cusp reflector, possibly due to the non-optimum double-cusp shape imposed by the lamp packing density. Table 7-1 summarizes reflector performance data taken using 30-cm ED-2 D disks in the 34-cm cavity.

Summary. The RDA concept has proved to be significantly ($\sim 30\%$) more efficient than conventional wraparound disk amplifiers. The RDA prototype and 34-cm Nova prototype amplifiers have clearly demonstrated proof of concept. Significant fabrication cost, maintenance cost and performance improvements will be realized with Nova as a result of implementing this amplifier concept.

Fig. 7-8. Gain coefficient vs bank energy for various pumping geometries in the RDA prototype.

Table 7-1. 34-cm Nova prototype RDA reflector assembly performance with 30-cm silicate disks.

Configuration	Gain coefficient at 200-kJ input energy [$\alpha(m^{-1})$]
16-lamp double-cusp reflector with gaps	3.85
16-lamp double-cusp reflector without gaps	4.17
16-lamp single-cusp reflector without gaps	4.17
20-lamp double-cusp reflector without gaps	4.19
20-lamp single-cusp reflector without gaps	4.36

References

- J. L. Emmett, A. L. Schawlow, and E. H. Weinberg, *J. Appl. Phys.* **35**, 2601 (1964).
- J. G. Edwards, *Appl. Opt.* **6**, 837 (1967).
- Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-82044 Preprint (1978)(to be published in *IEEE J. Quant. Electron.*).
- R. Winston, *Appl. Opt.* **17**, 1668 (1978); M. R. Siegrist, *Appl. Opt.* **15**, 2167 (1976).

- G. J. Linford, R. A. Saroyan, J. B. Trenholme, and M. J. Weber, "Measurements and Modeling of Gain Coefficients for Neodymium Laser Glasses," Lawrence Livermore Laboratory, Livermore, Calif., UCRL-82044 Preprint (1978)(to be published in *IEEE J. Quant. Electron.*).
- Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977), p. 2-222.

Author

W. E. Martin

Fig. 7-9. The 34-cm Nova prototype amplifier performance with two LG810 disks. This figure shows measured gain coefficient as a function of bank energy, as well as the app. rate, normalized GAINPK simulation.

7.2.2 Pulse Generation and Temporal Shaping

In previous publications and annual reports⁸⁻¹⁰ we described the development and construction of the oscillators for Argus and Shiva. The generation of high-energy short pulses in these oscillators is achieved by active mode-locking and Q-switching (AMQ). During the year these oscillators continued to operate reliably, producing short pulses in the range 100 ps to 1 ns for the target experiments, as described elsewhere in this report.

Our oscillator research and development program this year was aimed almost entirely at supporting these online oscillator systems and developing pulse-generation techniques for future needs. We also did further design work on the oscillator system for Nova. In this section we briefly describe changes in the Argus oscillator system, a simple pulse-shortening technique for Shiva, and initial characterization of Nd:YLF as potential oscillator material for Nova.

Argus. Two changes of significance were implemented in the Argus oscillator system. The switchout system timing now counts a fixed number of rf cycles after a single pulse is selected rather than counting cycles after the laser is Q-switched. As described in last year's annual report, this technique has worked well on Shiva.¹¹ Also, a new avalanche transistor driver of flat board design was implemented on each Pockels cell. With these changes, as discussed elsewhere, the Argus oscillator has performed even more reliably.

Shiva. For some of the Shiva target shots, it seemed desirable to have a 50-ps pulse. Shiva's existing oscillator produced pulses as short as 90 ps. A pulse-shortening method was needed that could be

added easily to the existing setup. A nonlinear optical technique was demonstrated that could shorten the pulse by as much as $\sqrt{3}$, accomplished by doubling part of the pulse to $0.53 \mu\text{m}$ in a type-I KD*P second harmonic generator and then mixing the doubled pulse with the remaining fundamental pulse in a type-II KD*P mixing crystal to give an orthogonally polarized pulse at $1.064 \mu\text{m}$. Since the intensity of the $1.064\text{-}\mu\text{m}$ pulse produced by this process is proportional to the cube of the intensity of the input Gaussian pulse, the pulse width is reduced by $\sqrt{3}$. Figure 7-10 shows the nonlinear process and polarization of the various signals. A demonstration of this technique in the laboratory produced the following:

- Pulse shortening from 100 to 60 ps.
- Energy conversion of 1 to 2%.
- Leakage of the shortened pulse compared with the original pulse (due to depolarization in the KD*P crystals) is in the ratio 1:300.

During 1978 the pulse stacker described in last year's annual report¹² was assembled and tested. This system will be installed on Shiva when needed to produce shaped pulses for target experiments.

Nova. In last year's annual report we described initial work with a Nd:YLF oscillator. This material lases at $1.053 \mu\text{m}$ and is presently considered acceptable for Nova. The fluorophosphate glasses have their peak gain at $1.051 \mu\text{m}$, but at $1.053 \mu\text{m}$ the gain is reduced only about 3.5%.

Mode-locking of the Nd:YLF oscillator was very similar to Nd:YAG, and operating characteristics of the YLF oscillator were almost identical to the YAG oscillator. The pulse widths were measured with an optical correlator as a function of

modulator drive, with the results shown in Fig. 7-11. Note that pulses as short as 66 ps were obtained, compared with about 100 ps for YAG under the same conditions. This is because of Nd:YLF's wider line width. The upper level lifetime in Nd:YLF is also longer than in Nd:YAG, giving a slower decay of the relaxation oscillations when the laser goes above threshold.

In Fig. 7-12 we compare characteristics of the two materials. With the good Nd:YLF crystals now available, this looks like a good oscillator for Nova.

References

8. D. J. Kuizenga, *Opt. Commun.* 22, 156 (1977).
9. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977), p. 2-289.
10. *Laser Program Annual Report—1977*, UCRL-50021-77 (1978), p. 2-205.

11. *Laser Program Annual Report—1977*, p. 2-17.
12. *Laser Program Annual Report—1977*, p. 2-4.

Author

D. J. Kuizenga

Major Contributors

J. E. Murray

B. C. Johnson

D. C. Downs

D. T. Bradley

7.2.3 Regenerative Amplifiers

This year we completed the experimental characterization of regenerative pulse compression. The purpose of this work was to demonstrate a technique for generating a probe pulse to diagnose laser fusion plasmas.¹³ To be most useful, the duration of the probe pulse must be from 10-30 ps at 1.06 μm and must be synchronized to the main heating pulse to within 10 ps. Regenerative compression provides a technique for generating the probe pulse directly from the main heating pulse whose duration ranges from 100 to more than 1000 ps. We have demonstrated regenerative compression performance that easily meets these requirements for the probe pulse.

The probe pulse is generated by temporally compressing a portion of the main pulse in a regenerative amplifier with an intracavity saturable dye. The numerical analysis¹⁴ of the pulse compression process completed last year indicated how to achieve both stable output and adequate compression. It showed the best performance for a dye con-

centration (d) less than a critical value,¹⁴ and it predicted improved performance from decreasing the cavity loss (l) and increasing the ratio (R) of the mode area in the dye relative to the amplifier. This year's work concentrated on optimizing these parameters experimentally.

Figure 7-13 shows the regenerative compressor schematically. A normal-cut YAG rod, a Brewster's-angle dye cell, and focusing cavity geometries were used to achieve a large area ratio R. The geometry of the schematic gave $R = 6.7$ and was very stable against thermal lensing in the YAG.

Single pass cavity loss l was minimized by using a cavity dump to extract the compressed pulse from the resonator rather than transmissive optics. The minimum cavity loss achieved was 0.08 ± 0.01 , measured with solvent only in the dye cell. Of this total, 0.025 came from the insertion loss of the KD*P Pockels cell for the cavity dump, 0.030 resulted from partial transmission in the resonator mirrors (for pulse injection and monitoring), and the remainder was distributed among the thin-film polarizer, acousto-optic Q-switch, dye cell, YAG rod, and mode-controlling iris.

Gain stability in the YAG amplifier was achieved by very tight control of both the current and voltage to the lamps with the same lamp driver that is used for the actively mode-locked and Q-switched (AMQ) oscillator.¹⁵ The stability produced by this lamp driver was comparable to that of the stabilization technique¹⁶ used earlier but did not generate the large amplifier gains of that technique. As a result, we were able to use an

Fig. 7-13. Cavity geometry of regenerative pulse compressor.

acousto-optic Q-switch in the regenerative compressor, also the same as used in the AMQ oscillator. The advantages of acousto-optic Q-switches compared with KD*P Q-switches are a lower insertion loss and an absence of acoustic echoes due to switching of the KD*P cells.

Figure 7-14 shows experimental data for typical operating conditions of the regenerative compressor. The data are for fixed values of the cavity parameters d , l , and R , as indicated, and for an injected pulsewidth of 120 ps. The displayed pulse parameters are the output pulsewidth, the intensity at the dye cell, and the stability of the cavity dumped pulse energy $\Delta E/E$. The lowest curve shows the number of round trips between injection and dumping. The data are plotted against initial net gain in the resonator, which was controlled by lamp current. The values of $\Delta E/E$ are the maximum deviations from the average output energy in a sampling of 100 shots. The samplings were taken over a 10- to 15-min interval, measuring 1 out of about every 150 pulses. All timing signals were derived from fixed time delays, as would be required in application. The measurement accuracy of d , l , R , and net gain was $\pm 10\%$ and of intensity and pulsewidth $\pm 20\%$.

For the data of Fig. 7-14, the dye concentration d was adjusted for a reasonable tradeoff between stability and compression. For larger values of d , the jump in the intensity curve became larger and steeper, and there was a corresponding sharpening of the other curves. The result was an overall increase in $\Delta E/E$ and less stability for the same output pulsewidth. For smaller d the overall stability improved but there was less compression. For each set of cavity parameters tested, the optimum d was about 90% of the critical value, in good agreement with the numerical analysis. However, the values of the critical dye concentrations were found to be about half those determined from the numerical analysis. The best operating point in Fig. 7-14 was at a net gain of 4.9%. The greatly improved stability at that point offset the somewhat shorter pulses—12 ps—obtained at 4.3%.

Table 7-2 summarizes the experimental results for four different values of the cavity parameters R , l , and d . In each case the values of d and net gain were adjusted to give the best combination of compression and stability, as discussed with respect to Fig. 7-14. The first row was obtained last year for an injected pulsewidth of 145 ps. The second

through fourth rows are for a 120-ps input. $I_{\max}$ was the maximum intensity reached in the regenerative compressor. It occurred at the YAG amplifier and served as an indicator of potential optical damage problems.

The data in the first two rows of Table 7-2 show that a large performance improvement resulted from the first 70% increase in R and a halving of l . However, a further increase in R from 6.7 to 9.6, shown in rows 2 and 3, did not produce significantly better performance. A possible explanation is the effect of increased B resulting from the higher intensities at the YAG rod. The last entry confirms that increasing R —row 4 vs 1—and decreasing l —row 3 vs 4—contributed to the observed performance improvement. There was no

Table 7-2. Experimental results for four different sets of cavity parameters R, l, and d.

Cavity parameter			$\tau(\mu\text{s})$	$\Delta E/E$ (%)	I_{max} (GW/cm ²)
R	l	d			
4.0	0.16	0.22	28	± 20	0.4
6.7	0.09	0.28	15	± 6.3	0.6
9.6	0.08	0.28	15	± 5.0	1.0
9.6	0.16	0.39	20	± 8.0	1.2

evidence of optical damage to the regenerative compressor components for any of these cavity configurations.

To summarize, the optimized cavity parameters are $R \approx 7-10$, $l < 10\%$, and $d \approx 0.25-0.30$. Under these conditions, a 120-ps injected pulse can be compressed to 15 ps with an output energy of $20 \mu\text{J}$, a shot-to-shot energy stability of $\pm 5\%$, and with minimal threat of optical damage. Pulses as short as 12 ps can be obtained under the same conditions but at the expense of less stability, $\pm 20\%$.

The synchronism between the original and compressed pulse was shown last year to be ± 5 ps or better.

As a summary demonstration of this diagnostic pulse capability, we displayed a probe pulse simultaneously with two potential heating pulses on a streak camera. Figure 7-15 shows the experimental arrangement and Fig. 7-16 the resulting streak camera displays. The top pulse in each picture in Fig. 7-16 is the original 120-ps Gaussian straight from the AMQ oscillator. The bottom pulse

Fig. 7-16. Streak photos of three synchronized pulses. The ± 120 -ps delay change of the compressed pulse was created by a ± 70 - μm mirror translation in the regenerative compressor.

is a 15-ps probe pulse compressed from the original, and the center pulse is a 1000-ps "square" pulse created by coherently stacking 10 of the original pulses.¹⁷ We created the variation in delay between

the compressed pulse and the other two by slightly changing the cavity length of the regenerative compressor. A mirror translation of ± 70 μm produced the ± 120 -ps timing change shown in Fig. 7-16. A timing change greater than the 10-ns interpulse time from the AMQ oscillator is available by this means, eliminating the need for large optical delays external to the regenerative compressor.

These experimental results demonstrate the utility of regenerative compression for producing short, stable, synchronized diagnostic pulses. A further improvement in performance may yet be possible from reduced cavity loss and improved gain stability, but the current results are more than adequate for the intended application.¹³ As such, they represent our final effort at optimizing regenerative pulse compression. Incorporation of a diagnostic pulse system on Argus using this technology is now under way.

References

13. D. T. Attwood, *IEEE QE-14*, 12, 909-923 (December 1978).
14. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), p. 2-210.
15. D. J. Kuizenga, *Opt. Commun.* 22(2), 156-160 (1977).
16. D. C. Downs, J. E. Murray, and W. H. Lowdermilk, *IEEE J. Quantum Electron.* QE-14(8), 571 (1978).
17. W. E. Martin and D. Milam, *Appl. Opt.* 15(12), 3054-3061 (1976).

Authors

J. E. Murray
D. J. Kuizenga
W. H. Lowdermilk
D. C. Downs

7.2.4 Compensated Pulsed Alternator

Capacitor banks have traditionally been used for storing the electrical energy needed for the rapid (0.5-ms) pulse that drives the laser's flashlamps. The stored energy requirement for Nova will exceed 100 MJ. For several years we have been seeking a more cost-effective pulse power system that would both store this much energy and provide the needed discharge power (at least 200 GW). The leading candidate now is a newly invented compensated pulsed alternator, or "Compulsator," from the University of Texas, Austin.

The Compulsator is a device that converts rotationally stored mechanical energy into a single high-power electrical pulse. Energy taken from

Fig. 7-17. Compensated pulsed alternator. An artist's version of the 2.5-MJ "Compulsator" (5 ft in diam, 10 ft long).

power lines over a period of several minutes and stored in the inertia of the rotor can be reconverted into electrical pulsed energy in 0.5 ms or less by virtue of the machine's special low-impedance design and flux-compression capability. A single Nova unit will be capable of providing more than 10 GW of power and 5 MJ of energy from a compact ($\sim 7\frac{1}{2}$ -ft-diam) package 15 ft long.

The advantages of using rotational, or inertial, energy storage are high energy density and low cost potential. The single advantage of Compulsators over other rotational energy storage devices are their high-voltage, high-power output capability. All other machines are either low voltage (e.g., the homopolar generator) or high impedance (e.g., a conventional pulsed alternator). Because of these limitations, no previous rotating machine has been capable of powering the flashlamps directly from the generator terminals.

2.5-MJ Compulsator Design. A design study for a 2.5-MJ Compulsator capable of driving approximately 100 Nova flashlamp circuits was performed by the University of Texas' Center for Electro-

mechanics.¹⁸ This machine, Fig. 7-17, would provide the waveforms shown in Fig. 7-18. Peak voltage and current occur together in the resistive flashlamp load and, for this design, are 18 kV and 422 kA, respectively. This translates into a peak power of 7.6 GW. A machine design of twice this energy (5 MJ) is now being considered for Nova that would deliver more than 10 GW of peak power in a 1-MA pulse, 500 μ s wide.

Principles of Operation. The advantages of the new alternator are best appreciated by understanding the principles and limitations of conventional electrical generators. Reduced to its simplest form, a generator requires a coil of wire to be spun in a magnetic field [see Fig. 7-19(a)]. To increase the generator's voltage, one must increase the magnetic field, spin the coil faster, or increase the number of turns of wire in the coil [Fig. 7-19(b)]. Because both the magnetic field strength and the rotational speed are limited by the physical properties of the materials used, the choice narrows to increasing the number of turns in the coil. Unfortunately, as the number of turns increases, so does

the inductance, and it is the inductance that limits the rate of rise of power the generator can produce. As shown in Fig. 7-19(c), the pulsed alternator solves this problem by using a stationary coil almost identical to the rotating coil. When the two coils are at closest proximity, the stationary coil counteracts the inductance of the rotating coil, reducing it to 5% of the uncompensated value. This reduction occurs near the peak of the output pulse, allowing very

high peak power to be generated. After the peak, the inductance again rises to its original (high) value, helping to turn off the pulse.

Besides providing minimum inductance at peak output, the rotationally coupled, compensated winding provides an $i(dL/dt)$ voltage that enhances the rise and fall of the pulse. Also, the compensation occurs over a relatively small fraction of the half-sinusoidal pulse of the alternator. This results in a

low di/dt at current zero, being governed by the relatively slow alternator frequency rather than by the fast compulsator output pulse (see Fig. 7-18). Thus, the output is self-commutating with a "soft" zero crossing typical of industrial power systems. This feature allows the use of triggered spark gaps, ignitrons, or solid state switches. It also means that the rotor does not have to be stopped during the discharge pulse but only slowed down by a few percent; the device can be continuously driven by a prime mover, leading to a rep-rateable system.

Figure 7-20 illustrates the principles of inductance compensation and magnetic field compression that enable the machine to deliver high peak power. For the sake of simplicity, this figure shows a single armature conductor rotating toward a single compensating conductor that is mounted on the inside rim of the stator. The radial B-field produced by current in the field windings of the stator induces a current in the moving armature conductor, as shown. The induced current flows through the slip rings and brushes to the load, as in a conventional alternator. If the current is then forced to return through the compensating conductor as indicated in Fig. 7-20, B-fields are produced around the two conductors in the direction shown.

As the two conductors are forced together, the compression of the combined fields acts to increase the flux density in the region between them because the fields cannot diffuse through the conductors during the pulse. This compression induces a higher voltage and causes a higher current to flow. Increasing

the current further increases the field, inducing more voltage, producing higher current, and so on. The result is an exponentially rising pulse that peaks when the two conductors are nearly in opposition (dotted line). Thereafter, the current falls off sharply as the armature conductor rotates away from the compensating conductor.

Note that the alternator's internal inductance is minimized at the time of peak output because the current in the compensating conductor images the current in the armature conductor, thus minimizing the volume in which the magnetic field can exist.

Application to Flashlamp Loads. A flashlamp is a nonlinear resistive load. When it is fully ignited, the voltage drop across it is about proportional to the $1/2$ power of the current. It must first be triggered, however. One method is to use a high-voltage pulse that is two or more times the voltage drop across the lamp at peak current. Alternatively, the flashlamps can be triggered when there is voltage across them by bumping the metal reflector with a high voltage impulse.

The requirement to produce a high-voltage spike to break down the flashlamps would unnecessarily complicate the Compulsator design; however, a two-switch circuit has been devised that will circumvent this problem. This circuit, shown in Fig. 7-21(a), uses a low-energy, high-voltage capacitor discharge to trigger the lamp by means of switch S_1 . This trigger pulse is followed by the high-energy, high-current Compulsator impulse when the main switch S fires.

An alternative circuit [Fig. 7-21(b)] makes use of the reflector "bumping" technique for flashlamp triggering. A capacitor is negatively dc-charged to about the same voltage magnitude as the peak positive output voltage of the Compulsator. This voltage is low enough so that the flashlamps can be directly connected across the capacitor terminals without breaking down. When the reflector is pulsed, the flashlamps fire, and a negative current at first flows through them. The main switch S is then triggered, and Compulsator current flows first into the capacitor, charging it positive, and then flows in a positive direction through the flashlamps. This circuit has the distinct advantage of providing initial startup current for the Compulsator, almost doubling the energy output of a given size machine. The circuit has received repeated laboratory tests, in which a 1/4-MJ capacitor bank, substituting for the Compulsator, has been repeatedly fired into 16 parallel flashlamps. The small capacitor to trigger the lamps is only about 2 kJ.

Either circuit in Fig. 7-21 has the additional feature that either small trigger capacitor can dou-

ble as the pulsed ionization lamp check (PILC) capacitor described earlier. As a result, no extra cost would be incurred from their use. Note that the present PILC circuit works very reliably, firing many flashlamps in parallel from a single capacitor. The peak current in this circuit reaches 10 or 15% of the full output current, but the stored energy is only 1% of the total energy delivered by the Compulsator.

A key requirement of either circuit is that the main switch S must extinguish after the pulse so the Compulsator will not produce additional output pulses to the flashlamps. (Note that the rotor stores 10 to 30 times more energy than is delivered in a single pulse.) Switch commutation can be readily achieved, however, because of the soft zero crossing of the current several milliseconds after the pulse (see Fig. 7-18).

We have studied the effect of the Compulsator waveshape on the energy W delivered to the load.¹⁹ Results reveal that the formula

$$W = f K_o \Delta t i_p^{3/2} \quad (1)$$

is accurate to a few percent for a wide range of waveshapes (f is the waveshape form factor), pulse halfwidths Δt , and peak currents i_p . The characteristic flashlamp constant K_0 was measured to be $173 \pm 4 \text{ V}/\sqrt{\text{VA}}$ for a series pair of 44-in.-long, 15-mm-bore flashlamps over a 5:1 range of energies. Also, the waveshape form factor f was computed to be 0.99 ± 0.03 for any anticipated Compulsator waveform and 0.83 ± 0.02 for the conventional

single-mesh capacitive discharge circuit. This appears to indicate that for a given peak current and pulse halfwidth, the Compulsator will deliver $0.99/0.83 = 1.19$ times more energy to the flashlamps than will the capacitive circuit.

A preliminary cost analysis¹⁹ revealed a need to shorten the current pulse Δt as much as possible consistent with flashlamp life and the strength of the machine materials. This is because the cost of the

Compulsator scales roughly as $i_p^{3/2} \Delta t^2$. In Fig. 7-22 this cost factor is plotted vs measured gain for two pulse halfwidths in an experimental Nova box amplifier. It is apparent that a Compulsator delivering a long low-current pulse may cost significantly more than one delivering a short high-current pulse. The reason is that more iron is needed for a slow-pulse machine. This preliminary study points up the need for more detailed analysis before the pulse width is finalized and after the strength of Compulsator materials is better established.

Compulsator Model. A 200-kJ engineering-prototype-model Compulsator is now being built at the University of Texas. This machine will drive 16 parallel 44-in.-long by 15-mm-bore flashlamps. Testing is scheduled for September 1979. Table 7-3 gives performance specifications for the device and its load.

The model is designed to demonstrate the feasibility of driving a parallel flashlamp load with a Compulsator. It has a 15-in.-diam rotor that will be mounted vertically in a steel framework (see Figs. 7-23 and 7-24).

During testing, the magnetic compression factor of the model will be determined and the results will be checked against magnetic code predictions. This verification is important to the design of a full-scale Nova machine of the 5-MJ class. Also to be

Table 7-3. Engineering-prototype Compulsator, performance characteristics.

Parameter	Value
Flashlamp load	
Impedance constant (K_0), ^a V/ $\sqrt{A}$	2.2
Peak current per lamp, kA	4.4
Peak voltage, kV	5.7
Maximum energy per lamp, kJ	12.5
Pulse half-width, μ s	500
Alternator	
Open circuit voltage, kV	5.8
Peak load current, kA	70
Peak terminal voltage, kV	6.2
Peak output power, MW	435
Rotor conductor temperature rise, °C	4.3
Pulse half-width, μ s	500
Maximum energy to load, kJ	200
Initial energy stored, MJ	3.5
Initial speed, rpm	5400
Final speed, rpm	5170
Final energy stored, MJ	3.2
Inductance variation (A_L)	5:1
Peak fault current, kA	153
Rotor conductor temperature rise, °C	~20
Pulse half-width, μ s	486

^a16 parallel xenon flashlamps: 1.5-cm bore, 112 cm long.

tested are the mechanical features of the Compulsator design, particularly the capability of the rotor winding to withstand radial tension and pulse shear and thermal stresses. The model is small enough to permit design iterations without excessive schedule slippage.

After the key uncertainties of the Compulsator design are examined and understood and the problem areas are corrected, design work will proceed on the full-scale Nova machine. It is anticipated that procurement of this machine could start early in FY 1980.

Summary. The compensated pulsed alternator—Compulsator—is a new rotating high power machine that promises to supplant energy storage capacitors in very large electrical discharge systems. Its operation on the 100-MJ+ Nova flashlamp system may be the first full-scale use of this new concept.

At present, a 200-kJ version of the machine is being built at the University of Texas. This device will be tested with a 16-circuit flashlamp load. The machine's electrical performance will be demonstrated, the magnetic calculations verified, and mechanical design integrity proved.

Following this test, a large ~5-MJ machine will be designed. This full-scale machine will be installed at LLL, where testing will be performed before production machines are procured for Nova.

Purchase of machines for Nova will of course be contingent upon proven performances by the

prototypes, and upon verification of cost effectiveness.

References

18. W. Weldon et al., *Pulsed Power Supplies for Laser Flashlamps*, Center for Electromechanics, University of Texas, Austin, Final Report, Lawrence Livermore Laboratory Subcontract No. 1823209 (1978).
19. B. Carder and B. Merritt, *Compulsator Optimization*, Lawrence Livermore Laboratory, Livermore, Calif., internal report EE-78-192 (1978).

Author

B. Carder

7.2.5 Development of Plasma Shutter for Target Retroreflection-Laser Isolation

We have developed and characterized a plasma shutter appropriate to Shiva and Nova. This shutter, which is contiguous to the output spatial filter pinhole, consists of a wire that is exploded to project a critical-density plasma across the optical beam path, thereby blocking retroreflected light from the target. For the large-aperture output stages of the laser, the Faraday rotator/polarizer combination used on Shiva is reliable but expensive and adds to the nonlinear phase contributions. We plan to use the new shutter to protect Nova.

A low-inductance parallel capacitor bank with uv-illuminated spark gaps produces a current rising at 5×10^{12} A/s and has 1-ns jitter. Two groups of capacitors within the bank are tuned to burst the wire optimally and propel the plasma magnetically.

The wire is contained within a nozzle and has the electrodes extended in a rail-gun configuration. This geometry directs the plasma across the beam path, minimizing vapor leakage toward the optics. A dump tank collects the bulk of the plasma; baffles with an auxiliary weak orthogonal magnetic field collect the plasma debris and protect the optics.

Experimental Configuration. The experiment (Fig. 7-25) was contained in a multiport vacuum chamber retrofitted into a Shiva γ - δ spatial filter²⁰ and had f/10 optics. Also used for some specific measurements was an alternative set of f/1.5 20-cm-aperture lenses with the spatial filter arms removed. As shown in Fig. 7-26, the wire was located in the chamber center near the focal point of the optics.

The 3-mm-long, 127- μ m-diam aluminum wire was located between two electrodes in a 1-mm-deep, 150- μ m-wide slot in dielectric material. This slot constituted a nozzle that confined the plasma during heating and directed it across the optical beam path into the dump tank. This geometry increased the density at the focal region of the laser, as compared with a freely expanding plasma, and also reduced the amount of vapor escaping toward the spatial filter optics.

The wire electrodes were connected by a low-inductance parallel-plate transmission line to the pulser, which contained six parallel Maxwell 0.22- μ F capacitors connected to the transmission line by six independent switches as shown in Figs. 7-25 and 7-27. The switches were midplane-triggered, uv-illuminated pressurized-air spark gaps²¹ retrofitted by us into Tachisto 501 switch bodies. As configured, the pulser could be charged to 50 kV and provided a current rising at 5×10^{12} A/s. These spark gaps, when triggered with a fast trigger pulse, provided nanosecond jitter and, hence, excellent current sharing of the parallel gaps and synchronization with the laser and diagnostics. When connected to the foil, and accounting for the vacuum feedthrough inductance, the current had a quarter-period of 300 ns.

Electrical circuit monitors recorded the charge voltage of the capacitors and the current and voltage near the foil. Witness plates of glass and/or metal collected the vapor, thereby allowing us, by microdensitometer scans of the plates, to determine the angular distribution of the emitted plasma.

A Faraday cup, built from a disk connected to a BNC connector, had a negative bias of 300 V applied to the disk. It was coaxially contained in a

Fig. 7-25. Plasma shutter experiment configuration consisting of a multiport vacuum chamber retrofitted into a silica γ -5 spatial filter and 1/10 optics.

grounded metal cylinder with two axial pinholes of $250\text{-}\mu\text{m}$ diameter located at 1-cm intervals between the Faraday collector and plasma source. Separate pumpout ports eliminated residual air from the assembly.

The plasma front velocity near the wire was recorded with a TRW streak camera focused along the optical axis and with the slit oriented parallel to the plasma expansion axis.

A cw YAG probe laser with a $10\text{-}\mu\text{m}$ narrow-band filter and uv blocking filter was used with an EG&G SGD-100A photodiode to monitor shutter action. The photodiode was biased at 100 V for 1 μs during the period of interest.

Model. We have developed a self-consistent Lagrangian numerical program²² to model the pre- and post-burst features of an exploding foil. This formulation, which includes the driving circuit parameters and magnetohydrodynamic effects, describes with reasonable accuracy the evolution of plasma density and temperature.

The program is presently two-dimensional and describes the essential features of plasma behavior. It has been invaluable in extrapolating from an initial experimental configuration to the present one and in guiding our interpretation of the data. We cannot overemphasize the utility of such a fast-running program in choosing the pulser circuit and wire dimensions to achieve a specific operating point, particularly in view of the nonlinear interactions that otherwise would make scaling difficult.

Results. Measurements with witness plates located 2 cm from the wire show that the plasma expands into a wedge no greater than a 20-deg half angle and that no easily detectable vapor escapes toward the optics.

Figure 7-28 shows the resistance of the wire for a quarter period of the current 300 ns, based on our program and a choice of representative data at the 20-kV charge voltage. This resistance agrees with voltage and current measurements. The predicted plasma temperature is shown in Fig. 7-29.

Fig. 7-26. Detailed view of electrode-nozzle region from Fig. 7-25.

Fig. 7-28. Calculated resistance of aluminum wire as a function of time.

From these data we see that the wire and subsequent plasma heating occurs mainly during a short period of high resistivity and that the plasma achieves a mean velocity of $2 \text{ cm}/\mu\text{s}$, which can be attributed mostly to resistive heating. During this period, the plasma expands to the exit of the nozzle.

Since the current is still rising toward its maximum value, the heating phase is followed, after a slight dip associated with the wire burst, by a magnetic propulsion phase during which it continues to accelerate to higher than thermal velocity. For the 20-kV charge voltage, this increases the plasma mean velocity to $2.4 \text{ cm}/\mu\text{s}$. The two phases are not entirely distinct here but have been dis-

Fig. 7-29. Plasma temperature as a function of time.

tinguished more clearly on other experimental and numerical runs with different wire diameters and charge voltages. This selected example has been optimized for a Shiva configuration.

Figure 7-30 shows the displacement of the center of gravity of the expanding plasma as calculated by the program. The plasma achieves a final velocity of $2.4 \text{ cm}/\mu\text{s}$. Using the Faraday cup located 10 cm from the wire, we recorded a final mean expansion velocity of $2.2 \text{ cm}/\mu\text{s}$.

Figure 7-30 also shows the expanding plasma front as recorded by the streak camera. The velocity of this front is in agreement with the Faraday cup data. Figure 7-31 shows the measured optical shutter action of the plasma shutter.

Fig. 7-31. Measured optical shutter action of the plasma shutter, controlled by a cu/VAC probe laser and photodiode.

We estimate the plasma density in the laser beam's focal region (0.25 cm from the initial wire position) by assuming that all the initial wire material is vaporized and bounding the volume of the expanding plasma with dimensions drawn from measured data. The axial length is unfolded from the Faraday cup reading. One transverse dimension is fixed by the electrodes and the other determined from witness plate data. On this basis, the particle density projected into the laser beam path is slightly greater than $10^{21}/\text{cm}^3$. The plasma or electron density can be appreciably higher depending on the degree of ionization at that location. This plasma volume has been estimated to be large enough to prevent burnthrough.

Using a radiotracer technique, we found that fewer than 10^{10} atoms/cm were deposited on the optics per shot, precluding damage to the optics. Our early experiment, however, did not have a nozzle and did contaminate the optics. We were therefore led²³ to incorporate the nozzle and use a higher plasma velocity to close the shutter in the required time.

Conclusions. We have examined a plasma shutter for use on Nova to replace the expensive Faraday rotators. The principle is burst and expansion of a wire to create an opaque plasma. The wire is located in a slot that functions first to contain the plasma during heating and then to direct it into a narrow solid angle. The wire is driven by a rapidly rising current, which is required to superheat the plasma significantly above its sublimation temperature. The continually rising current in a rail-gun geometry magnetically propels the plasma to a higher final directed velocity than that attributed to heating alone.

The operating point in this experiment was dictated by our application for a shutter. For this operating point, the plasma was projected into a wedge whose mean angle was less than 20 deg as measured by witness plates and whose final mean velocity was 2.2 cm/ μs as recorded by a Faraday cup. This result is in good agreement with numerical model predictions and streak camera measurements. Also, contamination of the optics by debris is minimized.

We are now developing a larger version of the shutter for Nova and will conduct high-power tests on the Nova prototype. An automatic wire changer and digital precheck circuits are being incorporated in the prototype. The shutter, which will eliminate

output Faraday rotator polarizers for Nova, provides a significant cost saving and increase in system efficiency.

References

20. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-74 (1975), p. 169, and *Laser Program Annual Report—1976*, UCRL-50021-76 (1977), p. 2-79.
21. H. Bacchi and J.C. Pauwek, *Proc. 9th Internat. Conf. High Speed Photography*, Denver, Colo., August 2-7, 1970, p. 489.
22. P. Koert, *FUSE: A Computer Simulation of an Exploding Foil Flyer Plate System*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-81363 Preprint (1978).
23. L. P. Bradley, W. L. Gagnon, and B. M. Carder, *Proc. 7th Symp. Eng. Problems in Fusion Research*, Knoxville, Tenn., October 15-28, 1977, p. 1666.

Author

L. Bradley

7.2.6 Rod Amplifiers

The Shiva laser system uses 47 rod amplifiers, which have performed to design specifications. However, several design improvements giving greater operational reliability have been implemented during the year. Two of most significant, both involving better protection against fluid

Fig. 7-32. Beam from the output end of an alpha rod amplifier that had leaking O-ring seals. Notice the heavy breakup of the beam perimeter. This effect can only be photographed when the rod flashlamps have been fired, thereby momentarily increasing the pressure in the index matching fluid.

Bellville spring maintains compression on the O-ring, automatically compensating for set. Figure 7-34 shows a section view of the gland.

Trigger rods were installed in the 2.5-cm (α) rod amplifier adjacent to the flashlamps. These rods, located 2 mm away from and parallel to each lamp, provide repeatable lamp triggering down to 12 kV, allowing the amplifier gain to be adjusted from 150 (at 22 kV with ZnCl + SmCl as the index matching fluid) to 12 (at 12 kV with water as the fluid). Figure 7-35 shows a flashlamp assembly with trigger rods installed.

These modifications increased the rod amplifier lifetime to more than 1000 shots and greatly increased the firing reliability when lower voltages were selected.

Authors

H. Patton

D. Wentworth

7.2.7 Large-Aperture Pockels Cells for System Isolation

Large solid state laser systems require fast-acting isolation devices between successive amplifier stages to suppress amplified spontaneous emission and prevent unwanted chain oscillations. Electro-optic crystals (Pockels cells) placed between polarizing elements are such devices; they have been used effectively on both Argus and Shiva in clear apertures up to 5 cm. For Nova, system design requirements call for developing Pockels cells of at least 10-cm clear aperture, as well as faster and more reliable means for driving them. In this section we describe our progress in 1978 toward these ends.

Several conceptual studies relating to fast (≥ 20 -ns rise time), large-aperture (≤ 10 -cm) Pockels cell switches were undertaken. The most conservative concept simply scales the dimensions of the cylindrical-ring-electrode (CRE) design used for Shiva.²⁴ The Shiva Pockels cell has a 5-cm clear aperture and requires a crystal about 7 cm long. Cleveland Crystals is growing several KD*P crystals under contract to LLL, which will be large enough to fabricate a 10-cm aperture CRE Pockels cell (which is about 15.0 cm in length). The estimated growth time is about eight months; thus, the crystals will not be available until about the middle of 1979. Although techniques are known

that might shorten the growth time, the impact on the optical quality of the as-grown crystals is not yet well characterized.

To get around the need for such large crystals, several new concepts aimed at reducing the crystal length are being explored. One of the most promising makes use of high-conductivity transparent liquid electrodes across the face of the (KD*P) Pockels cell crystal. In a preliminary study by Eyring Research Institute,²⁵ D. J. Thorne identified several organic liquids that are chemically compatible with KD*P, can be refractive index-matched, and are characterized by resistivities in the range 30 to 40 Ω -cm. Now, if a window were used to isolate the KD*P from the liquid electrode, then significantly lower resistivities (3 to 4 Ω -cm) might be obtained from other liquids. A second study with Eyring Research Institute was initiated in September 1978 to explore isolated liquid electrodes. The results of this study will be available early next year; however, some preliminary conclusions, similar to those above, have already been reached.

A third concept for large-aperture (and thin-crystal) switches makes use of external electrodes and contiguous dielectrics to "push" the fields to get maximum field uniformity in the crystal. Our preliminary studies indicate that uniform electric fields can be generated with external electrodes; however, one must pay a heavy penalty in drive voltage (typically an order-of-magnitude increase to > 30 kV). This concept is not particularly attractive at present.

Under consideration also are grid-electrode designs, which require an electrode pattern to be placed within the clear aperture of the crystal. For very large-aperture switches that may require segmented crystals, the grid-electrode technique may offer some advantages; however, diffractive effects related to electrode blockage of the beam are presently discouraging.

Finally, low-resistivity, high-damage-threshold indium/tin oxide films have been developed for LLL at Battelle. If these films can be developed with inherently low absorption at 1.05-1.06 μ m, large-aperture Pockels cells could be built with electrodes on the inside of the cell window. Tests on film performance in small-aperture cells will be completed early next year. The results will be used to design prototype large-aperture Pockels cells.

Concurrent with these studies, we have developed reliable fast-driver circuits with enough

Table 7-4. Eimac tube types of interest.

Parameter	Tube type		
	8940	8941	X2172
Plate voltage, kV	4.5	15	25
Maximum current, A	25	40	40
C input, PF	16	14	16
C output, PF	0.11	0.11	0.2
M	65	200	500

power capability to provide the electro-optic switching speeds required by such cells. These circuits are now being implemented on both Argus and Shiva; they are described in the following paragraphs.

Eimac has recently extended the development of their planar triode product line to include tubes with significantly higher plate voltage and peak cathode current capability. This development makes the application of these tubes to a number of our fast high-voltage switching tasks very attractive.

Table 7-4 lists the three tube types of most interest to us, along with some of their more important characteristics. These data are also shown in Fig. 7-36 in terms of peak power switching

capability. It should be noted that the 8941 and X2172 both have peak power capabilities approaching 1000 kW. This is significant because larger Pockels cells will require similar power to achieve rise times in the nanosecond range.

These tubes offer the advantages of very low jitter (≈ 100 ps), long life (10,000 h is typical), and a high degree of insensitivity to voltage transients.

We have designed and tested a planar triode pulse amplifier that switches 10-mm-aperture Pockels cells with an optical rise time of 2.5 ns. For

this preliminary test, rise time was limited by the driver input pulse, not by the planar triode. Figure 7-37 shows the pulse amplifier circuit used to drive the 10-mm Pockels cell. The 8940 planar triode is configured as a grounded cathode amplifier biased just beyond cutoff. Bridge-T constant resistance networks are used to mask both the input capacitance to the tube and the shunt capacitance of the Pockels cell. This network transforms these capacitances into pure resistances independent of frequency. The bridge-T network is one of a family of lumped-constant lines developed for distributed amplifier applications. Within this family, the bridge-T provides the highest gain-bandwidth product, eliminates the need for terminating half sections, and permits the network to be terminated

resistively. The image impedance of the bridge-T network is resistive and independent of frequency. A derivation of this network is included in one of the first papers on distributed amplifiers²⁶; various equivalent networks are shown in Fig. 7-38.

For the circuit shown in Fig. 7-37, the end-to-end capacitance of the Pockels cell is 15 pF. Referring to Fig. 7-39, if Z_0 is chosen as 200 Ω , then $L = 0.6 \mu\text{H}$ and the network cutoff frequency is 100 MHz. A similar network can be designed for the grid circuit with $Z_0 = 50 \Omega$. The load impedance for the planar triode is then 200 Ω resistive. For a half-wave voltage at the Pockels cell of 3.5 kV, the peak current is 17.5 A. Figure 7-40 shows a load line for this case on the constant current characteristics for the 8941. The grid must be driven to

Fig. 9-49. Bridge chart for bridge-T constant resistance networks.

Fig. 7-45. Typical constant current characteristics for the 6D4 planar triode.

about 70 V positive to achieve the necessary plate-voltage swing and peak current. The measured voltage pulse at the Pockels cell is shown in Fig. 7-41.

These techniques can be extended to larger aperture Pockels cells, with relatively high end-to-end capacitances, by sharing total capacitance through several bridge-T networks, each driven by a planar triode. Alternatively, several networks might be driven in parallel by a single planar triode. The final arrangement will be determined by trading off the requirements of bandwidth (rise time), terminating impedance, and voltage and current capability of the driving tubes. We foresee no substantial impediments to realizing rise times less than 10 ns with Pockels cells of 10-cm clear aperture.

References

24. M. A. Summers and B. C. Johnson, *Design and Performance of Large Aperture KD*P Pockels Cells*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-79952 Preprint (1977)(prepared for submittal to Electro-Optical Systems Design Conference/International Laser Exposition, Anaheim, Calif., October 25-27, 1977).
25. D. J. Thorne, *Final Report: Liquid Ribbon Electrodes for Pockels Cells*, Eyring Research Institute (prepared under contract for Lawrence Livermore Laboratory, UCRL-13798).
26. E. L. Ginzton, W. R. Hewlett, J. H. Jasberg, and J. D. Noe, "Distributed Amplification," *Proc. I.R.E.*, August 1948, pp. 956-962.

Authors

W. E. Martin
M. M. Howland
S. J. Davis

7.3 Optical Materials

Optical materials dictate the design and performance of high-power lasers. During the past several years, we have had an extensive effort devoted to the discovery and characterization of improved optical materials for fusion lasers. This work has been reviewed in the 1977 Annual Report. Our major goals for 1978 in support of Nova have been the development of prototype neodymium (Nd)-doped fluorophosphate laser glass and the search for more damage-resistant optical coatings.

Fluoride glasses, because of their small non-linear refractive index n_2 , good energy storage, and moderate stimulated emission cross section, are well suited to the requirements for large, parasitic-limited Nd^{3+} disk amplifiers. Beginning with known fluorophosphate glass compositions having n_2 values $\leq 0.7 \times 10^{-13}$ esu, we subsequently identified mixed fluoride glass compositions that contain only a few mole percent phosphate and that have lower n_2 values ($\approx 0.5 \times 10^{-13}$ esu). This further reduced the problems of self-focusing, while preserving favorable spectroscopic properties and laser parameters. Having established the glass composition, we concentrated on

- Producing large, high-optical-quality pieces of the glass.
- Increasing the threshold for laser-induced damage.
- Developing satisfactory edge claddings.
- Formulating techniques for optical finishing.

We have made progress on all of the above objectives. As shown in Fig. 7-42, Nd:fluorophosphate glass disks ($34 \times 64 \times 5$ -cm) have now been successfully cast by three glass companies (Hoya, Owens-Illinois, and Schott). High damage thresholds have been achieved in small experimental melts, but further work is required to increase the damage thresholds of glass for large production melts. Two edge claddings—frit and monolithic—have been applied to the new fluorophosphate glasses; results to date indicate that the edge cladding requirements can be satisfactorily met. The low-index fluorophosphate glass, being a new glass with different physical properties, has necessitated experimentation with optical finishing processes. Again, we have obtained encouraging progress toward achieving good optical surfaces. §7.3.1 reviews the fluorophosphate laser glass work.

Fig. 7-42. New low-index fluorophosphate laser glass disk ($34 \times 64 \times 5$ cm). Vitreous edge-cladding is added to suppress parasitic oscillations.

We have also continued our investigation of fluoroberyllate glasses. These ultralow n_2 , ultraviolet transmitting glasses may be useful in future laser systems. Corning Glass [under contract to the Department of Energy (DOE)] has produced inclusion-free, high-damage-threshold fluoroberyllate glass and disk sizes ranging up to 20-cm diam by 3-cm thick. To quantify the moisture resistance of these glasses, we compared the solubility in water of some fluoroberyllate compositions with other optical glasses and crystals.

To extend our survey of Nd-doped glasses, we examined several tellurite glasses, including one with the highest stimulated emission cross section we ever observed. This high cross section arises in part from the high refractive index of these glasses,

which introduces a concomitant high nonlinear refractive index.

We have now surveyed the spectroscopic properties of several hundred Nd-doped glasses. To disseminate this information, we prepared a loose-leaf binder containing a condensed 4-page data summary on each of approximately 200 glasses. This book, created from computer-generated camera-ready copy, relied heavily on our computer-based laser glass data correlation system. Data summaries of new glasses will be added in the future.

Looking ahead toward the optical materials requirements of lasers operating at shorter wavelengths and longer pulse durations, we are assembling apparatus to explore the spectrum of two-photon absorption in wide bandgap materials.

Also, we have examined other contributions to self-focusing such as electrostriction and anomalous dispersion. For longer pulses, the relaxation rate of the terminal laser level of Nd^{3+} affects energy extraction. In the 1977 Annual Report, we described an experiment to measure this rate as well as detect possible excited-state absorption and spectral hole burning. We illustrated this experiment for ED-2 silicate glass. In 1978, we measured the relaxation rates for phosphate and fluorophosphate glasses.

Glass lasers operate on inhomogeneously broadened transitions, something not evident in lasers operating under conditions of small-signal gain. However, under large-signal or saturated gain conditions, spectral hole burning in the gain profile and a nonuniform rate of energy extraction may occur. We have used a simple technique of laser-induced fluorescence line narrowing to demonstrate that Nd^{3+} laser transitions in glass at ambient temperatures are not effectively homogeneous and that cross-relaxation between ions in spectrally different sites is slow. To quantify these effects and their consequences for laser gain saturation, we are using the homogeneous and inhomogeneous line widths, transition probabilities, and energy levels obtained from other fluorescence line-narrowing studies to model the distribution of Nd^{3+} energy-level schemes. Subsection 7.3.2 presents other applications of laser-excited fluorescence to probe the local fields and interactions in amorphous materials.

Damage to optical components limits the energy output from Argus, Shiva, and Nova. The antireflection coatings (AR) used on lenses throughout Argus and Shiva are particularly vulnerable, because they experience the highest fluence and have the lowest damage threshold. The Nova design uses bare (uncoated) optics at critical locations. This increases the system's damage immunity by more than a factor of 2 and uniformly stresses coated and uncoated surfaces. As discussed elsewhere, present production coatings are just barely adequate to meet Nova requirements. We can obtain a significant increase in Nova performance as well as in present operating system performance by obtaining improved coatings.

We have conducted numerous experiments to improve the damage thresholds and to provide empirical scaling laws needed for laser design. Our experiments, reviewed in §7.3.3, include (1) accurate measurement of the damage thresholds for different substrates, surface preparations, coating materials,

and coating designs; (2) determination of the causes of damage; and (3) identification and further development of the most promising techniques. Significant thresholds measured for 1-ns, 1064-nm pulses are

- Gradient refractive index antireflection surfaces—12 J/cm².
- Silicon dioxide (SiO_2) overcoat layers on high-reflection coatings—15 J/cm².
- SiO_2 /tantalum pentoxide (Ta_2O_5) antireflection coatings—13 J/cm².

A meeting was held at Lawrence Livermore Laboratory (LLL) in July 1978 to review the current status and future requirements for high-damage-threshold optical coatings. The program underway at LLL and external programs funded by LLL and the DOE Office of Laser Fusion were presented to about 100 attendees from industry, universities, and other government laboratories.

In addition to the above activities, three research programs are supported by the Office of Basic Energy Sciences, DOE, under their Materials Sciences Program. Their titles are

- Low-Index Optical Materials Research.
- Optically Induced Damage in Transparent Dielectric Materials.
- Laser-Excited Fluorescence Studies in Amorphous Solids.

These programs complement those of the laser fusion program by exploring basic phenomena of potential importance for laser materials. As an example, to gain further insight into the local environment at a Nd^{3+} site in a glass and its consequences for laser performance, we have initiated Monte Carlo simulations of glass structure.

Author

M. J. Weber

7.3.1 Laser Glass Development

Fluorophosphate Glasses. We concentrated our efforts to develop Nd-doped fluorophosphate glass for Nova on four areas during 1978:

- Increase glass size.
- Formulate a technique for finishing the glass.
- Find a suitable edge cladding.
- Increase the threshold for laser damage.

We did only a bit more investigating of compositional-dependent variations in the spectroscopic properties of these glasses; the previous results are discussed extensively in the 1977 Annual Report. In addition, we designed an AR coating for fluorophosphate laser glass.

We received six large (34- × 64- × 5-cm) edge clad fluorophosphate laser disks from Hoya, Owens-Illinois, and Schott; an example is seen in Fig. 7-42. These disks were purchased for test purposes as part of our fluorophosphate development program (see 1977 Annual Report). We are currently measuring the optical quality, spectroscopic properties, and performance in an amplifier. The resulting data will establish what additional development is required. Some preliminary results have been obtained. The optical quality of these disks varies from horrendous (presence of large amounts of striae) to good (homogeneities of $\pm 1.3 \times 10^{-6}$ over 25 cm). Smaller (22 cm × 42 cm) disks are of higher quality. The glass companies believe that high quality 34-cm disks are obtainable based on their experiences in melting the present disks.

Spectroscopic measurements of the disk properties agreed with previous data from small research melts. We tested the disks in a 34-cm box amplifier.

In the optical glass market, fluorophosphate glass is a new development. As a result, little was known about techniques required to finish and polish this glass. Thus, we supported programs internally and with outside vendors to establish a fluorophosphate polishing process. Our goal was to produce low-scattering surfaces with high laser-damage thresholds.

We made substantial progress in fluorophosphate finishing during the past year. First, we found the major steps in the finishing process necessary for an adequate polish. Second, to facilitate surface characterization, we developed a new instrument for measuring surface roughness. Third, vendors developed handling methods for this relatively fragile glass.

Cracks propagate readily in fluorophosphate glass; also, it is soft and more chemically active than silicate glass. A year ago, most samples were heavily sleeked, scratched, and covered with fine pits lying generally along the traces of previous scratches. We obtained good surfaces with difficulty and only occasionally (20 to 30% of the time). Also, the only polishing compound identified as acceptable for

fluorophosphate was not suitable for silicate glasses. This was a serious drawback, because the process used so successfully to date for polishing large laser flatwork depends on the simultaneous polishing of large, temperature insensitive cer-vit or fused silicate truing tools.

During the past year, we found a combination of pitch and slurry that will simultaneously and consistently polish both fluorophosphates and silicates. This process appears usable and scalable, but it needs more development.

Samples of small-to-moderate size have been placed with outside optical finishing shops for a best effort polish. This program has enabled these vendors to acquire the necessary handling techniques. The vendors have demonstrated excellent to superb workmanship and figure control with these smaller samples.

However, we and these vendors observe higher scattering from fluorophosphate glass surfaces than from polished silicate surfaces. Surface profile measurements confirm that the fluorophosphate surfaces are three to four times rougher than those of the best silicate glasses. Recently, G. Som-margren has developed a roughness meter capable of resolving root mean square roughness in the angstrom range with a 10-min turnaround time. It is presently engaged in providing relative roughness values in terms of which processes can be compared. This permits systematic research and improvements. We are establishing an in-house metrology service for our vendors based in part on this instrument.

The development of a suitable edge cladding for fluorophosphate laser glasses continued in 1978 and has resulted in claddings that meet the Nova requirements. To suppress parasitic oscillations in a disk, the edge cladding must not reflectively feed-back the 1.06- and 1.33- μ m fluorescence present in a pumped disk. The reflection from the edge cladding is minimized by:

- Matching the refractive indices of the cladding glass and the laser glass, and using dopant ions in the cladding glass to absorb 1.06- and 1.33- μ m light.

- Keeping the bubble density, or porosity, of the cladding low.

The last condition is important because bubbles or voids, especially those at the cladding-laser glass interface, make large contributions to the reflectivity.

Development efforts on edge claddings have concentrated on two types, "frit" and "monolithic." These are distinguished by their application techniques. The frit cladding is produced by a multi-step process:

- Melt the raw materials and cool them to form a glass.
- Grind this glass into powder and add an organic solution to act as carrier and binder.
- Spray this heterogeneous mixture onto the disk edge.
- Fire the laser disk close to its annealing temperature to fuse the (lower melting temperature) cladding glass.

The monolithic cladding is applied by simply melting and pouring the cladding glass into a mold surrounding the laser disk.

The composition of the monolithic cladding can be adjusted to give perfect index matching and reasonable absorption; its thickness can be any convenient value. Bubbles within the cladding are not a problem, and the formation of interface bubbles can be prevented by proper cleaning and handling techniques. Its main disadvantages are the requirement for special molds plus the need to grind down the cladding to its final thickness. The frit cladding process, on the other hand, needs less initial capital investment. But, it has great difficulty in meeting the cladding requirements listed above, primarily because of its greater porosity.

During 1978, we supported development of both types of cladding. Battelle Memorial Institute, with LLL funding, and three glass companies—Hoya, Owens-Illinois, and Schott—with internal funds, have worked on frit cladding for fluorophosphate glass. Owens-Illinois, partially with LLL funds, and Schott have developed monolithic claddings that are very promising.

In 1977, R. Bennett and K. Shillito of Battelle undertook the task of developing frit claddings for fluorophosphate glasses. During the initial phases of this work, it became clear that meeting the index matching requirement would be difficult because the low-index cladding glass compositions tend to devitrify upon firing.²⁷ During 1978, they determined that control of the atmosphere during fusion firings was necessary to obtain reproducible melts.²⁸ Firing in dry rather than in ambient atmospheres produced much better cladding microstructures. Moisture is thus strongly suspected as the devitrification culprit. Also, firing in dry oxygen or dry

air atmospheres gave better fusion results than firing in dry argon or dry nitrogen atmospheres. Although it has not been proven, we suspect that oxygen may be incorporated into the cladding during fusion, thereby stabilizing the glass (at the expense of a higher index).

Table 7-5 lists the edge cladding glass compositions developed by Battelle for the fluorophosphate laser glasses: LHG-10, E-309, and LG-812. The claddings all have an index mismatch of 0.06 to 0.08 (resulting in a reflectivity of ~0.1 to 0.25%). This is only marginally acceptable. Attempts to lower the refractive index of the cladding glass have thus far resulted in devitrification.

The Cu^{2+} ion used to absorb 1.06- μm light in edge claddings also absorbs visible light. Thus, these claddings are subjected to high thermal loading from xenon flashlamp radiation. Ideally, we need an ion that absorbs 1.06 μm but passes visible light. Thus, Battelle performed a small study on other absorbing ions in edge cladding glasses. The ions (Sm^{3+} , Pr^{3+} , Dy^{3+} , V^{3+} , and Fe^{2+}) were substituted into the glass compositions. In all cases, absorption proved to be inadequate at dopant levels that would allow homogeneous glass fabrication. Under these conditions, the glass properties (i.e., refractive index and softening point) were driven in the wrong direction. Thus, Cu^{2+} is still the ion of choice.

Owens-Illinois and Schott have applied good monolithic claddings to fluorophosphate glass. Under LLL contract, Owens-Illinois produced 10- $\times$ 20-cm and 22- $\times$ 44-cm disks with monolithic claddings. An added advantage of the monolithic cladding is that split or segmented disks can be made. Figure 7-43 shows the edge of a monolithically clad B-disk.

We tested both types of edge cladding for their reflectivity and ability to withstand flashlamp irradiation. Further, amplifier tests of the 34-cm fluorophosphate disks gave us data on the survivability of the frit cladding under loading by amplified fluorescence.

We measured the reflectivities at 45° of several edge claddings in a standard test apparatus with a Nd:yttrium-aluminum-garnet (YAG) laser source. We also measured both the specular reflection and scattered light into a 0.325-sr solid angle. Table 7-6 lists the results. The reflectivities of the monolithic claddings are much lower than those of the frit type because of better index match and lower porosity.

Table 7-5. Properties and compositions of edge claddings for fluorophosphate glass.

Parameter	Laser glass (cladding glass)		
	LG-812 (LSP-13-2aB)	E-309 (LSP-13-2aD)	LHG-10 (LSP-X ₂ D)
Composition, wt%			
P ₂ O ₅	53.7	53.7	56.4
B ₂ O ₃	3.6	3.6	4.4
Al ₂ O ₃	0.9	0.9	0.9
Na ₂ O	9.0	9.0	9.3
K ₂ O	9.0	9.0	5.7
ZnO	2.7	8.1	4.4
MgO	5.4	5.4	3.5
BaO	5.4	—	3.5
CuO	5.4	5.4	5.3
F ₂	5.1	5.1	6.5
Laser glass index	1.432	1.443	1.459
Cladding glass index	1.51	1.51	1.52
Fusion temp, °C	415-435	415-435	415-425

Fig. 7-43. Edge of a "monolithically clad" fluorophosphate disk (10 × 20 cm). The scale shown is in centimeters.

Table 7-6. Reflectivity and scattering of edge claddings at 45°.

Sample ^a	Type		Specular	Scatter into 0.325 sr
B: LHG-10, ELP 10	Frit		$<2 \times 10^{-5}$	1.2×10^{-4}
B: E309, OI-FP-D-011 split disk	Mono	Worst	$<2 \times 10^{-5}$	2.6×10^{-4}
		Typical	$<2 \times 10^{-5}$	1.3×10^{-4}
B: E309, OI-FP-D010	Mono	Worst	$<2 \times 10^{-5}$	1.5×10^{-4}
		Typical	$<2 \times 10^{-5}$	6.4×10^{-5}
B: E309, D5-NO-4	Mono		$<2 \times 10^{-5}$	$<2 \times 10^{-5}$
B: E309, D5-5	Frit		1.9×10^{-4}	1.9×10^{-2}
C: ED-2	Frit		1.8×10^{-3}	1.4×10^{-2}
C: E309	Mono	Worst	$<2 \times 10^{-5}$	1.5×10^{-4}
		Typical	$<2 \times 10^{-5}$	5.4×10^{-5}

^aB and C refer to 10- × 20-cm and 20- × 40-cm disks, respectively.

We subjected both cladding types to a flashlamp loading of 10 J/cm²; they sustained no visible damage. However, some of the frit claddings on the large 34-cm disks were damaged, presumably from amplified fluorescence, during amplifier tests. On two of the disks, the claddings were almost completely removed; we determined that these claddings were inadequately fired. Two other disks had no visible cladding damage, while a fifth disk lost cladding at the major axis ends.

We believe that the high absorption coefficient of the cladding at 1.05 μm results in a huge thermal gradient at the laser glass-cladding interface. A thermal analysis indicates that a temperature rise of 200 to 400° occurs; thus, repeated thermal stressing could indeed fracture the cladding on the laser glass. A more detailed analysis is in progress.

From our test results, we conclude that monolithic edge cladding can meet Nova requirements. Frit cladding is only marginally acceptable and still has several problems that must be solved. We expect that, in the future, large disks will have monolithic cladding.

Early in 1978, we measured the damage threshold of fluorophosphate glasses for 1-ns, 1064-nm laser pulses. The bulk thresholds were very low, <4 J/cm². Because the design of the Nova laser calls for damage thresholds of >20 J/cm² on bare surfaces at normal incidence, we initiated an effort to isolate and correct the damage source. The glass companies investigated the dependence of damage threshold on melting procedures and raw material purity. Damage threshold measurements were done

in the Laser Damage Facility (§7.3.3); LLL and the National Bureau of Standards (NBS) used optical and electron microscopy to examine the samples.

We made damage measurements using techniques previously described in detail.²⁹ We obtained 1-ns, 1064-nm pulses by gating out a portion of a 30-ns, Q-switched Nd:YAG laser pulse. Pulses were subsequently amplified in a series of Nd:glass rod amplifiers. A collimated beam of 2- to 3-mm diam (e^{-1}) was incident on the samples. The spatial profile of the beam at the sample was recorded for each shot using a vidicon and video disk recorder and an absolute flux computed by an online data reduction system.³⁰ We recorded the waveform of each pulse to insure constancy of pulse shape.

Bulk damage was detected by observation of induced light emission during irradiation and by permanent alteration of bulk scattering levels. Samples with high bulk damage thresholds were examined by Nomarski microscopy to determine surface damage thresholds.

We initially irradiated samples at flux levels of 4 to 6 J/cm². If damage was induced on the first firing at this level, we discontinued the test. If the sample failed to damage at 4 to 6 J/cm², we continued the test until a threshold was determined.

Samples consisted of two types of fluorophosphate glass (Table 7-7 gives their general compositions). The principal differences between the Group I and Group II fluorophosphate compositions are a reduction of the oxygen/fluoride ratio and an increase in the proportion of low atomic number cations. Both of these differences result in a

Table 7-7. Refractive index, Abbe number, and approximate compositions (mol %) of fluorophosphate glasses tested for damage.

Glass	Type	Source	n_D	ν
Fluorophosphate I	FK-51, LG-800	Schott	1.487	84
	E-123	Owens-Illinois	1.485	84
Fluorophosphate II	FK-54, LG-812	Schott	1.431	93
	LHG-10	Hoya	1.459	90
	E-309	Owens-Illinois	1.436	90

Typical composition		
Compound	Fluorophosphate I	Fluorophosphate II
AlF_3	20	32
LiF	12	—
NaF	1	12
KF	—	—
MgF_2	7	8
CaF_2	16	27
SrF_2	23	8
BaF_2	12	8
$Al(PO_3)_3$	7	5
Al_2O_3	2	—

lowering of linear and nonlinear refractive indices.

The fluorophosphate samples in most cases were polished using cerium oxide and standard finishing techniques. However, for surface damage measurements, we polished some samples with zinc oxide, which produces excellent surfaces on fluorophosphate glasses.³¹ The fluorophosphate samples were obtained from both small (<1 liter) and large (10 to 20 liter) melts poured from platinum crucibles.

Table 7-8 summarizes and compares threshold data for bulk and surface damage of fluoro-

phosphate glasses with BK-7 and SiO_2 . For fluorophosphate I, the results represent typical values; for fluorophosphate II, the best values measured to date are given. Large variations in bulk damage threshold were seen in the fluorophosphate II glasses. For example, the flux levels at which bulk damage is observed in fluorophosphate II glasses (plotted in Fig. 7-44) range over a factor of 10.

Bulk damage in fluoride glasses is evidenced by the presence of tracks in the region exposed to the laser beams. These tracks are caused by scattering from a large number of approximately 2- μ m-diam

Table 7-8. Observed damage thresholds for 1.0-ns, 1.064-nm laser pulses incident at 10° from normal.

Material	Damage threshold (J/cm^2)		
	Bulk	Rear surface	Comments
Borosilicate (BK-7)	>40	20	PH-4 quality
Fused silica	>40	22	Optical grade
Fluorophosphate I (FK-51)	>20	20 ± 3	
Fluorophosphate I (LG-802)	>20	13	40 J/cm^2 at 40 ns (Ref. 32)
Fluorophosphate II (E-309)	>25	16 ± 2	Small melt

Fig. 7-44. Measured bulk damage thresholds of fluorophosphate glasses for 1.0-ns and 1064-nm laser pulses.

Fig. 7-45. Possible damage center in fluorophosphate glass. (Crystalline inclusion has more Na and less P than glass.)

spherical inclusions. Identification of the site has not been made as yet because of the difficulty in isolating it on the surface for x-ray analysis.

We and the vendors are attempting to (1) identify the damage center and its composition and (2) determine the melting conditions or raw material purity or both under which low damage thresholds occur. Possible microscopic damage centers can be divided into three categories.

- **Metallic Inclusions.** These can reach very high temperatures under laser irradiation.

- **Bubbles.** The index discontinuity produces optical field enhancement, which could lead to damage at the bubble surface.

- **Crystals.** With associated voids, large optical field enhancements are possible. Also, the crystal-glass interface is a region of large compositional gradients. It may contain impurities, which, along with associated voids and stress fields, are deleterious for damage threshold.

Many fluorophosphate samples were examined by optical and electron microscopy for possible damage-inducing defects. We observed bubbles ranging in diameter from 2 to 70 μm in many samples. Also, crystallites of various shapes and varied composition appeared on fractured surfaces of fluorophosphate glass, an example of which is shown in Fig. 7-45.

We eliminated bubbles as a possible damage source by examining them before and after laser irradiation with optical microscopy; we found no change in the bubble region. Also, a series of samples containing different amounts of bubbles showed a correlation of high-damage-threshold values with high bubble density.

Platinum (Pt) inclusions in silicate laser glasses have historically been a severe damage problem.³³ The techniques of x-ray fluorescence and emission spectroscopy have revealed little evidence of Pt in fluorophosphate glass. Analyzed levels of Pt in fluorophosphate glasses are <1 ppm; one analysis gave <70 ppb.³⁴ On the other hand, even at these concentrations, small (<100 nm) Pt particles could be present.

Iron (Fe) is a common impurity in the fluoride raw materials. Local concentrations of Fe (>1%) have been seen in some samples with only 30 ppm of Fe. If the Fe is in metallic form, its absorption is sufficient to cause damage.

We extensively examined defects and inclusions in fluorophosphate with scanning electron-beam microscopy in collaboration with LLL's Chemistry Department. Initial studies were done on polished surfaces. However, the possible contamination of the surface by the polishing components, along with the difficulty of surfacing small inclusions, caused us to abandon this technique in favor of fractured surfaces. Defects in glass are more easily revealed on a fractured surface because the fracture propagation is affected by the large compositional inhomogeneities, stress fields, and voids associated with inclusions and crystals in the glass. In general, glass samples with high densities of "dirt" have

Fig. 7-46. (a) A fluorophosphate glass with low damage threshold ($< 4 \text{ J/cm}^2$). (b) A fluorophosphate glass with high damage threshold ($> 25 \text{ J/cm}^2$).

rough fractured surfaces, whereas the fracture of "clean" glass samples is relatively smooth (Fig. 7-46).

We have observed that fluorophosphate glass samples with large compositional variations on a $1\text{-}\mu\text{m}$ scale have low damage thresholds. Also, samples with high thresholds had no differences in composition over their fractured surfaces. The sample shown in Fig. 7-46(a) has areas with high Fe content. In a volume of this same sample that had suffered massive damage at 4 J/cm^2 , areas with the appearance of melted material were seen, as shown in Fig. 7-47. Thus, the experimental evidence strongly suggests that an absorbing inclusion, perhaps

metallic Fe particles, is the source of the damage. Presently, we are still investigating the combination of impurity levels and melt conditions that produces the damage inclusions.

During 1978, we have measured damage thresholds of more than 60 sample glasses. Also, we have attempted to find a method of estimating damage thresholds without resorting to time-consuming, detailed damage tests. We and others have found that scattering of a helium-neon laser beam in fluorophosphate glass correlates with damage threshold values.³⁴ Table 7-9 illustrates this correlation. In this table, samples are divided into six classes based on the magnitude of scattering. It is

Fig. 7-47. SEM photomicrograph of a damaged region in fluorophosphate glass.

clear the low scattering is necessary, but not sufficient, for high damage thresholds. (The comparison of damage and scattering levels is complicated by the necessity of separating out the amount of scattering caused by bubbles, since these appear to have no effect on damage thresholds). Thus, the magnitude of scattering present in a fluorophosphate glass sample can act as a coarse screen for finding high-damage-threshold samples.

Based on the above evidence, we have drawn the following conclusions concerning the prospect for high-damage-threshold fluorophosphate glasses:

- Laser damage thresholds are sufficiently high for Type I fluorophosphates. (However, their spectroscopic and optical properties are not as favorable for use in large laser systems).

- High-damage-threshold Type II fluorophosphates are not intrinsically prohibited. However, high-threshold samples ($>23 \text{ J/cm}^2$) have only been obtained from small melts (<1 liter); 15 J/cm^2 has been measured in a few large (10 to 20 liter) melts.

- The effects of raw material purity and melt conditions on the damage threshold require more systematic study.

Table 7-9. Correlation between scattering intensities at 632.8-nm and 1-ns, 1.064-nm damage thresholds.

Scattering class (low to high)	Average threshold (J/cm^2)	Range (J/cm^2)	
1	13	8	>25
2	10	8	15
3	5	4	8
4	3.3	3	6
5	5-8 (high bubble content)	5	8

AR coatings are required on the rods and lenses used in high power lasers. Because fluorophosphate glass could perhaps be used for these components, we have investigated possible coating materials for this glass type. Fluorophosphate glass, because of its high thermal expansion coefficient, is susceptible to thermal shock. Thus, the coating should be applied at room temperature, if possible. We also desire the coating to be acid-strippable to avoid costly rework.

We successfully deposited a 3/4-wave-layer cold coating ($\text{MgF}_2\text{-Al}_2\text{O}_3\text{-MgF}_2$) on fluorophosphate rods. The coating has the following desirable properties:

- Refractive indices at $1.064\ \mu\text{m}$:
 - (1) Magnesium fluoride (MgF_2)—1.37.
 - (2) Aluminum oxide (Al_2O_3)—1.57.
- Reflectance per surface on substrates of index $1.40\text{--}1.52\text{--}0.1\%$.
- Damage threshold at $1\ \text{ns} \sim 5.5\ \text{J}/\text{cm}^2$.
- Acid soluble (no damage to substrate).
- Deposited in vacuum on room temperature substrate.

Thus, a useful AR coating is definitely available for fluorophosphate glass.

In summary, we have seen tremendous progress in fluorophosphate development in 1978. Glass, size finishing techniques, and edge cladding availability have all shown improvement. Undoped versions of this glass for use as a low index, low dispersion optical glass are commercially available from Schott and Hoya. However, the glass is not ready for production. Work is needed in all areas, particularly for the laser damage problem.

References

27. K. R. Shillito and R. B. Bennett, "Development of Claddings for Advanced Laser Glass Materials," Battelle Memorial Institute, Columbus, Ohio, Summary Report on SANL 605/003 (1978).
28. R. B. Bennett and K. R. Shillito, "Development of Claddings for Advanced Laser Glass Materials, Phase III," Battelle Memorial Institute, Columbus, Ohio, Summary Report on SANL 605/003 (1978).
29. D. Milam, "Laser-Induced Damage at $1064\ \mu\text{m}$, 125 ps," *Appl. Opt.* **16**, 1204 (1977).
30. W. L. Smith, A. J. DeGroot, and M. J. Weber, "Silicon Vidicon System for Measuring Laser Intensity Profiles," *Appl. Opt.* **17**, 3938 (1978).
31. N. J. Brown and R. T. Many, "Optical Fabrication of Fluorophosphate Laser Glasses," Lawrence Livermore Laboratory, Livermore, Calif., UCRL-81081 (1978).
32. O. Deutschlein, M. Faulstich, W. Jahn, G. Krolla, and N. Neuroth, *Appl. Opt.* **17**, 228 (1978).
33. R. W. Hopper and D. R. Uhlmann, "Mechanism of Inclusion Damage in Laser Glass," *J. Appl. Phys.* **41**, 4023 (1970).
34. P. Vergano, Owens-Illinois, private communication (May 1978).

Authors

S. Stokowski
M. Weber
R. Wirtensen
N. Brown

Major Contributors

W. Haller
R. Landingham
T. Quick
D. Milam
F. Rainer
J. Lynch
S. Roberts

Fluoroberyllate Glasses. We continued the exploration of beryllium fluoride (BeF_2)-based glasses discussed in previous annual reports. The following subjects were investigated in 1978:

- Threshold for laser-induced damage.
- Durability in water.
- Compositional studies to vary the wavelength of peak gain.
- Gain measurements of small cross section, long lifetime Nd glass.

Also, Corning Glass Works, under a contract funded by the DOE Office of Laser Fusion, has developed the technology to produce large, inclusion-free pieces of fluoroberyllate glass. Disks 20 cm in diameter and 3-cm thick of undoped and 2 mole % doped neodymium fluoride (NdF_3) have been cast; examples are shown in Fig. 7-48. (LLL has performed the optical polishing using facilities described in the 1977 Annual Report.) This success, combined with good transparency, ultralow- n_2 , excellent laser properties, and high damage threshold, has made these glasses very promising materials for visible and ultraviolet optical systems.

We performed damage tests of several representative beryllium fluoride glasses obtained from small melts. Low-index fluoride glasses are of interest to test empirical scaling laws for the dependence of laser damage on refractive index.³⁵ Damage threshold data for a large class of transparent dielectric materials indicate that damage thresholds are inversely proportional to the index of refraction.^{36,37} Because of their low indices, fluoride glasses and pure BeF_2 in particular have promise as very damage-resistant materials.

The two glasses studied most extensively were vitreous BeF_2 and a fluoroberyllate laser glass. Their compositions and sources appear in Table 7-10. Unlike fluorophosphate glasses, which are melted and poured from platinum crucibles, the fluoroberyllate glass was melted in a graphite crucible-mold. Thus, possible damage initiated by platinum inclusions was not an issue. The BeF_2 glass from UCLA was vacuum-distilled to improve purity and to remove water. Because of the hygroscopic nature of BeF_2 , the surfaces of this material were susceptible to water contamination. The other fluoroberyllate glass, however, had satisfactory chemical durability in normal atmospheres.

We rough-polished the glasses with $0.5\text{-}\mu\text{m}$ diamond powder and ethylene glycol on a pella pad.

Fig. 7-48. Disks of undoped and Nd-doped fluoroberyllate glass (20 cm in diam by 3 cm thick), melted by Corning Glass and polished at I.I.J..

The final polish was achieved using tin oxide and ethylene glycol on a lap made of a 1:1 mixture of 64 and 73 Gulgoz pitch. With good temperature control, satisfactory optical polish can be obtained. We also tried high-purity cerium oxide, but it was too hard and did not yield a good surface. Finished samples had areas $>1 \text{ cm}^2$.

Damage measurements were made using procedures previously described. We detected bulk damage by observing induced light emission during irradiation and permanent alteration of bulk scattering levels. Samples with high bulk damage thresholds were examined by Nomarski microscopy to determine surface damage thresholds.

Table 7-10. Observed damage thresholds of beryllium fluoride glasses for 1.0-ns, 1.064-nm laser pulses incident at 10° from the normal.

Material	Source	Damage threshold (J/cm ²)	
		Bulk	Rear surface
BeF ₂ (vitreous)	UCLA, LLL	6 ± 1	—
K-Ca-Al-BeF ₂	Corning	>25	12-15

Table 7-10 summarizes threshold data for bulk and surface damage. In early samples of fluoroberyllate glasses, the presence of seeds and solid inclusions (including graphite particles) had resulted in low damage thresholds of $\approx 7 \text{ J/cm}^2$. The use of vitreous carbon crucibles and better melting techniques has yielded excellent fluoroberyllate glasses with no inclusions visible by optical microscopy and the high thresholds reported in Table 7-10. In the case of glassy BeF₂, the presence of transition metal impurities and poor surface quality due to the hygroscopic nature of this material has contributed to low damage threshold; we do not believe this indicates the "intrinsic" limits for this material.

Thus far, the internal quality and surface finishes of our BeF₂ glass samples have been insufficient to test the validity of the empirical rule that low-index materials should have high damage thresholds.

The lack of good moisture resistance has deterred, in part, the consideration of BeF₂ glasses for optical systems. Vitreous BeF₂ is extremely hygroscopic. On exposure to air, it reacts with atmospheric water, resulting in surface clouding and a

sticky finish. Several workers have developed multicomponent fluoroberyllate glasses having improved moisture resistance. Subsequent studies have shown that durability can be increased by reducing the amounts of BeF_2 glass-former and alkali fluoride glass-modifiers and substituting alkaline earth and other modifier ions. The addition of a few weight percent of cerium fluoride (CeF_3) and NdF_3 was also reported to improve durability. Aluminum and yttrium trifluoride increased moisture resistance; but, they also increased the tendency for crystallization.³⁸⁻⁴⁰

To quantify and compare the moisture resistance of BeF_2 glasses with other optical materials, we measured the water solubility of several fluoroberyllate glass compositions, several optical and laser glasses, and representative fluoride and alkali halide crystals. A standard durability test procedure prescribed by the Inorganic Glass Section of NBS for fluorophosphate glasses⁴¹ was used

for all materials. The samples were cubic solids with edges of 1.0 cm. All faces of the sample were finished with 600-grit silicon carbide paper using ethylene glycol as the lubricant. We conducted the durability test in a 4-liter borosilicate beaker filled with 3 liters of deionized water. The water was stirred continuously with a Teflon-coated magnetic stirrer and maintained at $23 \pm 1^\circ\text{C}$ throughout the test.

Table 7-11 lists the time in water, initial weight, and weight loss for all materials studied. The solubility is given by the weight loss of the sample, normalized to 1.0 cm^2 surface area and 24 h. Dissolution can be hindered by the accumulation of glass dissolution products.³⁸ Less stable materials may also form protective coatings, and the solubility rate may change with time. We had not attempted to correct for these effects or for the change in surface area with time. The relative durability of BeF_2 -based glasses can also be altered

Table 7-11. Solubility of glasses and crystals in water at 23°C (sample surface area $\approx 6\text{ cm}^2$).

Material	Time (h)	Initial weight (g)	Weight loss (g)	Solubility ($\text{g/cm}^2/24\text{ h}$)
Fluoroberyllate glasses (mol %)				
100 BeF_2 (vitreous)	24	1.97659	0.39868	0.0661
99 BeF_2 +1 NdF_3	24	2.03198	0.47538	0.0788
92 BeF_2 +5 AlF_3 +3 NdF_3	24	2.17754	0.32876	0.0542
92.5 BeF_2 +7.5 AlF_3	24	2.06519	0.12795	0.0213
47 BeF_2 +27 KF +14 CaF_2 +10 AlF_3 +2 NdF_3	24	2.08710	0.38852	0.0646
34 BeF_2 +19 MgF_2 +10 CaF_2 +12 BaF_2 +25 AlF_3	24	3.20725	0.05873	0.0098
Other glasses				
BK-7 borosilicate	48	2.70759	nil	nil
ED-2 silicate	48	2.75164	0.00150	8.27×10^{-5}
EV-2 phosphate	48	2.90826	0.00144	1.14×10^{-4}
LHG-5 phosphate	48	2.88635	0.00209	1.65×10^{-4}
LHG-10 fluorophosphate	48	3.93363	0.00424	3.34×10^{-4}
Crystals				
MgF_2	24	3.49689	0.00022	3.5×10^{-5}
CaF_2	48	3.39653	0.00264	2.08×10^{-4}
LiF	6	2.82151	0.35297	0.225
NaCl	1/15	2.48981	1.08530	58.3
KBr	1/30	2.97890	1.63581	183.7

by changing the test conditions. This can be seen, for example, by comparing the results in Table 7-11 with those obtained for unstirred 50°C water.⁴²

Of the fluoroberyllate glasses, simple BeF₂ is very soluble. The addition of aluminum fluoride (AlF₃) to BeF₂ does improve the durability and also increases the hardness and elastic constants.⁴² The potassium-calcium-aluminum-neodymium multi-component fluoroberyllate glass is representative of compositions that have good resistance to crystallization and good laser properties.^{43,44} In a normal room or laboratory environment, this glass exhibits none of the surface deterioration characteristic of simple BeF₂.

The durability of this glass in the above test was low, however. The samples appeared clear in the water solution but developed a white opaque crust after removal. This suggested that an alkali-free "gel" layer might be on the surface as is observed in durability tests on soda silicate glasses.

The best of the fluoroberyllate glasses for durability was the one containing alkaline earths, no alkali, and a large quantity of AlF₃; this agreed with earlier conclusions. However, solubility was still higher than the most soluble of the other Nd laser glasses tested, a fluorophosphate glass. The solubility was also higher than that for crystalline calcium fluoride (CaF₂) or magnesium fluoride (MgF₂). On the other hand, when compared with

other fluoride and alkali halide crystals, including many used for optical components in the ultraviolet, visible, and infrared spectral regions, the moisture resistance of fluoroberyllate glasses is superior. Because fluoroberyllate glasses transmit from less than 160 to approximately 4000 nm,⁴⁵ they are potentially useful for many applications.

C. Baldwin of UCLA has prepared a series of Nd-doped simple binary alkali BeF₂ glasses with a composition chosen to maximize the alkali content. Spectroscopic properties associated with the ⁴F_{3/2} → ⁴I_{11/2} transition of Nd³⁺ appear in Table 7-12. The refractive index and predicted nonlinear refractive index exhibit a behavior characteristic of alkali ion variation. The Judd-Ofelt intensity parameters Ω, however, show only a small change, barely beyond experimental uncertainty. This can be contrasted with similar compositional series for silicate⁴⁶ and phosphate⁴⁷ glasses and for more complex fluoroberyllate glasses.⁴⁸ In these series, larger variations have been observed in the Ω's and resulting cross sections with alkali ion change.

The systematic decrease of effective line width in Table 7-12 contributes to a small increase in the stimulated emissions cross section with increasing alkali ion size. There is also a change in the total Stark splitting and in the relative transition probabilities between Stark levels. This is seen from

Table 7-12. Spectroscopic properties of Nd³⁺ in alkali fluoroberyllate glasses at 295 K [composition (mol %): 55 BeF₂, 44 MF, 1 NdF₃].

Parameter	Li ⁺	Na ⁺	K ⁺	Rb ⁺
n_D	1.312	1.308	1.323	1.339
$n_2, 10^{-13}$ esu	0.26	0.25	0.27	0.30
Intensity parameters (10^{-20} cm²)				
Ω ₂	0.47 ± 0.27	0.38 ± 0.33	0.87 ± 0.17	0.23 ± 0.25
Ω ₄	3.98 ± 0.40	4.28 ± 0.48	3.96 ± 0.25	3.98 ± 0.37
Ω ₆	4.89 ± 0.18	5.24 ± 0.22	5.21 ± 0.11	5.10 ± 0.17
⁴F_{3/2} → ⁴I_{11/2} fluorescence				
σ, 10 ⁻²⁰ cm ²	3.21 ± 0.14	3.89 ± 0.20	4.04 ± 0.11	4.02 ± 0.16
λ _p , nm	1047	1050.5	1050.5	1050
Δλ _p , nm	23.4	20.8	19.7	19.7
τ _R , μs	632	596	599	584

the relative widths and the change in peak of the ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ fluorescence for the lithium (Li) and potassium glasses shown in Fig. 7-49.

The fluorophosphate glasses for Nova have peak gain at about 1050 to 1051 nm. Because of the higher stimulated emission cross sections and lower n_2 values for fluoroberyllate glasses, they are attractive for initial high-gain amplifier stages (where parasites are not a limitation) if the peak wavelength mismatch is not severe. Several compositions in Table 7-12 and more complex compositions such as (mole %) 60 beryllium fluoride-32 potassium fluoride-6 cadmium fluoride have peak emission wavelengths of approximately 1050 nm. Thus, a laser amplifier chain combining the advantages of fluorophosphate and fluoroberyllate glasses is possible without suffering a large spectral mismatch.

Table 7-13. Peak wavelength λ_p , cross section σ , and line width $\Delta\lambda_{\text{eff}}$ of ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ emission, and calculated radiative lifetime τ_R of Nd^{3+} in different fluoroberyllate glasses.

Composition (mol %)	Peak wavelength λ_p (nm)	Cross section σ (10^{-20} cm^2)	Line width $\Delta\lambda_{\text{eff}}$ (nm)	Lifetime τ_R (μs)
100 BeF_2	1046	2.0	27.7	915
95 BeF_2 , 5 AlF_3	1046	1.6	29.0	1035
60 BeF_2 , 32 KF , 6 CdF_2	1046	3.8	20.0	600
49 BeF_2 , 27 KF , 14 CaF_2 , 10 AlF_3	1047	3.2	23.2	610

As noted previously, fluoroberyllate glasses are transparent over a wide spectral range. The improved ultraviolet transmission of these glasses makes possible added optical pumping of Nd^{3+} by means of higher lying $4f^n$ states. In Fig. 7-50, we show the near-ultraviolet absorption spectrum of Nd^{3+} in a fluoroberyllate glass. Using our VODEP xenon flashlamp pumping code, we have found that the added Nd^{3+} absorption bands accessible to optical pumping contribute a further 7% increase to the small-signal coefficient gain and stored energy.

Low stimulated emission cross section, long-fluorescence-lifetime, Nd-doped glasses provide good energy storage. Of the fluoroberyllate glass compositions we have investigated, simple BeF_2 exhibits these properties. To improve its atmospheric durability, one can add AlF_3 without greatly altering its spectroscopic properties. Table 7-13 has examples of the spectroscopic properties of these

glasses; it includes the lowest cross section and longest lifetimes of the fluoroberyllate glasses studied to date. (Comparable lifetimes and even lower cross sections can be obtained in silicate glasses but with much larger n_2 values.) A $4.8 \times 8.4 \times 1.5$ -cm disk of 1.2 mole % NdF_3 glass was prepared at LLL and measured in our standard laser glass amplifier test facility.⁴⁸ After correcting for some impurity absorption, we observed that the gain coefficient agreed with that expected from our GAINPK simulation program.

References

35. J. R. Bettis and A. H. Guenther, "Scaling Laws for Damage," in *Optical Materials for High Power Lasers* (Academic Press, New York, to be published).
36. J. R. Bettis, A. H. Guenther, and A. J. Glass, *Laser Induced Damage in Optical Materials*; 1974, A. J. Glass and A. H. Guenther, Eds. (U.S. Government Printing Office, Washington, D.C., 1974), NBS Special Publication 414.
37. J. R. Bettis, R. A. House, A. H. Guenther, and R. R. Austin, *Laser Induced Damage in Optical Materials*; 1975, A. J. Glass and A. H. Guenther, Eds. (U.S. Government Printing Office, Washington, D.C., 1975), NBS Special Publication 435, p. 289.
38. N. I. Grebenshchikova and G. T. Petrovskii, "Dissolution Kinetics of Some Fluoride Glasses," *Iv. Akad. Nauk. SSR, Neorg. Mater.* **4**, 116 (1968).
39. A. A. Margaryan and K. S. Evstropov, "The Chemical Stability of Beryllium Fluoride Glasses," *Iv. Akad. Nauk. SSSR, Neorg. Mater.* **4**, 116 (1968).
40. G. P. Nikolenko, V. D. Khalilov, and K. S. Evstropov, "Moisture Resistance and Crystallization of Fluoroberyllate Glasses," *Iv. Akad. Nauk. SSSR, Neorg. Mater.* **6**, 582 (1970).
41. J. Wenzel and W. Haller, "Fluorophosphate Glass Durability, Interim Durability Standard," June 1977 (unpublished).
42. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), p. 2-177.
43. G. T. Petrovskii, M. N. Tolstio, P. P. Feofilov, G. A. Tsurikova, and V. N. Shapovalov, "Luminescence and Stimulated Emission of Neodymium in Beryllium Fluoride Glasses," *Opt. and Spectry.* **21**, 126 (1976).
44. O. Deutschbein and C. Pautrat, "CW Laser at Room Temperature Using Vitreous Substances," *IEEE J. Quant. Electron.* **QE-4**, 48 (1968); also French patent, No. 1,502,709 (1966).
45. C. F. Cline and M. J. Weber, "Beryllium Fluoride Optical Glass: Preparation and Properties," in *Proc. 1st Otto Schott Symp., Jena, East Germany*, 1978.
46. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-74 (1975).
47. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-75 (1976).
48. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977); also G. F. Linford, R. A. Saroyan, J. B. Trenholme, and M. J. Weber, "Measurements and Modeling of Gain Coefficients for Neodymium Laser Glasses," *IEEE J. Quant. Electron.* (in press).

Authors

C. F. Cline
M. J. Weber

Major Contributors

S. Stokowski
D. Milam
D. Kingman

Tellurite Glasses. The highest stimulated emission cross sections for the $^4F_{3/2} \rightarrow ^4I_{11/2}$ transition of Nd^{3+} in glass are those reported by Singh, Van Uitert, and Grodkiewicz⁴⁹ for tellurite (TeO_2) glasses at room temperature. The values obtained ranged from approximately 7 to $11 \times 10^{-20} \text{ cm}^2$ and are much larger than the cross sections in other oxide glasses.⁵⁰ Part of the difference may arise from differences in the experimental techniques used because Singh et al. cite a cross section for ED-2 glass of $3.5 \times 10^{-20} \text{ cm}^2$ compared with values of 2.4 to $3.1 \times 10^{-20} \text{ cm}^2$ reported by others.

TeO_2 glass samples were provided by D. Blackburn of NBS and J. D. Myers of Kigre, Inc. (the latter included new phosphotellurite glasses). To obtain clear, uncolored glass, it was necessary to use ultrapure TeO_2 and an oxygen-rich atmosphere to prevent reduction. Chemical analysis of two of the glasses showed excellent agreement between nominal and actual Nd content.

Tables 7-14 and 7-15 summarize our results. All measurements were made at 295 K. For several glasses, we also determined the $^4F_{3/2} \rightarrow ^4I_{13/2}$ cross section.⁵¹ Both the $^4I_{11/2}$ and $^4I_{13/2}$ cross sections of TeO_2 glasses are large and include the highest values obtained to date for any glass using the Judd-Ofelt approach.⁵² However, our stimulated emission cross sections are only about one-half as large as those found by Singh et al. Included in Table 7-14 are the wavelength of peak emission (λ_p), effective fluorescence line width ($\Delta\lambda_{\text{eff}}$), the calculated radiative lifetime (τ_R), and the measured concentration independent lifetime (τ_0). Note the large spectral shift of λ_p with phosphate addition. Table 7-15 provides the Judd-Ofelt intensity parameters used to calculate stimulated emission cross sections and radiative lifetimes.

Table 7-16 compares the range of spectroscopic properties for Nd^{3+} in TeO_2 glasses with that observed in silicate and phosphate glasses. (These are not necessarily the extreme values possible because all possible glass-forming compositions have not been examined.)

Because of the high refractive index and high dispersion (Abbe value ~ 20) of the tellurite glasses,

Table 7-14. Spectroscopic properties of Nd^{3+} in tellurite glasses at 295 K.

Composition (mol %)	Peak wavelength λ_p (nm)	$^4F_{3/2} \rightarrow ^4I_{11/2}$		Peak wavelength λ_p (nm)	$^4F_{3/2} \rightarrow ^4I_{13/2}$		$^4F_{3/2}$ lifetime (μs)	
		Cross section $\sigma(10^{-20} \text{ cm}^2)$	Effective line width $\Delta\lambda_{\text{eff}}(\text{nm})$		Cross section $\sigma(10^{-20} \text{ cm}^2)$	Effective line width $\Delta\lambda_{\text{eff}}(\text{nm})$	τ_R	τ_0
77 TeO_2 , 22 P_2O_5	1056	3.17 ± 0.08	29.4	1327	0.87 ± 0.03	50.2	217	≈ 240
88 TeO_2 , 11 P_2O_5	1058	3.70 ± 0.10	29.6	—	—	—	180	≈ 209
88 TeO_2 , 11 Nb_2O_5	1062	3.12 ± 0.09	31.3	1338	0.87 ± 0.03	51.0	207	—
Monovalent modifiers								
79 TeO_2 , 20 Li_2O	1062	4.60 ± 0.17	28.1	1336	1.16 ± 0.04	50.8	154	170
79 TeO_2 , 20 Na_2O	1062	4.93 ± 0.13	26.4	—	—	—	154	177
79 TeO_2 , 20 K_2O	1061	5.06 ± 0.16	26.4	1336	1.34 ± 0.04	45.7	149	—
79 TeO_2 , 20 Rb_2O	1061	4.68 ± 0.21	27.4	1335	1.18 ± 0.05	48.8	152	—
89 TeO_2 , 10 K_2O	1061	4.96 ± 0.16	28.4	1337	1.28 ± 0.04	50.5	141	—
89 TeO_2 , 10 Cs_2O	1061	4.52 ± 0.14	28.1	1336	1.12 ± 0.04	51.3	155	—
Divalent modifiers								
82 TeO_2 , 17 BaO	1063	4.71 ± 0.17	28.7	1338	1.25 ± 0.04	45.6	147	175
68 TeO_2 , 31 ZnO	1062	4.11 ± 0.15	29.2	—	—	—	163	181

Table 7-15. Judd-Ofelt intensity parameters for tellurite glasses.

Composition (mol %)	Judd-Ofelt parameter (10^{-20} cm^2)		
	Ω_2	Ω_4	Ω_6
77 TeO ₂ , 22 P ₂ O ₅	3.08 ± 0.11	3.03 ± 0.17	3.44 ± 0.08
88 TeO ₂ , 11 P ₂ O ₅	3.14 ± 0.13	3.98 ± 0.20	3.90 ± 0.09
88 TeO ₂ , 11 Nb ₂ O ₅	3.52 ± 0.13	3.47 ± 0.18	3.51 ± 0.08
Monovalent modifiers			
79 TeO ₂ , 20 Li ₂ O	3.64 ± 0.23	4.88 ± 0.33	4.55 ± 0.15
79 TeO ₂ , 20 Na ₂ O	4.06 ± 0.16	4.79 ± 0.23	4.62 ± 0.11
79 TeO ₂ , 20 K ₂ O	5.74 ± 0.19	5.02 ± 0.29	4.73 ± 0.13
79 TeO ₂ , 20 Rb ₂ O	5.14 ± 0.26	5.10 ± 0.39	4.44 ± 0.17
89 TeO ₂ , 10 K ₂ O	4.82 ± 0.21	5.29 ± 0.31	4.98 ± 0.14
89 TeO ₂ , 10 Cs ₂ O	4.65 ± 0.18	4.91 ± 0.27	4.44 ± 0.12
Divalent modifiers			
82 TeO ₂ , 17 BaO	4.03 ± 0.22	5.13 ± 0.33	4.76 ± 0.15
68 TeO ₂ , 31 ZnO	3.62 ± 0.20	4.63 ± 0.29	4.26 ± 0.13

their nonlinear refractive index n_2 is predicted to be very high. Hence, the advantage of large σ is only helpful in applications where self-focusing is not an important consideration.

The fundamental absorption edge of our TeO₂ glasses begins at ≈ 400 nm, as shown in Fig. 7-51. Thus, the Nd³⁺ pump bands around 350 nm and at lower wavelengths are not used. The xenon flashlamp pumping efficiency in the 400- to 950-nm region, as computed using our VODEP program,⁵³ is a few percent better than ED-2 glass and comparable to that of high-gain phosphate glasses for the same spectral region. The concentration quenching behavior is comparable to that found in silicate and other Nd laser materials.⁵⁴ Thus, for short pump pulses (to compete with the faster $^4F_{3/2}$ decay rate), TeO₂ glasses should exhibit large gain.

One may ask why the cross sections of the TeO₂ glasses are larger than those of other oxide glasses (borates, phosphates, silicates, germanates). In all cases, the nearest-neighbor ligands are O²⁻ ions, although the coordination number may vary; the number and type of ions in the second and more distant coordination spheres will definitely be different. From Table 7-16, we see that the TeO₂ emission line widths are not the narrowest nor are the intensity parameters Ω the largest for observed oxide glasses. The large peak cross sections and short radiative lifetimes of the TeO₂ glasses are due in part to the large index of refraction of the host glass. As pointed out previously,⁵² the emission cross section and the spontaneous emission probability have a local correction multiplier approximated by $(n^2+2)^2/9n$ and $n(n^2+2)^2/9$, respectively. Because

Table 7-16. Range of spectroscopic properties associated with $^4F_{3/2} \rightarrow ^4I_{11/2}$ transition of Nd³⁺ measured in various oxide glasses at 295 K.

Glass	Cross section $\sigma(10^{-20} \text{ cm}^2)$	Peak wavelength $\lambda_p(\text{nm})$	Line width $\Delta\lambda(\text{nm})$	Lifetime $\tau_R(\mu\text{s})$
Silicates	1.0-3.2	1057-1065	28-35	300-1000
Phosphates	2.0-4.7	1053-1057	19-28	280-530
Tellurites	3.0-5.1	1056-1063	21-27	140-230

the sodium D-line refractive index of TeO₂ glasses is in the range 2.0 to 2.1, as compared with 1.5 to 1.6 for most phosphate and silicate laser glasses, the σ 's and τ 's are correspondingly large.

References

49. S. Singh, L. G. Van Uitert, and W. H. Grodkiewicz, *Optics Commun.* **17**, 315 (1976).
50. *Laser Program Annual Report—1974*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-74 (1975).
51. R. R. Jacobs and M. J. Weber, "Induced-Emission Cross Sections for the $^4F_{3/2} \rightarrow ^4I_{13/2}$ Transition of Neodymium Laser Glasses," *IEEE J. Quant. Electron.* **QE-11**, (1975).
52. R. R. Jacobs and M. J. Weber, "Dependence of the $^4F_{3/2} \rightarrow ^4I_{11,2}$ Induced Emission Cross Section for Nd³⁺ on Glass Composition," *IEEE J. Quant. Electron.* **QE-12**, 102 (1976).
53. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-75 (1976).
54. A. Lempicki, R. M. Klein, and S. R. Chinn, "Spectroscopy and Lasing of a High Nd Concentration Al-Phosphate Glass," *IEEE J. Quant. Electron.* **QE-14**, 283 (1978).

Author

M. J. Weber

Nd:Glass Laser Properties. As larger Nd:glass lasers for inertial confinement fusion experiments evolved, it became clear that we needed laser glasses with improved properties (e.g., increased energy storage, lower nonlinear refractive index, or different cross section for stimulated emission or all of these). In 1973, we initiated a program, in cooperation with industrial, governmental, and university

laboratories, to systematically measure and study the variation of spectroscopic and optical properties of Nd:glass with composition. One aspect of this program was illustrated by the development of fluorophosphate laser glass for the Nova laser.

The compositional space of laser glass is immense, and we did not intend our study to be comprehensive or exhaustive. Instead, we concentrated on the investigation of

- The effects of different glass network-former and network-modifier ions on the optical properties of Nd³⁺.
- A compositional series in which a single modifier ion, such as an alkali or alkaline earth, was varied. (These series were discussed in previous Laser Program Annual Reports.⁵⁵)
- Specific compositional regions, to achieve a low nonlinear refractive index, a choice of stimulated emission cross section, and high energy storage capacity.

The rest of this subsection discusses a laser glass handbook we have published. This handbook includes spectroscopic and optical properties of Nd:glass. Also, we discuss intensity parameters, branching ratios, the Deutchstein relationship for estimating cross sections, and our glass data correlation system.

In the laser glass study, we obtained data on the optical and spectroscopic properties of over 300 glasses. These data were distributed to a small number of glass research groups in a series of volumes of data sheets as described in the 1977 Annual Report.⁵⁶

To achieve a wider distribution of the data in an easily retrievable form, we decided in 1977 to publish a handbook that contained our data on the spectroscopic and optical properties of Nd:glass. It would also include supplemental data on optical, thermal, mechanical, and solubility properties obtained in other laboratories.

This handbook, titled "Laser Glass: Nd-Doped Glass Spectroscopic and Physical Properties," has been published. It contains 10,000 units of data, described and listed on 900 pages, in a custom looseleaf binder. These handbooks have been distributed to 40 LLL personnel and more than 100 researchers outside LLL. The data presented in this book should be useful in developing laser glass systems, in laser glass research, and to users and manufacturers of low-index, low-dispersion optical materials.

The major sections of the handbook and their contents follow:

- **Introduction.** Justification, overall approach, general description.

- **Measurement Techniques and Accuracy.** Describes techniques to obtain LLL data (which comprise ~90% of data in the book).

- **Data Analysis.** Explains theoretical analysis applied to obtain stimulated emission cross sections, absorption efficiencies, and fluorescence decay functions, all of which are used to predict laser amplifier performance.

- **Description of Data Sheets.** Defines terminology and illustrates, by example, where to find data in the standard format.

- **Selected Bibliography.** Contains 60 references relating to Nd:doped laser glass properties.

- **Tabular Index of Glasses.** Nine tables that list glasses by name or numerically by property; these aid in finding glasses of interest.

- **Data Sheets.** Divided into six subsections according to glass type. Each section is prefaced by five figures and five to nine tables showing ranges of compositions and properties. (61 properties, 3 graphs, and glass composition, for 192 glasses, are presented in the 4-page format shown in Fig. 7-52.)

Space limitations do not permit presentation of all the information contained in the handbook. However, many of the indices, tables, and figures from the book provide a convenient summary of Nd:glass laser properties and are produced here, as noted below. The calculated emission cross section, nonlinear index coefficient, radiative lifetime, and relative absorption cross section are important properties to the laser designer. The values of these properties are listed in ascending order in index tables, as exemplified in Table 7-17. In these index tables, the sample number is a unique number assigned by LLL to each sample.

The compositions in cationic % of the glasses contained in the handbook can be found in Tables 7-18 to 7-23, separated according to glass type. Also, Figs. 7-53 and 7-54 diagram the glass compositional space (as investigated for silicates and phosphates).

The range of values of selected spectroscopic properties is illustrated by histograms in the glass data book. Figure 7-55 reproduces these figures for variations in radiative lifetime of the $^4F_{3/2}$ state according to each glass type.

The method for accurately transferring large amounts of data from the laboratory to the published book deserves special mention. Our CDC 7600 computers automatically generated the data pages illustrated by Fig. 7-52 on camera-ready copy paper. Furthermore, the indices, along with statistical, tabular, and graphical presentation of data were easily generated by computer.

We have decided to use the computer generation method primarily because of the accuracy and high quality provided. Also, we have had the data available as part of our data correlation system for laser glasses, as described later in this subsection. This technique also simplifies changes and additions to the data pages or indices because the change is made in the data, not in individual data pages or indices. This feature is important, because updates and corrections will obviously be made in the future.

With respect to the Nd^{3+} intensity parameters, the intensity of a transition between two J-states of a rare earth ion can be related to a linear combination of Judd-Ofelt intensity parameters,⁵⁷⁻⁵⁹ i.e.,

$$S(aJ \rightarrow bJ') = \sum_{\tau=2,4,6} \Omega_{\tau} |\langle aJ || U^{(\tau)} || bJ' \rangle|^2, \quad (2)$$

where a and b denote other quantum numbers specifying the eigenstates. Coefficients Ω_2 , Ω_4 , Ω_6 in Eq. (2) involve

- The odd harmonics in the expansion of the local crystalline field, which admix opposite-parity states into the $4f^3$ configuration, thus allowing electric-dipole transitions.

- The energy separations of states of the $4f^3$ and opposite-parity configurations.

- The interconfigurational radial integrals. These properties depend on the local environment, and large site-to-site variations in the Ω values are possible. Ab initio calculations of the Ω intensity parameters are intractable at present; thus, the quantities are experimentally determined.

The double-reduced matrix elements of the unit tensor operator $U^{(\tau)}$ are calculated in an intermediate coupling approximation. Krupke⁶⁰ gives their values for the Nd^{3+} absorption and emission transitions.

(Continued on page 7-63)

August 1978

Current status: Commercial product

Melt: ED-2.2, 1973

COMPOSITION

Compound	Mole %	Weight %
SiO ₂	60.0	-
Li ₂ O	27.5	-
CaO	10.0	-
Al ₂ O ₃	2.5	-
CeO ₂	0.16	-
Nd ₂ O ₃	-	2.012

Measured neodymium concentration	2.012	wt % Nd ₂ O ₃
Neodymium number density ρ_N	$1.829 \cdot 10^{20}$	cm ⁻³

Compositional series:

PROPERTY SUMMARY

Peak stimulated emission cross section	σ_p	$2.7 \cdot 10^{-20}$	cm ²
Calculated radiative lifetime	τ_R	359	μ sec
Zero-concentration lifetime	τ_0	359	μ sec
Nd ³⁺ concentration @ $\tau_0/2$	Q	$3.89 \cdot 10^{20}$	cm ⁻³
Nonlinear refractive index coefficient	γ	$3.77 \cdot 10^{-20}$	m ² · W ⁻¹
Nonlinear refractive index	n_2	$1.41 \cdot 10^{-13}$	esu
Refractive index at peak-fluorescence wavelength	$n(\lambda_p)$	1.56123	
Peak-fluorescence wavelength	λ_p	1061	nm
Linewidth (FWHM)	$\Delta\lambda$	27.8	nm
Linewidth (effective)	$\Delta\lambda_{eff}$	34.4	nm
Density	ρ	2.5394	g · cm ⁻³

Fig. 7-52. Sample data pages from the Laser Glass Handbook.

August 1978

ABSORPTION PROPERTIES

Integrated absorption cross section relative
to ED-2 from 400 to 950 nm

1.00

Absorption efficiency coefficients for 15-mm
xenon flashlamp at $1000 \text{ A} \cdot \text{cm}^{-2}$

(340 to 940 nm):

$$\epsilon = A [1 - B \exp(-C \rho_N d) - (1 - B) \exp(-D \rho_N d)] \quad \left\{ \begin{array}{ll} A = 0.108734 & B = 0.712730 \\ C = 0.134343 & D = 1.116667 \text{ cm}^2 \end{array} \right. \quad \left. \begin{array}{l} \text{where } \rho_N d \text{ is in } 10^{20} \text{ Nd ions} \cdot \text{cm}^{-2} \end{array} \right\}$$

Judd-Ofelt parameters:

Ω_2	$3.2 \pm 0.2 \cdot 10^{-20}$	cm^2
Ω_4	$4.6 \pm 0.3 \cdot 10^{-20}$	cm^2
Ω_6	$4.8 \pm 0.1 \cdot 10^{-20}$	cm^2

Fig. 7-52. Sample data pages from the Laser Glass Handbook. (Continued)

FLUORESCENCE PROPERTIES

Peak-fluorescence wavelength	λ_p	1061	(1335) [a]	nm
Linewidth (FWHM)	$\Delta\lambda$	27.8		nm
Linewidth (effective)	$\Delta\lambda_{eff}$	34.4	(67) [a]	nm
Peak stimulated emission cross section	σ_p	$2.7 \cdot 10^{-20}$ [k]	$(0.72 \cdot 10^{-20})$ [a]	cm^2
Calculated radiative lifetime	τ_R	359		μsec
Zero-concentration lifetime	τ_0	359		μsec
Nd ³⁺ concentration @ $\tau_0/2$	Q	$3.89 \cdot 10^{20}$		cm^{-3}

Branching ratios:

$$({}^4F_{3/2} \rightarrow {}^4I_J) \quad J = 9/2, 11/2, 13/2, 15/2 \quad 0.421, 0.484, 0.091, 0.004$$

Measured decay properties: three e-folding times 309, 360, 358 μsec

Decay function: $I/I_0 = A \exp(-Bt) + C \exp(-Dt) + E \exp(-Ft)$

A = 0.057261	B = 7434.59	sec^{-1}
C = 0.492229	D = 2272.96	sec^{-1}
E = 0.450510	F = 4387.23	sec^{-1}

Fig. 7-52. Sample data pages from the Laser Glass Handbook. (Continued)

August 1978

OPTICAL PROPERTIES

Refractive index at sodium D line	n_D	1.5716	
Refractive index at peak fluorescence	$n(\lambda_p)$	1.56123	
Abbe number, $(n_D - 1)/(n_F - n_C)$	ν	57.5	
Index temperature coefficient (25 to 100°C, 633 nm)	$\partial n / \partial T$	$2.9 \cdot 10^{-6}$ [b,c]	°C ⁻¹
Thermal coefficient of optical path length (25 to 100°C, 633 nm)	$\partial s / \partial T$	$8.0 \cdot 10^{-6}$ [b]	°C ⁻¹
Nonlinear refractive index coefficient	γ calc	$4.29 \cdot 10^{-20}$	m ² · W ⁻¹
	γ meas	$3.77 \pm 0.38 \cdot 10^{-20}$ [d]	m ² · W ⁻¹
Nonlinear refractive index	n_2 calc	$1.60 \cdot 10^{-13}$	esu
	n_2 meas	$1.41 \pm 0.14 \cdot 10^{-13}$ [d]	esu
Stress optic coefficient	ΔB	2.06 [b,c]	nm · cm · kg ⁻¹

THERMAL PROPERTIES

Thermal expansion coefficient (25 to 100°C)	α	$9.26 \cdot 10^{-6}$ [b,f]	°C ⁻¹
Specific heat at constant pressure (25°C)	C_p	0.92 [b]	J · cm ⁻³ · °C ⁻¹
Thermal heat conductivity (100°C)	κ	1.35 [b,g]	W · m ⁻¹ · °C ⁻¹
Softening point	T_g^y	590 [b]	°C
Transformation point	T_g	468 [b]	°C

MECHANICAL PROPERTIES

Density	ρ	2.5394	g · cm ⁻³
Knoop hardness (200 g)	K_H	599 [b,h]	kg · mm ⁻²
Young's modulus	E	9189 [b,i]	kg · mm ⁻²
Shear modulus	G	3698 [b,j]	kg · mm ⁻²
Poisson ratio	σ	0.242 [b]	

SOLUBILITY

Stability in water (mg · cm ⁻² · day ⁻¹ , 50°C)	0.05 [b]
Stability in acid (mg · cm ⁻² · day ⁻¹ , 50°C, 0.1N H ₂ SO ₄)	0.03 [b]

REFERENCES and NOTES

- [a] R.R. Jacobs and M.J. Weber, *IEEE J. Quantum Electron.* QE-11, 846 (1975).
 [b] Owens-Illinois.
 [c] 3.1 ± 0.5 , 10 to 40°C @ 1064 nm, Univ. of Rochester.
 [d] D. Milam and M.J. Weber, *J. Appl. Phys.* 47, 2497 (1976).
 [e] 1.92 ± 0.1 (1064 nm), Univ. of Rochester.
 [f] 7.7 ± 0.5 , -20 to 50°C, Univ. of Rochester.
 [g] 1.26 ± 0.03 (20°C) 1.21 ± 0.03 (0°C), Univ. of Rochester.
 [h] 612 (200 g), Univ. of Rochester.
 [i] 9620 ± 130 , Univ. of Rochester.
 [j] 3633 ± 130 , Univ. of Rochester.
 [k] For other values, see "Induced-emission Cross Section in Neodymium Laser Glasses", W.F. Krupke, *IEEE J. Quantum Electron.* QE-10, 450 (1974).

Fig. 7-52. Sample data pages from the Laser Glass Handbook. (Continued)

Table 7-17. ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ peak stimulated emission cross section (10^{-20} cm^2).

Cross section	Sample no.	Common name	Glass type	Wavelength (nm)
1.0	7503	3669A	Silicate	1058.5
1.0	8087	L-217	Silicate	1059.5
1.1	6501	LG-650	Silicate	1057
1.1	6522	BK-1	Borosilicate	1059.5
1.2	6010	MG-915	Silicate	1058.5
1.2	8017	L-178	Silicate	1059.5
1.3	6517	BK-7	Borosilicate	1062
1.4	5001	5001	Silicate	1060
1.4	5007	5007	Silicate	1059.5
1.4	5008	5008	Silicate	1060.5
1.4	5011	5011	Silicate	1059.5
1.4	9016	9016	Silicate	1088
1.5	5009	5009	Silicate	1061.5
1.5	5010	5010	Silicate	1061.5
1.5	8130	K-564	Silicate	1060
1.5	8131	K-566	Silicate	1062
1.6	5003	5003	Silicate	1059
1.6	B816	B816	Fluoroberyllate	1046
1.7	5001	5001	Silicate	1059
1.7	5002	5002	Silicate	1060
1.7	5012	5012	Germanate	1060.5
1.7	8083	L-213	Silicate	1060
1.7	8089	L-219	Silicate	1063
1.8	8016	L-15	Silicate	1061.5
1.8	8021	L-65	Aluminate	1067
1.8	8088	L-216	Silicate	1063
1.9	5006	5006	Silicate	1061
2.0	3076	P-112	Phosphate	1055
2.0	7001	X-2182	Phosphate	1054.5
2.0	B800	B800	Fluoroberyllate	1046
2.1	5013	5013	Borate	1059.5
2.1	7501	C2828	Silicate	1062
2.1	8090	L-220	Silicate	1063
2.1	8146	K-766	Borosilicate	1063
2.2	1106	E-132	Fluorophosphate	1051
2.2	1146	E-210	Fluorophosphate	1050.5
2.2	5005	5005	Silicate	1061
2.2	B128	B128	Fluoroberyllate	1047
2.3	5060	LHG-L	Fluorophosphate	1049
2.3	6512	P-008	Silicate	1065
2.3	8012	L-113	Phosphate	1053.5
2.3	8056	L-183	Borate	1059

Table 7-17 (contd.)

Cross section	Sample no.	Common name	Glass type	Wavelength (nm)
2.3	8085	L-215	Silicate	1060.5
2.3	8109	K-871-A	Fluorophosphate	1050
2.4	1105	E-131	Fluorophosphate	1051
2.4	1109	E-134	Fluorophosphate	1050.5
2.4	5019	LSG-91H	Silicate	1061.5
2.4	8059	L-186	Germanate	1062.5
2.4	8127	K-555	Borate	1054
2.4	8128	K-556	Borate	1058
2.4	8132	K-567	Borate	1055
2.4	8162	K-824	Silicate	1064.5
2.4	9013	9013	Phosphate	1055.5
2.4	9023	9023	Phosphate	1053
2.4	9101	9101	Phosphate	1057
2.4	B111	B111	Fluoroberyllate	1047.5
2.5	1125	E-119	Fluorophosphate	1055.5
2.5	1129	E-133	Fluorophosphate	1050.5
2.5	1110	E-206	Fluorophosphate	1050.5
2.5	1111	E-309	Fluorophosphate	1050.5
2.5	1111	E-202	Fluorophosphate	1052
2.5	1161	E-269	Fluorophosphate	1051.5
2.5	3026	L-109	Borate	1061
2.5	7006	EK-2160	Silicate	1061
2.5	8111	L-240	Germanate	1060.5
2.5	8133	K-574	Borate	1060
2.5	8236	K-1056	Fluorophosphate	1050.5
2.5	9015	9015	Phosphate	1055
2.6	1131	E-181	Fluorophosphate	1050.5
2.6	5057	LLG-10	Fluorophosphate	1050.5
2.6	6534	EK-51	Fluorophosphate	1053.5
2.6	6548	LG-812	Fluorophosphate	1051
2.6	8237	K-1057	Fluorophosphate	1050.5
2.6	B116	B116	Fluoroberyllate	1047.5
2.6	B134	B134	Fluoroberyllate	1050
2.7	1009	ED-2	Silicate	1061
2.7	1044	ED-M	Silicate	1060.5
2.7	1100	E-102	Fluorophosphate	1053
2.7	1126	E-121	Fluorophosphate	1056
2.7	1139	E-1	Fluorophosphate	1051.0
2.7	1143	E-199	Fluorophosphate	1053
2.7	1155	E-252	Fluorophosphate	1052
2.7	3024	L-107	Borate	1059
2.7	6544	LG-802	Fluorophosphate	1052
2.7	8139	K-625	Fluorophosphate	1052
2.7	8238	K-1058	Fluorophosphate	1051.0
2.7	9028	9028	Fluorozirconate	1049

Table 7-17 (contd.)

Cross section	Sample no.	Common name	Glass type	Wavelength (nm)
2.7	9114	9114	Phosphate	1052.5
2.8	1102	E-104	Fluorophosphate	1053
2.8	1110	E-135	Fluorophosphate	1052.5
2.8	1154	E-249	Fluorophosphate	1052.5
2.8	5035	5035	Phosphate	1053.5
2.9	1004	ED-8	Silicate	1061.5
2.9	1006	GS-107	Silicate	1062
2.9	1068	ED-3	Silicate	1061
2.9	1103	E-123	Fluorophosphate	1052.5
2.9	1153	E-245	Fluorophosphate	1054
2.9	1160	E-266	Fluorophosphate	1052.5
2.9	5036	5036	Phosphate	1055.5
2.9	8126	8126	Fluorozirconate	1049
2.9	8129	K-557	Borate	1060.5
2.9	8239	K-1066	Fluorophosphate	1051.5
2.9	B112	B112	Fluoroberyllate	1047.9
2.9	B115	B115	Fluoroberyllate	1048
2.9	B120	B120	Fluoroberyllate	1047
2.9	B121	B121	Fluoroberyllate	1047.5
2.9	B133	B133	Fluoroberyllate	1050
2.9	B402	816-KY	Fluoroberyllate	1047.5
3.0	1030	GS-114	Silicate	1061.5
3.0	1040	GS-131	Silicate	1061.5
3.0	6009	6009	Borate	1062.5
3.0	9021	9021	Fluorozirconate	1048.5
3.0	9104	9104	Phosphate	1055
3.0	9111	9111	Phosphate	1054.5
3.0	9115	9115	Phosphate	1054.5
3.0	B119	B119	Fluoroberyllate	1047
3.1	1093	E-113	Fluorophosphate	1053.5
3.1	1096	E-122	Fluorophosphate	1053.5
3.1	9118	9118	Phosphate	1055.5
3.2	1041	GS-132	Silicate	1062
3.2	1152	E-241	Fluorophosphate	1054.5
3.2	1159	E-263	Fluorophosphate	1054
3.2	5037	5037	Phosphate	1055.5
3.2	7010	X-2353	Borate	1059
3.2	8097	L-222	Fluorophosphate	1054
3.2	B101	B101	Fluoroberyllate	1047.5
3.3	8096	L-221	Fluorophosphate	1053
3.3	B116	L-245	Fluorophosphate	1054
3.3	8118	L-247	Fluorophosphate	1055
3.3	8140	K-626	Fluorophosphate	1053.5
3.3	B123	B123	Fluoroberyllate	1048
3.4	3038	P-104	Phosphate	1055.5

Table 7-17 (contd.)

Cross section	Sample no.	Common name	Glass type	Wavelength (nm)
3.4	3041	P-101	Phosphate	1054.5
3.4	8098	L-223	Fluorophosphate	1053.5
3.4	8152	K-808	Fluorophosphate	1055
3.4	8157	K-816	Fluorophosphate	1053.5
3.5	1094	E-114	Fluorophosphate	1054
3.5	1095	E-115	Fluorophosphate	1054
3.5	1158	E-259	Fluorophosphate	1054
3.5	3040	P-102	Phosphate	1054
3.5	3042	P-105	Phosphate	1056
3.5	5038	5038	Phosphate	1054.5
3.5	8117	L-246	Fluorophosphate	1055.5
3.5	8148	K-800	Fluorophosphate	1052
3.5	B155	A-7	Fluoroberyllate	1047
3.6	1091	E-111	Fluorophosphate	1054
3.6	1092	E-112	Fluorophosphate	1054
3.6	7005	EK-2236	Silicate	1063.5
3.6	8115	L-244	Fluorophosphate	1054
3.6	8120	L-249	Fluorophosphate	1053.5
3.6	8153	K-809	Fluorophosphate	1054
3.6	9030	9030	Chlorophosphate	1055
3.7	3043	P-106	Phosphate	1054
3.7	3046	P-108	Phosphate	1055.5
3.7	3081	P-118	Phosphate	1055
3.7	3082	P-119	Phosphate	1056
3.7	6505	LG-700	Phosphate	1053.5
3.7	8114	L-243	Fluorophosphate	1054.5
3.7	8151	K-807	Fluorophosphate	1054.5
3.8	3044	P-107	Phosphate	1054
3.8	6507	LG-710	Phosphate	1053.5
3.8	8113	L-242	Fluorophosphate	1054.5
3.8	8150	K-815	Fluorophosphate	1054.5
3.8	8159	K-818	Fluorophosphate	1054.5
3.8	B118	B118	Fluoroberyllate	1047
3.8	B140	B140	Fluoroberyllate	1048
3.9	3045	P-100	Phosphate	1056
3.9	5027	LHG-7	Phosphate	1053
3.9	7504	SU-1	Sulphate	1055
3.9	8119	L-248	Fluorophosphate	1054
3.9	9110	9110	Phosphate	1055.5
4.0	3074	P-26	Phosphate	1054.5
4.0	3083	P-120	Phosphate	1055.5
4.0	3118	Q-88	Phosphate	1054
4.0	5094	LHG-8	Phosphate	1053
4.0	B139	B139	Fluoroberyllate	1049
4.1	1090	E-101	Fluorophosphate	1054.5

Table 7-17 (contd.)

Cross section	Sample no.	Common name	Glass type	Wavelength (nm)
4.1	5033	LHG-6	Phosphate	1053.5
4.1	5041	LHG-5	Phosphate	1053
4.2	1042	GS-133	Phosphate	1054.5
4.2	3084	P-121	Phosphate	1055
4.2	5014	5014	Phosphate	1053
4.3	3077	P-113	Phosphate	1054
4.3	8158	K-817	Fluorophosphate	1055
4.4	1088	EV-2	Phosphate	1053
4.4	1089	EV-3	Phosphate	1054
4.4	5039	5039	Phosphate	1053.5
4.4	B146	B146	Fluoroberyllate	1050
4.5	3078	P-114	Phosphate	1054
4.6	3073	P-25	Phosphate	1054.5
4.7	3079	P-115	Phosphate	1054
4.8	1043	GS-134	Phosphate	1054.5

October 1978

We investigated variations in the intensity parameters Ω_2 , Ω_4 , Ω_6 with composition for 225 glasses. It is known that Ω_2 is the best indicator of differences in the local environment of Nd^{3+} in materials. This fact is reflected in Fig. 7-56, which shows the distribution of Ω_2 values.

Marked on the Ω_2 distribution are the ranges of Ω_2 by glass type. One sees that the Ω_2 fluorides span the range of 0.1 to $2.0 \times 10^{-20} \text{ cm}^2$ while oxides

cover 2.0 to $7.0 \times 10^{-20} \text{ cm}^2$. The distribution of fluorophosphates is interesting because it joins regions of Ω_2 that might otherwise be separate. The fluorophosphate glass compositions vary from those with only minor amounts of fluorine to those where the oxygen content is very low (see Table 7-20). Thus, Ω_2 is very sensitive to oxygen content.

(Continued on page 7-69)

Table 7-18. Compositions of silicate laser glasses (cationic %) in order of decreasing silicon percentage.

Group V	Group IV		Group III		Group II						Group I			Others			Sample number	
Ta	Si	Ti	B	Al	Mg	Ca	Sr	Ba	Zn	Cd	Li	Na	K	Ce	Bi	Nd		
	99.8																0.18	9016
	90.7												8.5				0.8	8131
	81.8												17.3				0.9	8130
	66.3												33.2				0.5	5004
	64.5							4.3	4.3				26.0				0.9	8016
	64.2							11.4						22.3			2.1	8047
	59.7												39.8				0.5	5003
	58.0							15.6						26.0			0.5	5011
	56.2							17.3			26.0						0.5	5005
	56.2							17.3				26.0					0.5	5006
	56.2							17.3					26.0				0.5	5007
	56.2				17.3									26.0			0.5	5008
	56.2					17.3								26.0			0.5	5009
	56.2						17.3							26.0			0.5	5010
	55.5	17.4											26.1				1.1	8089
	53.6												42.9				0.5	5002
	49.8												49.4				0.7	8083
	49.6										49.4						0.7	8085
	49.8													49.4			0.7	8087
	47.9											51.6					0.4	5001
	45.8			3.8		7.6						42.0					0.8	1030
	45.7			1.5		3.7						48.3					0.7	1044
	45.2			3.1	8.8							42.3					0.5	7006
	39.6			4.0		19.8						35.7			0.1		0.8	1006
	39.3	20.0											39.9				0.9	8090
	38.9	35.1						24.6									1.4	8088
	37.9			3.8		15.2						41.7			0.1		1.2	1004
	35.7			4.0		23.8						35.7			0.1		0.8	1040
	35.0									25.5						38.6	0.9	7005
	33.0			4.1		33.0					28.9				0.1		0.8	1041
28.9	32.3				26.8			11.1									0.9	8162

October 1978

Table 7-19. Compositions of phosphate laser glasses (cationic %) in order of decreasing phosphorous percentage.

Group V		Group IV	Group III	Group II							Group I				Others			Sample number	
P	As	Si	Al	Be	Mg	Ca	Sr	Ba	Zn	Cd	Li	Na	K	Rb	Mn	La	Nd		
80.0						8.9		10.7										0.4	5039
75.0			24.8															0.2	9114
74.6			25.0															0.4	9023
73.4								9.9					16.4					0.3	5014
72.1			22.4						5.0									0.5	7001
68.9					25.0												5.9	0.4	5035
68.8						25.0											5.9	0.4	5036
68.8							25.0										5.9	0.4	5037
68.8								25.0									5.9	0.4	5038
68.7				25.0													5.9	0.4	3076
67.0			22.5									10.0						0.5	8012
66.8					33.0													0.25	9101
66.8						33.0												0.25	9118
66.8							32.9											0.3	9111
66.8								33.0										0.23	9115
66.7									33.0									0.23	9104
66.7										32.9								0.23	9110
65.1					25.0											8.3		1.5	9013
59.5			4.6			8.1					27.0							0.8	3043
57.9			4.5			5.3					31.6							0.7	3044
57.9			4.5			5.3						31.6						0.7	3077
57.9			4.5			5.3							31.6					0.7	3078
57.9			4.5			5.3								31.6				0.7	3079
54.5								9.0					35.9					0.6	3073
54.1	2.7		4.6			5.4					32.4							0.8	3040
54.1			4.6			8.1					32.4							0.8	3041
54.1			4.6					8.1					32.4					0.8	3084
53.7					7.5								38.1					0.6	3074
53.5									9.1				36.4					1.1	1042
53.5								9.1					36.4					1.1	1043
48.8			4.7			8.1					38.0							0.4	3038
47.4			4.5			5.3					26.3	15.8						0.7	3046
47.4			4.5			5.3					42.1							0.7	3081
45.0			4.3								25.0	25.0						0.7	3045
45.0			4.3								25.0		25.0					0.7	3082
45.0			4.3									25.0	25.0					0.7	3083
44.4			4.8			11.1					38.9							0.8	3042
35.6	0.5				62.6													1.3	9015

October 1978

Table 7-20. Compositions of fluorophosphate laser glasses (cationic %) in order of increasing oxygen/fluorine ratio.

Oxygen/fluorine ratio	Group V	Group III	Group II				Group I			Others				Sample number
	P	Al	Mg	Ca	Sr	Ba	Li	Na	K	Pb	La	Y	Nd	
0.03	2.0	44.0	← 39.2 total →										1.5	5060
0.08	5.6	37.4	9.3	28.0	9.3	9.3							0.9	1146
0.10	7.4	37.0	9.3	27.8	9.3	7.4						0.9	0.9	1105
0.10	7.1	28.4	7.1	21.3	7.1	7.1				20.2			1.8	8239
0.11	7.7	30.7	7.7	23.0	7.7	7.7				13.9			1.7	8238
0.12	8.2	32.7	8.2	24.5	8.2	8.2				8.0			.6	8237
0.12	8.6	34.4	8.6	25.8	8.6	8.6				3.9			.5	8236
0.13	9.0	36.0	9.0	27.0	9.0	9.0							0.0	1106
0.13	8.9	36.3	9.0	27.0	9.0	9.0							0.8	8189
0.16	10.7	31.2	8.9	26.8	7.1	10.7						3.6	1.0	1129
0.16	10.6	31.8	8.0	25.6	8.0	8.0	3.5	3.5					1.0	1131
0.17	10.6	28.3	8.0	25.7	8.0	8.0	5.3	5.3					0.9	1139
0.17	10.6	31.9	7.1	24.8	7.1	7.1		10.6					0.9	1140
0.18	12.3	30.7	4.4	25.4	7.9	12.3						6.1	0.9	1109
0.19	11.5	22.6	17.7	17.7		17.7		11.5			0.9		0.4	8096
0.21	12.9	25.9	10.1	30.2	10.1	10.1							0.9	1144
0.21	12.9	31.9	6.9	23.3	6.9	6.9		10.3					0.9	1141
0.22	12.9	25.9	8.6	25.9	8.6	8.6		8.6					0.8	1155
0.23	13.0	22.6	17.4	16.5		16.5		13.0					0.9	1140
0.29	16.7	20.8	19.1	19.2	11.7								0.8	1102
0.30	13.4	28.6	21.7	21.7				13.4			0.9		0.4	8139
0.36	16.9	24.1	5.6	13.2	19.1	8.7	10.1	0.5					0.8	1103
0.44	22.9	22.9	8.9	26.7	8.9	8.9							0.8	1143
0.47	22.9	22.9	7.6	22.9	7.6	7.6		7.6					0.8	1154
0.47	22.9	30.5	5.1	15.3	5.1	5.1		15.3					0.8	1161
0.49	22.9	22.9	6.4	19.1	6.4	6.4		15.3					0.8	1160
0.50	19.6	20.0	11.4	16.0	11.0	10.7		10.1	0.3				0.8	1096
0.51	22.1	25.7	11.0	14.7	3.7	22.1							0.8	1110
0.52	22.9	7.6	22.9			45.0							1.5	8118
0.62	21.3	14.3	19.3				23.0	21.3					0.8	8148
0.94	25.7	13.9	2.7				26.5	29.7					1.5	8140
1.1	37.3	12.4	18.6			30.9							0.8	1125
1.1	37.3	18.6	6.2	18.6	6.2	6.2		6.2					0.6	1153
1.2	37.3	12.4	16.5			32.5							1.2	8117
1.2	37.3	12.4	7.2	21.7	7.2	7.2		6.2					0.6	1152
1.2	37.3	18.6	5.2	15.5	5.2	5.2		12.4					0.6	1159
1.3	37.3	12.4	6.2	18.6	6.2	6.2		12.4					0.6	1158
1.4	36.9	12.3		15.8		12.6	22.1						0.3	8097
1.5	33.9	11.3		9.8			44.3						0.7	1091
1.5	35.0	11.7		17.5				35.2					0.6	1095
1.5	30.3	10.1		20.2			38.8						0.6	8156
1.5	30.3	10.1	20.2				38.8						0.6	8157
1.5	30.3	10.1			20.2	20.2	38.8						0.6	8158
1.5	30.3	10.1			20.2		38.8						0.6	8159
1.8	33.9	11.3					54.1						0.7	1090
1.8	32.2	10.7					33.6	22.1					1.3	8119
2.0	32.2		16.1				31.5	18.8					1.3	8120
2.2	37.5	12.5					49.7						0.3	8096
2.3	41.4	13.8	8.7					35.7					0.4	1093

Table 7-20 (contd.)

Oxygen/fluorine ratio	Group V	Group III	Group II				Group I			Others				Sample number
	P	Al	Mg	Ca	Sr	Ba	Li	Na	K	Pb	La	Y	Nd	
2.3	41.4	13.8		8.7				35.7					0.3	1094
2.4	34.3	11.4				10.3	42.9						1.1	8113
2.4	34.3	11.4			10.3		42.9						1.1	8114
2.4	34.3	11.4		10.3			42.9						1.1	8115
2.4	34.3	11.4	10.3				42.9						1.1	8116
2.7	41.4	13.8						44.4					0.3	1092
2.8	41.2	13.7				22.2	22.2						0.6	8151
2.8	41.2	13.7				22.2		22.2					0.6	8152
2.8	41.2	13.7				22.2			22.2				0.6	8153
3.6	32.4	32.4						34.8					0.5	1126

October 1978

Table 7-21. Compositions of fluoroberyllate laser glasses (cationic %) in order of decreasing beryllium percentage.

Group III		Group II				Group I					Others		Sample number
Be	Al	Mg	Ca	Sr	Ba	Li	Na	K	Rb	Cs	Cd	Nd	
98.0												2.0	B800
93.0	5.0											2.0	B816
58.6								40.4				1.0	B146
58.0								40.0				2.0	B134
58.0								40.0				2.0	B133
58.0						20.0		20.0				2.0	B140
58.0								20.0		20.0		2.0	B139
49.0	5.0		14.0					30.0				2.0	B115
49.0	26.0		14.0					15.0				2.0	B116
47.0	10.0		14.0			27.0						2.0	B111
47.0	10.0		14.0				27.0					2.0	B112
47.0	10.0		14.0					27.0				2.0	B101
47.0	10.0		14.0						27.0			2.0	B123
47.0	10.0		14.0							27.0		2.0	B155
47.0	10.0	14.0						27.0				2.0	B120
47.0	10.0			14.0				27.0				2.0	B121
46.0	20.0	2.5	10.0				20.0					1.5	B128
45.0	20.0		18.0					15.0				2.0	B118
45.0	20.0			18.0				15.0				2.0	B119
34.0	23.0	19.0	10.0		14.0							1.0	B402

October 1978

Table 7-22. Compositions of borate and borosilicate laser glasses (cationic %) in order of decreasing boron percentage.

Group III		Group IV	Group II			Group I			Others			Sample number
B	Al	Si	Ca	Sr	Ba	Li	Na	K	Ta	La	Nd	
89.0						10.0					1.0	8132
84.0						15.0					1.0	8127
78.3						13.9				7.3	0.4	7010
73.4					9.9			16.4			0.3	5013
72.5					9.9		16.5				1.1	8056
70.6	10.9				17.6						0.8	3026
69.4					10.4	14.1				5.3	0.8	3024
69.0						30.0					1.0	8128
61.5						37.5					1.0	8133
54.0						45.0					1.0	8129
53.6			16.1		6.7					10.7	1.1	6009
24.2		26.0			15.7				32.7		1.4	8146
14.8	0.1	52.0	0.1		1.9		12.6	12.5			6.0	6517
11.1		53.0	1.5				8.0	21.8			4.5	6522

October 1978

Table 7-23. Compositions of miscellaneous laser glasses (cationic %).

Fluorozirconate glasses											Sample number
Zr	Th	Al	Ca	Ba	Pb	Li	Na	Ce	La	Nd	
60.6				33.8					3.9	1.7	9024
53.0	7.7	0.6	0.4	22.0	1.8	6.9	3.4			4.2	9028
50.0				23.0			25.0			2.0	8126
Germanate glasses											Sample number
			Ge	Ba	Na	K	Nd				
			99.96				0.04				8111
			57.90	15.6		26.0	0.50				5012
			56.90	15.5	25.9		1.70				8059
Sulfate glass											Sample number
			SO ₄	Zn	K	Nd					
			41.6	24.8	33.1	0.5					7504
Aluminate glass											Sample number
			Al	Si	Ca	Ba	Nd				
			43.8	7.9	39.2	3.8	0.8				8021
Chlorophosphate glass											Sample number
			P	Zn	Na	Nd					
			37.3	25.1	37.3	0.3					9030

October 1978

Fig. 7-35. Ranges of peak-fluorescence wavelength ($^4F_{3/2} \rightarrow ^4I_{11/2}$ transition) according to glass type.

On the other hand, Ω_4 and Ω_6 do not vary as much as Ω_2 with glass type; i.e., 90% of all glasses, independent of type, have values between 3.0 and $5.5 \times 10^{-20} \text{ cm}^2$ for Ω_4 and 3.0 and $6.5 \times 10^{-20} \text{ cm}^2$ for Ω_6 .

The $^4F_{3/2} \rightarrow ^4I_{11/2}$ branching ratio $\beta_{11/2}$ depends on the Ω_4/Ω_6 ratio (Fig. 7-57). The variation in $\beta_{11/2}$ is <15% over the full compositional space investigated so far, from pure BeF_2 glasses to tellurites.

Otto Deutschbein⁶¹ showed that the $^4F_{3/2} \rightarrow ^4I_{11/2}$ emission cross section could be estimated from the strength of the 750 absorption band of Nd^{3+} (S_{750}) and the normalized integrated intensity

of the $^4F_{3/2} \rightarrow ^4I_{11/2}$ emission band, $\int I(\lambda) d\lambda / I(\lambda_p)$, which we define as the effective line width $\Delta\lambda_{\text{eff}}$. Deutschbein's relation is

$$\sigma = 27 S_{750} / \Delta\lambda_{\text{eff}} \quad (3)$$

where $\Delta\lambda_{\text{eff}}$ is in nm, and he demonstrated its validity with 13 glasses. Implicit in the above expression is the assumption that the ratio of Ω_4 to Ω_6 along with the refractive index remain constant.

We have checked this relation for the ~200 glasses we have analyzed, and plot $S_{750} / \Delta\lambda_{\text{eff}}$ vs σ in

Fig. 7-58(a). A revised coefficient from data is 25. The 750-n:n band strength was calculated from

$$\bar{S}_{750} = 0.001 \Omega_2 + 0.0448 \Omega_9 + 0.6582 \Omega_6 \quad (4)$$

rather than from the measured strength that

Deutschbein used. The difference between measured and calculated strengths at 750 nm is about $-0.1 \times 10^{20} \text{ cm}^2$ independent of glass type. Clearly some glasses fall outside the validity range of Deutschbein's relation. The high-cross-section glasses are tellurites, which have large refractive indices; the glasses that fall below the somewhat fitted

Fig. 7-58. Correlation between the absorption cross section ($S_{798}/A\lambda^{eff}$) and the 798-nm absorption band strength divided by the $^{45}\text{Ti}^{3+}$ fluorescence line width. (a) Plot of $S_{798}/A\lambda^{eff}$ vs σ . (b) Plot of $S_{798}/A\lambda^{eff}$ vs σ local field correction/line width.

line are fluoroberyllates, which have low refractive indices.

Thus, we concluded that the local field correction to the cross section cannot be neglected. We found that the relation

$$\sigma = 18.9 \left[(n^2 + 2)^2 / 9n \right] \left[S_{750} / \Delta\lambda_{\text{eff}} \right], \quad (5)$$

where n is the refractive index, fits very well as shown in Fig. 7-58(b).

We performed the above studies with the glass data correlation system (introduced in our 1977 Annual Report), which provides a means of manipulating glass data by computer. It is designed to

- Cross-correlate glass properties as a function of glass composition.
- Generate lists, tables, statistics, and graphs.
- Perform calculations with the data.

Fig. 7-59 schematically shows the system components.

Data for 240 glasses are stored in data libraries, which are accessed by the programs, DCS and DCSM, written in the LLL languages TRIX⁶² and MATHSY,⁶³ respectively. In the DCS program, data are treated as a collection of characters (strings) that are displayed in various ways. Such processing, known as string manipulation, is the type of processing for which TRIX was designed. In DCSM, data are used mathematically to create new quantities of interest that are usually displayed in graphical form. MATHSY is a mathematics and graphics language developed for such tasks. Reference 64 provides a complete description of the system.

The DCS program comprises three parts:

- A table of properties.
- Data-independent routines.
- Data-dependent routines.

The properties table defines the data stored in the system. These definitions are used in the data-independent routines, which provide services required by any type of data. The data-dependent routines were solely designed for laser glass data. This division allows the use of the system for data other than glasses by replacing the properties table and data-dependent routines.

DCS contains commands for producing lists and tables, selecting glass by property value or composition, and creating data files for MATHSY. For

Fig. 7-59. Data correlation system.

example, Fig. 7-60 is a computer-generated list of borate and zirconate glass compositions satisfying the condition that their cross sections are between 2.5×10^{-20} and 3×10^{-20} cm². The properties appearing in the list can be varied, and any number of conditions may be specified. Other commands are available to find the date of data entry, sample numbers from common names, a description of property mnemonics (used in commands), and formatted lists.

The DCSM program contains commands to perform the functions of data retrieval, data correlation, curve fitting, and statistical calculations. There are two types of commands. One command obtains data and labels from disk files, performs a function, and displays the result. Other commands assume the data to be present in arrays and operate on those arrays. Labels are requested and displayed with the data and may be changed as required. These commands allow data to be obtained and modified in any way before the function is performed. Figures 7-55 to 7-58 illustrate the graphical features of DCSM.

References

55. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-75 (1976), pp. 195-200; *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977), pp. 2-235 to 2-247.
56. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978), pp. 2-177 to 2-178.

Borates and Zirconates with $2.5 \leq \text{cross section} \leq 3.0$
1 June 1978

Compound (mole %)	5024 L-177	5028 L-108	5008 5008	5129 K-887	5123 K-887	5128 5128	5024 5024	5028 5028
NaBO3	0.7	0.7	0.88	1.0	1.0	0	0	0
BBO3	62.9	60.0	27.85	54.0	61.9	0	0	0
LiBO3	12.8	0	0	45.0	37.8	0	0	0
BaO	16.8	30.0	9.88	0	0	0	0	0
LaBO3	4.8	0	7.83	0	0	0	0	0
AlBO3	0	2.3	0	0	0	0	0	0
SiO2	0	0	17.8	0	0	0	0	0
CaO	0	0	23.88	0	0	0	0	0
NaF3	0	0	0	0	0	2.0	1.8878	4.2
ZrF4	0	0	0	0	0	50.0	50.628	53.0
NaF	0	0	0	0	0	25.0	0	2.4
BaF2	0	0	0	0	0	25.0	25.78	22.0
LaF3	0	0	0	0	0	0	5.8378	0
LiF4	0	0	0	0	0	0	0	7
LiF	0	0	0	0	0	0	0	6.9
PbF2	0	0	0	0	0	0	0	1.8
AlF3	0	0	0	0	0	0	0	0.8
CeF3	0	0	0	0	0	0	0	0.4

Fig. 7-69. Example of properties table generated by the glass data correlation system.

57. B. R. Judd, "Optical Absorption Intensities of Rare-Earth Ions," *Phys. Rev.* **127**, 750 (1962).
58. G. S. Ofelt, "Intensities of Crystal Spectra Rare-Earth Ions," *J. Chem. Phys.* **37**, 511 (1962).
59. R. D. Peacock, "The Intensities of Lanthanide f-f Transitions," *Structure and Bonding* **22**, 83 (1975).
60. W. F. Krupke, "Induced-Emission Cross Sections in Neodymium Glasses," *IEEE J. Quant. Electron.* **QE-10**, 450 (1974).
61. O. K. Deutschbein, "A Simplified Method for Determination of Induced-Emission Cross Section of Neodymium-Doped Glasses," *IEEE J. Quant. Electron.* **QE-12**, 551 (1976).
62. H. F. Moll, *TRIX—An Interactive, Interpretive Language for Manipulating Strings of Characters*, Lawrence Livermore Laboratory, Livermore, Calif., UCID-30100 (1976).
63. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977), p. 2-359.
64. R. A. Saroyan, *Production of a Handbook: Nd-Doped Glass Spectroscopic and Physical Properties*, Lawrence Livermore Laboratory, Livermore, Calif., UCID-18094 (1979).

Authors

S. Stokowski
R. A. Saroyan

Major Contributors

M. Weber
J. Lynch
B. Jarman
W. Hamilton

Fluorescence Sensitization. More efficient Nd:glass amplifiers could be constructed if a greater

fraction of the flashlamp energy were used in generating excited Nd ions. Present Nd-doped laser disks absorb only 40% of the xenon flashlamp radiation available in the 340- to 950-nm wavelength region. Codoping laser glass with a sensitizing ion, i.e., an ion that absorbs flashlamp energy not absorbed by Nd and transfers it to Nd, can raise the amplifier efficiency.

An ion must have the following characteristics to be a good sensitizer of Nd:

- Absorption bands in spectral regions where Nd³⁺ does not absorb.
- Efficient energy transfer to Nd³⁺.
- No significant quenching of the Nd³⁺ ⁴F_{3/2} state.

The rare-earth ion cerium (Ce³⁺) and the transition-metal ion chromium (Cr³⁺) have been considered as possible candidates for sensitization of Nd: laser glass. Preliminary experiments with Ce³⁺ in silicate glasses were described in the 1975 Annual Report⁶⁵; Cr³⁺ sensitization measurements were discussed in the 1976 Annual Report.⁶⁶ Added studies of Cr³⁺ sensitization are described below; tests of Ce³⁺ sensitization are underway.

The transition-metal ion Cr³⁺ has long been considered a likely candidate for sensitizing Nd. The Cr³⁺ absorption bands, shown in Fig. 7-61, cover spectral regions that have weak Nd³⁺ absorption bands. Transfer from Cr³⁺ to Nd³⁺ is

Fig. 7-61. Energy levels and absorption spectra of Nd^{3+} and Cr^{3+} in phosphate glass.

energetically allowed, and one expects the $4F_{3/2}$ state of Nd^{3+} to be efficiently populated by Cr^{3+} absorption. However, after many unsuccessful attempts to improve Nd:laser performance with Cr, only recently has efficient Cr^{3+} cross pumping been observed, in the crystal $\text{Nd}(\text{Al,Cr})_3(\text{BO}_3)_4$.⁶⁷

The nonradiative transfer rate from Cr to Nd is obtained by measuring the Cr fluorescence decay rate as a function of Nd concentration. The decay rate W can be expressed as

$$W = W_R + W_{NR} + W_T^{NR}, \quad (6)$$

where W_R = radiative decay rate of Cr^{3+} , W_{NR} = nonradiative decay rate of Cr^{3+} , and W_T = Cr-to-Nd transfer rate (nonradiative).

The nonradiative transfer efficiency η_{NR} is given by

$$\eta_{NR} = \frac{W_T}{W}. \quad (7)$$

The presence of a sensitizer ion affects the absorption efficiency of laser glass in two competing ways:

- Some fraction of the energy absorbed by the sensitizer is transferred to Nd, which raises the overall efficiency.

- The sensitizer robs pump energy from Nd in regions where the absorption spectra of the two ions overlap, thus decreasing the efficiency. In the presence of the sensitizer, the conversion efficiency of pump energy into excited Nd ions is given by

$$\epsilon = \frac{1}{P_{in}} \int_{\lambda_1}^{\lambda_2} P(\lambda) \frac{\lambda}{\lambda_p} \left\{ \frac{\alpha_{Nd} + \eta \alpha_{Cr}}{\alpha_{Nd} + \alpha_{Cr}} \right\} \times [1 - \exp(-\alpha_{Nd}l - \alpha_{Cr}l)] d\lambda, (8)$$

where

P_{in} = input power to flashlamps.

$P(\lambda)$ = radiative output from flashlamps.

λ_p = peak fluorescence wavelength.

α_{Nd} = absorption coefficient of Nd.

α_{Cr} = absorption coefficient of sensitizer, in this case Cr^{3+} .

η = efficiency of Cr to Nd transfer.

l = thickness of material.

λ_1 = lower wavelength cutoff.

λ_2 = upper wavelength cutoff (=0.95 μ m).

The term in the braces is the fraction of the absorbed energy at a given wavelength that finds its way to Nd. Equation (8) is evaluated in a program called TRANS4, which uses the xenon flashlamp spectrum, the measured absorption spectra of Cr^{3+} and Nd^{3+} , and transfer efficiencies estimated from decay data or excitation spectra.

In 1976, we investigated Cr^{3+} sensitization in phosphate glass. On the basis of decay measurements, it appeared that the Cr-to-Nd transfer efficiency was high.⁶⁶ As a result, we tested three sets of Cr-doped Q-88 phosphate glass disks for small signal gain and compared them with standard Q-88. In all cases, we observed that the presence of Cr lowered the gain.

In 1978, we studied Cr-doped fluorophosphate and phosphate glasses to determine the source of the above discrepancy. The effect of Nd on the Cr^{3+} decay rate is shown in Fig. 7-62. Because the Cr decay was nonexponential, we approximated the actual decay function by the sum of two exponential decays. The large effect of Nd on the Cr decay rate indicated efficient nonradiative energy transfer.

However, excitation spectra showed that this transferred energy was *not* being emitted from the $Nd^{3+} {}^4F_{3/2}$ state. We calculated effective transfer efficiencies from these excitation measurements. Table 7-24 compares their values with those from

Table 7-24. Chromium-neodymium transfer efficiencies.

Glass type	Neodymium concentration (10^{20} cm^{-3})	Source	
		Excitation spectra	Decay rates
Phosphate	1.0	0.10	0.45
	3.0	0.25	0.70
	5.0	0.35	0.80
Fluorophosphate	1.0	0.05	0.35
	3.0	0.15	0.60
	5.0	0.25	0.70
	6.6	0.30	0.75

Table 7-25. Observed gain ratios in chromium-neodymium doped Q-88 A-disks.

Concentration (10^{20} cm^{-3})		Bank energy (kJ) ^a			
Neodymium	Chromium	50	100	150	200
2.91	—	1.00	1.00	1.00	1.00
1.94	0.42	0.68(0.77)	0.69(0.77)	0.68(0.78)	0.67(0.78)
1.94	0.147	0.81(0.95)	0.85(0.96)	0.86(0.96)	0.87(0.96)
2.91	0.147	0.81(0.92)	0.83(0.92)	0.84(0.93)	0.84(0.93)

^aNumbers in parentheses are theoretical ratios.

the decay measurements. From these results, we concluded that although the Cr^{3+} efficiently transferred energy to nearby Nd^{3+} ions, the quantum efficiency of these Nd ions was severely decreased by back-transfer to Cr^{3+} . We substantiated this conclusion by observing a decrease in the Nd^{3+} lifetime at high concentrations of Cr^{3+} .

Added confirmation of this conclusion is provided by a comparison of the calculated and measured gains of the Q-88 disks, using the lower transfer efficiency obtained from the excitation spectra in the TRANS4 program. The ratios of the small signal gains appear in Table 7-25. We predict the correct ordering of gains, but the Cr-doped disks have 10 to 12% less measured gain than our best prediction. This difference can be explained by our hypothesis that some excited Nd ions are quenched because of Cr. This quenching process is not included in our calculations.

To further support this theory, we find that as Cr is added to Nd-doped fluorophosphate glass, the strengths of the Nd excitation bands decrease. This also indicates quenching of Nd^{3+} . At a chromium sesquioxide (Cr_2O_3) concentration of $0.39 \times 10^{20} \text{ cm}^{-3}$, 7% of the Nd ions appear to be quenched. This result approximately agrees with the phosphate gain measurements. Consideration of possible microscopic models quantifying the detailed quenching mechanism is in progress.

References

65. *Laser Program Annual Report—1975*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-75 (1976), p. 201.
66. *Laser Program Annual Report—1976*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-76 (1977), p. 2-263.
67. H. D. Hattendorff, G. Huber, and H. G. Danielmeyer, "Efficient Cross Pumping of Nd by Cr in Nd (Al, Cr) (BO₃) Lasers," *J. Phys. C: Solid State Phys.* **11**, 848 (1978).

Author

S. Stokowski

Major Contributors

M. Weber
R. A. Saroyan
C. Layne
R. Morget
G. Linford
S. Yarema

Faraday Rotator Materials. We have continued a small effort on more cost-effective Faraday rotation materials for use in optical isolators for Nd fusion lasers. A figure of merit for a Faraday rotator material oriented perpendicular to the beam is nV/η_2 . Our search has concentrated on paramagnetic materials with larger Verdet constants V , smaller nonlinear refractive index η_2 , and lower cost paramagnetic rotator ions. The work in 1978 was mainly an extension of the activities described in last year's report.⁶⁸

Low- η_2 fluorophosphate glasses developed as hosts for Nd^{3+} laser ions are also usable as hosts for Faraday rotator ions. Owens-Illinois, under a contract with LLL, has melted several terbium ion (Tb^{3+})-containing fluorophosphate glasses. The compositions of three glasses are in Table 7-26; measured Verdet constants and estimated nonlinear indices at 1064 nm are in Table 7-27 and compared with FR-5 glass. Glass GS-320 has the highest figure of merit but has a tendency to crystallize even in small sizes. GS-309 can be made in large sizes (10-cm-diam pieces were supplied), but its figure of merit is significantly lower than that for FR-5. The glass labeled FR-7 was based on Hoya's composition⁶⁹; it offers a 10% improvement in figure of merit over that for FR-5.

Table 7-26. Compositions of fluorophosphate Faraday rotator glasses prepared by Owens-Illinois (mol %).

Compound	Formulation		
	GS-309	FR-7	GS-320
P ₂ O ₅	5.0	14.29	1.00
Al ₂ O ₃	15.0		3.00
AlF ₃			32.00
LiF			2.75
NaF		12.57	2.75
MgF ₂		25.14	6.19
CaF ₂			19.94
SrF ₂			6.19
BaF ₂	60.0	25.14	6.19
TbF ₃	20.0	22.86	20.00

The Owens-Illinois results confirm the results of other studies at Hoya and Kigre to the effect that improvements obtainable by the use of fluorophosphate glasses are modest, at best. The improvement achieved by lowering n_2 is nullified by the lower Verdet constant due to the inability to incorporate a high density of Tb³⁺ into the present fluorophosphate glasses.

Crystalline KTb₃F₁₀ has a larger Verdet constant and a lower n_2 value at 1064 nm than those for the best Faraday rotator glasses. This material, whose properties are described in Ref. 70, has been grown by the Czochralski method but only in small sizes. The material is grown from a non-stoichiometric melt.

In preparation for further growth efforts, the Crystal Physics Laboratory of MIT conducted phase diagram studies. Sanders Associates used this information to grow large single-crystals of KTb₃F₁₀ under a purchase order from LLL.

Crystals of 35-mm diam were grown in 1978; the final objective of this exploratory effort is 70-mm diam crystals.

Because the material is cubic, it is amenable to hot forging to increase the diameter. Samples of KTb₃F₁₀ crystals were sent to Honeywell to investigate this possibility. The work at Sanders-M.I.T. and Honeywell was supported under contracts from the DOE Office of Laser Fusion.

A major factor contributing to the high cost of Tb³⁺-doped Faraday rotator materials is the high cost of terbium compounds. Among alternative paramagnetic ions, we considered Ce³⁺.⁶⁸ When present in concentrations of ≥20 mole % in CaF₂, this material has a figure of merit comparable to or greater than that for FR-5. Attempts to grow high optical quality, 10-cm diam crystals of 30 mole % CeF₃ at Optovac proved to be difficult; the prospects for 20 to 25 mole % CeF₃ are more promising.⁷¹ Because the CaF₂:CeF₃ crystal is cubic, it can also be hot-forged to increase the diameter. The Verdet constant is only about one-third that of FR-5; thus, to obtain the same rotation in a given field, three times more volume of material is required. The final cost per unit volume of producing this material in the size and quantity needed for Nova is being investigated.

We have also surveyed materials for Faraday rotators operating in the 250- to 300-nm region. The Verdet constant and nonlinear index are again important, but the absorption coefficient is also a consideration. Absorption, which is negligible or a solvable problem at 1064 nm, severely limits the selection of Faraday rotation materials. None of the presently used Faraday rotator materials at 1064 nm is applicable for the 248- to 266-nm spectral region because both Ce³⁺ and Tb³⁺ absorb strongly at these wavelengths.

Table 7-27. Verdet constant at 27°K, estimated nonlinear index, and figure of merit at 1064 nm for terbium-doped fluorophosphate glasses (FR-5 included for comparison).

Glass	Tb ³⁺ (10 ²¹ cm ⁻³)	V(min-Oe ⁻¹ cm ⁻¹)	n_D	$n_2(10^{-13} \text{ esu})$	$n_D V/n_2$
GS-309	2.83	-0.019	1.579	1.33	0.023
GS-320	4.11	-0.027	1.470	0.65	0.061
FR-7	4.75	-0.035	1.546	0.97	0.056
FR-5	7.8	-0.071	1.686	2.4	0.049

We considered only paramagnetic materials because large diamagnetic rotation is accompanied by unacceptably large n_2 values. For paramagnetic materials, $V \propto (\lambda^2 - \lambda_1^2)^{-1}$, where λ_1 is an effective transition wavelength. At 250 nm, the $\lambda^2 - \lambda_1^2$ difference is much smaller than at 1064 nm and the V is correspondingly larger. Thus, the paramagnetic ion concentrations required to achieve a given rotation at uv wavelength are modest.

Of the various transition and posttransition groups, trivalent rare earths again include some promising candidates for uv rotation. Figure 7-63 shows the extent of the energy levels of the $4f^n$ and

$4f^{n-1}5d$ electronic configurations of trivalent rare earths.^{72,73} At 250 nm ($40,000 \text{ cm}^{-1}$), 5d band-absorption rules out Ce^{3+} and Tb^{3+} . Except for praseodymium (Pr^{3+}), thulium (Tm^{3+}), and ytterbium (Yb^{3+}) ions, all other rare earths have f-f transitions that overlap or are near the desired wavelength range. (In some cases, depending on the exact operating wavelength, the absorption may be negligible.) Because Pr^{3+} combines the advantages of no nearby f-f bands and low-lying 5d bands (hence, large λ_1), we chose it for study.

Host materials that are transparent (low loss) at $\approx 250 \text{ nm}$ and can be heavily doped with rare

Table 7-28. Praseodymium Faraday rotator materials.

Composition	Structure	Density (g/cm^3)	$\text{Pr}^{3+}/\text{cm}^3$	n_D	ν
$\text{Pr}(\text{PO}_3)_3$	Glass	3.32	5.30×10^{21}	1.5896	≈ 60
CaF_2 -5 wt% Pr	Cubic	3.38	5.13×10^{20}	1.4457	≈ 92
PrF_3	Hexagonal	6.28	1.91×10^{22}	~ 1.60	

Table 7-29. Lasers and wavelengths used for measuring Verdet constants.

Lasers	Wavelength (nm)	Operation
Nd:YAG (4th harmonic)	266	P
Rh 6G (2nd harmonic)	273-300	P
He-Cd	325	CW
He-Cd	442	CW
He-Ne	633	CW
Nd:YAG	1064	CW

earths include both glasses and crystals. Borate, phosphate, and silicate glasses that transmit 250-nm radiation (of low intensity) are known, although some band-edge absorption and large Fresnel losses may be present. Incorporation of 5 to 10% Pr sufficient for rotation in moderate magnetic fields should not be a serious problem. Fluoroberyllate glasses are good uv-transparent materials if oxygen and other impurities are controlled. Based on our results, doping of these glasses to rare-earth ion densities of several times 10^{21} cm^{-3} is possible.

Fluoride crystals are good host possibilities because of their large band gaps and small n_2 values. Candidates include solid solutions of cubic $\text{CaF}_2 \cdot x\text{RF}_3$, cubic $\text{KY}_{3(1-x)}\text{R}_3\text{F}_{10}$, and uniaxial $\text{LiY}_{1-x}\text{R}_x\text{F}_4$ and RF_3 ($\text{R} \equiv$ trivalent rare earth).

We measured the Faraday rotation of one glass, a metaphosphate from NBS, and two crystalline fluoride materials, from Optovac, containing Pr^{3+} . Table 7-28 summarizes the compositions and several physical properties. Sample sizes were roughly 10-mm diam by 15-mm long. We measured Verdet constants using a dc magnetic field (to 1.2 T) and the pulsed (P) and continuous (CW) lasers and wavelengths listed in Table 7-29. The Verdet constants measured at 295 K are in Table 7-30. The experimental accuracy ranged from $\pm 4\%$ at 266 nm to $\pm 6\%$ at 1064 nm. Our data for

$\text{Pr}(\text{PO}_3)_3$ agree well with the results of Berger et al.⁷⁴ in the 400- to 700-nm region. No meaningful data were obtained for the PrF_3 crystal. Observation in a polariscope indicated that the PrF_3 was badly strained or not a single crystal.

The data in Table 7-30 were least-squares-fit to the following simple⁷⁵ expression for the wavelength dependent of the Verdet constant:

$$V = K/\lambda_t^2 - \lambda^2 \quad (9)$$

We omitted the datum at 442 nm because it is affected by the strong f-f transition at this wavelength (Fig. 7-64). The constants K and λ_t in Eq. (9) are in Table 7-31. The effective 4f-5d transition wavelength λ_t reasonably agrees with the position of the lowest 5d band, given by λ_{5d} in Table 7-31.

For comparison, the Verdet constant of FR-5 glass at 1064 nm is -0.071 min/Oe-cm . On a per ion

Table 7-30. Verdet constants measured at 295 K.

Material	Wavelength (nm)					
	266	280	325	442	633	1064
$\text{Pr}(\text{PO}_3)_3$	-1.883	-1.635	-0.761	-0.086	-0.136	-0.042
CaF_2 -5wt% Pr	-0.172	-0.163	-0.082	-0.009	-0.017	-0.004

Table 7-31. Parameters in Eq. (9) describing the wavelength dependence of the Verdet constant. Wavelengths, λ_{5d} , of the lowest 5d band and reference are included for comparison.

Material	K (min-cm/Oe)	λ_t (nm)	λ_{5d} (nm)
$\text{Pr}(\text{PO}_3)_3$	4.68×10^6	216	210
$\text{CaF}_2:\text{PrF}_3$	5.35×10^5	206	219

basis, the Verdet constant for Pr^{3+} is not as large as for Tb^{3+} because of the larger $g(J+1)$ factor for the latter.⁷⁶

We recorded absorption spectra for $\text{Pr}(\text{PO}_3)_3$ and $\text{CaF}_2:\text{Pr}$ at 295 K; the former is shown in Fig. 7-64 together with the Verdet constant measurements and best-fit curve. Both samples showed some weak absorption below 400 nm, which is attributed to impurities, including Ce^{3+} . Some absorption from the tails of the lowest 4f-5d absorption band and the beginning of the host absorption band may also be present at 266 nm.

For practical use of the above materials in high-power lasers, we need data on the laser-induced damage thresholds, two-photon absorption coefficients, and nonlinear refractive indices in the ultraviolet. 2PA can arise from partially allowed 4f-6s transitions ($\approx 76\,000\text{ cm}^{-1}$) or other interconfiguration or charge transfer transitions. Experimental data on the frequency dispersion of the nonlinear index are not available.

References

68. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978).
69. Y. Asahara and T. Izumitani, *Development of Fluoride-Containing Faraday Rotation of Glass with a Figure of Merit*, Hoya Optics U.S.A., Inc., Menlo Park, Calif., First Quarterly Report, ERDA Contract #ES-77-C-03-1448 (1978).
70. M. J. Weber, R. Morgret, S. Y. Leung, J. A. Griffin, D. Gabbe, and A. Linz, "Magneto-Optic Properties of KbF_{10} and LiTbF_4 Crystals," *J. Appl. Phys.* **49**, 3464 (1978).
71. W. Hargreaves, Optovac, North Brookfield, Mass., private communication, (1978).
72. G. Dicke, in *Spectra and Energy Levels of Rare Earth Ions in Crystals*, H. M. Crosswhite and H. Crosswhite, Eds. (Wiley, New York, 1968), p. 54.
73. W. S. Heaps, L. R. Elias, and W. M. Yen, "Vacuum-Ultraviolet Absorption Bands of Trivalent Lanthanides in LaF_3 ," *Phys. Rev. B* **13**, 94 (1976).

74. S. B. Berger, C. B. Rubinstein, C. R. Kurkjian, and A. W. Treptow, "Faraday Rotation of Rare-Earth (III) Phosphate Glass," *Phys. Rev.* **133**, A723 (1964).
75. The wavelength dependence of the refractive index, which enters in the local field correction,⁶⁸ was not included.
76. E. Loh, "Ultraviolet Absorption Spectra of Pr^{3+} Ion in Alkaline-Earth Fluorides," *Phys. Rev.* **158**, 273 (1967).

Author	Major contributors
M. J. Weber	E. Hildum S. E. Stokowski

7.3.2 Glass Physics

Nonlinear Refractive Index. Activity in 1978 on the nonlinear refractive index reflected the anticipated directions of our laser fusion program toward longer pulses and shorter wavelengths.

Fusion experiments in the future may require laser pulses of up to 10-ns duration to effectively drive targets of large mass. To estimate the magnitude of the nonlinear refractive index (n_2), because no direct measurements are yet available in the nanosecond domain, we have considered the response time of the various sources of n_2 . They are the optical Kerr effect, electrostriction, thermal self-focusing,⁷⁷ and the so-called inversion saturation nonlinearity.⁷⁸

The optical Kerr response comprises two components—electronic and nuclear. The electronic polarization responds in 10^{-15} s to changes in the optical electric field. The nuclear response time is about 10^{-12} s, the time to execute a lattice vibration. The optical Kerr response thus follows the laser pulse waveform adiabatically in the 100-ps to 10-ns time domain. Hence, the experimental n_2 values measured previously,⁷⁹ with 150-ps laser pulses without the presence of the other n_2 sources, should be accurate for the optical Kerr contribution to n_2 in the 1- to 10-ns regime.

Electrostrictive index changes are caused by strains induced by gradients in the transverse electric field distribution of an intense laser pulse. The response time for this effect is A/v , where A , for fusion laser pulses, is the radius of the smallest spatial noise ripple on the pulse and v is the longitudinal sound velocity ($\approx 5 \times 10^5$ cm/s). For current Nd:glass fusion lasers, A is typically 0.5 cm and the response time is 10^{-6} s. Thus, for 1- to 10-ns fusion, the electrostrictive contribution does not grow to its steady-state magnitude.

Thermal self-focusing arises from absorptive heating and has a response time equal to that for

electrostriction. According to the work of Feldman et al.,⁷⁷ for the small absorption permissible in fusion laser components, thermal self-focusing will be unimportant for 1- to 10-ns, 1064-nm pulses.

The final source, inversion saturating nonlinearity, is not so easily dismissed. The origin of this nonlinearity is the change in the population inversion, and hence in the anomalous dispersion, of an amplifying medium during the passage of the laser pulse. Hellwarth⁷⁸ has predicted that in an ED-2 glass amplifier medium with a small-signal gain of 10, this n_2 contribution in esu is about $10^{-11} \tau$, where τ is the pulse duration in ns. For τ equal to 10 ns, this contribution would be large—1000 times greater than the typical n_2 value of 10^{-13} esu for picosecond pulses. However, this effect would be greatly reduced by operating near the line center of the lasing transition. Furthermore, the contributions for a given ion may be of either sign depending on the operating wavelength, and cancellation can be expected to occur.⁷⁸ Because the inversion saturation nonlinearity may be important for long-pulse, saturated-gain operation, this topic will be examined further.

The dispersion of n_2 at wavelengths approaching the fundamental electronic absorption edge is a subject of long-standing curiosity. As powerful ultraviolet fusion lasers step closer to reality,⁸⁰ interest in this topic becomes more widespread. At present, no experimental data are available for comparison with general theoretical predictions⁸¹ that n_2 will monotonically increase, in a Kramers-Kronig fashion, with photon energy $\hbar\omega$ up to $\hbar\omega = \mathcal{E}_G/2$ where $\mathcal{E}_G$ is the optical band gap energy. The maximum increase in n_2 over the infrared value, according to the calculation for LiF by Duthler,⁸¹ is roughly a factor of three.

We used a method of extrapolating 1064-nm n_2 data to shorter wavelengths in 1978 to estimate n_2 in silica at 266 nm. This scheme made use of the large 1064-nm data base on n_2 from previous years.⁷⁹ It also made use of the empirical rule for n_2 derived by Boling, Glass, and Owyong:⁸²

$$n_2 (10^{-13} \text{ esu}) = \frac{68 (n_d - 1) (n_d^2 + 2)^2}{n_d \left[1.517 + \frac{(n_d^2 + 2) (n_d + 1) n_d}{\delta n_d} \right]^{1/2}}, \quad (10)$$

where n_d and ν_d are the linear refractive index and Abbe number for the d-line (587.56 nm), respectively. We obtained the numerical prefactor 68 in this expression from a fit to a body of experimental data taken at 1064 nm.

To extrapolate Eq. (10), we formed a new Abbe number ν about 266 nm by selecting wavelengths in a fashion similar to those about the d-line. For this silica, this new value, ν_{266} , was about 33, compared with $\nu_d = 67$. The only remaining quantity to be adjusted for the new wavelength was the prefactor 68. Unfortunately, this quantity was not amenable to calculation, and we did not know how to scale it for wavelength.

This obstacle can be circumvented, however, by inquiring whether a silicate glass exists with $\nu_d \approx 33$ and measured n_2 in agreement with that predicted by Eq. (10). We then have some assurance that the prefactor 68 is not overly sensitive to reasonable changes of n or ν . Rather, this prefactor is indicative of the typical total oscillator strength in the variety of silica-based glass for which n_2 has been measured thus far. SF-7 has $\nu_d = 35$ and a predicted n_2 within $\sim 30\%$ of the measured value of 5.8×10^{-13} esu.⁷⁹ This agreement supports, in the absence of alternatives, the use of the prefactor 68 for extrapolation to shorter wavelengths. Hence, with $n_{266} = 1.500$ and $\nu_{266} = 33$ substituted into Eq. (10), we predict that n_2 for silica at 266 nm is $\sim 3 \times 10^{-13}$ esu, a factor ~ 3 larger than at 1064 nm.

The assumptions of the two approaches above, each of which resulted in a projected n_2 increase of $3\times$, are different. The calculation by Duthler⁸¹ neglected dispersion in n and other linear properties and only treated the increase in n_2 resulting from two-photon absorption resonance. The model of Boling et al.,⁸² on the other hand, neglected electronic resonance behavior with the assumption $\hbar\omega < \mathcal{E}_G$. Hence, the two estimations taken together imply that n_2 at 266 nm may exceed the value at 1064 nm by at least the factor 3. We will experimentally investigate this surmise in the future.

References

77. A. Feldman, D. Horowitz, and R. M. Waxler, "Mechanisms for Self-Focusing in Optical Glasses," *IEEE J. Quant. Electron.* QE-9, 1054 (1973).
78. R. Hellwarth, *Characterization of Self-Focusing Mechanisms in Laser Materials*, under subcontract 7513005 to Lawrence Livermore Laboratory, Livermore, Calif. (1974 and 1975).

79. M. J. Weber, D. Milam, and W. L. Smith, "Nonlinear Refractive Index of Glasses and Crystals," *Opt. Eng.* **17**, 463 (1978).
80. J. J. Ewing, R. A. Hass, J. C. Swingle, E. V. George, and W. F. Krupke, "Optical Pulse Compressor Systems for Laser Fusion," *IEEE J. Quant. Electron.* **QE-15**, 368 (1979).
81. C. J. Duthler, in *Theoretical Studies of High-Power Ultra-violet and Infrared Materials*, Xonics, Inc., Van Nuys, CA 91406, 5th Tech. Rept., under contract DAHC 15-73-C-0127 (1975), p. 166.
82. N. Boling, A. J. Glass, and A. Owyong, *An Empirical Relationship for Predicting Nonlinear Refractive Index Changes in Optical Solids*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-75628 (1974); also in *IEEE J. Quant. Electron.* **QE-14**, 601 (1978).

Author

W. L. Smith

Laser-Excited Fluorescence. The technique of laser-induced fluorescence line narrowing (FLN) continued to shed new insights into the local structure and interactions in glass. During 1978, we used this technique to explore

- Hole burning and ion-ion energy transfer in Nd laser glass.

- Mixed-anion glasses such as fluorophosphates.

- Structural modifications in borate glasses.

Also, we began calculations of glass structures by the Monte Carlo method. From the resulting structure surrounding a rare-earth ion, relative crystal-field parameters can be calculated and compared with data obtained from laser-excited fluorescence studies.

The optical spectra of paramagnetic ions in glass are inhomogeneously broadened due to site-to-site variations in the strengths of the local crystal field, electrostatic, and spin-orbit interactions. This inhomogeneity is not evident in glass lasers operating under conditions of small-signal gain. But, under large-signal or saturated gain conditions, hole burning in the gain profile and a slower rate of energy extraction can occur, although it is not expected to be large in present Nd laser glasses at 300 K.

We have used laser-induced FLN techniques to

- Unambiguously demonstrate the inhomogeneous nature of the $^4I_{11/2} \rightarrow ^4F_{3/2}$ laser transition of Nd^{3+} in glass.

- Measure the rate of cross-relaxation between Nd^{3+} ions in glass in spectrally different sites.

There is an intimate relation between hole burning and fluorescence line narrowing. In the technique of laser-induced FLN, a small subset of ions resonant with the laser are excited; the fluorescence resulting from this isochromat is observed. Hole burning, which involves the selective de-excitation of excited ions, is the inverse of selective excitation in FLN. The existence of resonant fluorescence line narrowing at excitation frequency ω is a necessary and sufficient condition for hole burning by a saturating beam of frequency ω .

To prove that hole burning will occur, we observed fluorescence line narrowing of the $^4F_{3/2} \rightarrow ^4I_{11/2}$ laser transition at 295 K in ED-2 silicate laser glass with Nd_2O_3 concentrations ranging from 0.1 to 6 wt%. The excitation source for the $^4I_{11/2} \rightarrow ^4F_{3/2}$ transition was an Nd:YAG laser operated at 1052, 1064, and 1074 nm. We scanned the fluorescence spectrum with a 1-m grating monochromator equipped with a cooled indium-gallium-arsenic-phosphorus photomultiplier. Because of the small thermal population in the $^4I_{11/2}$ state at 295 K ($\sim 10^{-5}$), the fluorescence was weak and we used photon-counting electronics.

Fluorescence spectra for $^4I_{11/2} \rightarrow ^4F_{3/2}$ excitation change with laser wavelength. These spectra show a small line-narrowed emission peak resonant with the laser. Nonresonant transitions between other Stark levels of $^4I_{11/2}$ and $^4F_{3/2}$ exhibit residual inhomogeneity and negligible line narrowing at 295 K. This is due to accidental coincidence of excitation transitions.⁸³

To avoid cross-relaxation, we made the Nd_2O_3 concentration small, 0.3 wt%. For a 6-wt% sample, the spectra observed under the same gating conditions and excitation wavelengths exhibited no line-narrowing.

Cross-relaxation between Nd^{3+} ions in spectrally different sites reestablishes an equilibrium spectral distribution. It leads to partial gain recovery following saturation. We measured the rate of this process by monitoring the time evolution of the FLN spectrum. For time-resolved spectra, we fed pulses into an AND gate of variable width and delay. Both the $^4F_{3/2} \rightarrow ^4I_{11/2}$ and $^4F_{3/2} \rightarrow ^4I_{9/2}$ emissions were studied. A flashlamp-pumped dye laser and a temperature-tuned lithium niobate ($LiNbO_3$) optical parametric oscillator provided tunable excitation to probe the $^4I_{9/2} \rightarrow ^4F_{3/2}$

Fig. 7-65. FLN spectra of ED-2 silicate glass 3 wt% Nd_2O_3 at 295 K. The spectra were recorded with a 50- μs gate and variable delay after the excitation pulse. The width of the initial line-narrowed peak is about twice the homogeneous linewidth⁸⁴; this width was about 25 cm^{-1} for all excitation wavelengths. Note that with increasing delay, the resonant line-narrowed peak decreases and the wings, corresponding to the other Stark transitions, increase. The spectrum at 800 μs is essentially the same as that for the broadband-excited fluorescence. The effective transfer time derived from the decay has an average value of 200 μs . For a 1-wt% neodymium oxide (Nd_2O_3) glass, the transfer time increases to $>1\text{ ms}$; for a 6-wt% Nd_2O_3 glass, it is $<100\text{ }\mu\text{s}$.

transition. We used surface excitation and observation to minimize radiation trapping at the high-energy portion of the ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{9/2}$ band.

Figure 7-65 shows several FLN spectra, normalized to unit area. We recorded these spectra with a 50- μs gate and variable delay after the excitation pulse. The width of the initial line-narrowed peak is about twice the homogeneous linewidth⁸⁴; this width was about 25 cm^{-1} for all excitation wavelengths. Note that with increasing delay, the resonant line-narrowed peak decreases and the wings, corresponding to the other Stark transitions, increase. The spectrum at 800 μs is essentially the same as that for the broadband-excited fluorescence. The effective transfer time derived from the decay has an average value of 200 μs . For a 1-wt% neodymium oxide (Nd_2O_3) glass, the transfer time increases to $>1\text{ ms}$; for a 6-wt% Nd_2O_3 glass, it is $<100\text{ }\mu\text{s}$.

Relaxation of the line-narrowed peak and growth of the inhomogeneously broadened continuum occurs by means of pairs of resonant ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{9/2}$, ${}^4\text{I}_{9/2} \rightarrow {}^4\text{F}_{3/2}$ transitions. Concentration quenching of the Nd^{3+} fluorescence involves transitions such as ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{15/2}$, ${}^4\text{I}_{9/2} \rightarrow {}^4\text{I}_{15/2}$ and, based on estimates made using Judd-Ofelt intensity parameters,⁸⁵ are predicted to occur at a much slower rate. For the 3-wt% sample, the observed ef-

fective rates of these two processes are 5000 and 600 s^{-1} , respectively. Our results also indicate that the predicted rate of ${}^4\text{I}_{11/2} \rightarrow {}^4\text{I}_{9/2}$: ${}^4\text{I}_{9/2} \rightarrow {}^4\text{I}_{11/2}$ cross-relaxation, which can affect the rate of relaxation of the terminal laser level, is very much smaller than the observed relaxation rate.⁸⁶ This indicates that multiphonon processes are the dominant source for relaxation of the ${}^4\text{I}_{11/2}$ state.

Our FLN results prove that

- The inhomogeneity of the ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{11/2}$ transition in Nd laser glasses will cause hole burning under saturating conditions.

- Hole filling by cross-relaxation will occur in the time domain of tens to hundreds of microseconds for Nd_2O_3 concentrations of a few wt% in ED-2 glass at 295 K.

To quantify the amount of hole burning, we are using the homogeneous and inhomogeneous line widths, transition probabilities, and energy level distributions obtained from present and other FLN studies.⁸⁷ We are doing this to model the distribution of Nd^{3+} energy level schemes and the rate of energy extraction. A further consequence of inhomogeneous broadening in glass is that energy extraction does not have a simple exponential time dependence.

Added complications at a laser ion site in glass ensue when more than one type of anion is present, such as in fluorophosphate glasses. This constitutes a further dimension of the usual structural disorder inherent in a glass. Upon the normal range of variation of the coordination structure another variable—the identity of the coordinating species—becomes superimposed. This variation may have two different effects:

- One is the purely statistical effect of replacing a specified number of one type of anion by another without materially altering the geometry of the first coordination shell; this makes itself felt through the different electro-negativities of the anions and the strengths of their respective bonds with the central ion.

- The other, arising from differences in the ionic radii of the two ions, causes variations not only in the geometry of the coordination structure but also in the coordination number itself. Since fluorine and oxygen ions have almost identical radii, this latter effect is negligible in fluorophosphate glasses and may be disregarded.

Most of the optical properties of Nd^{3+} in the fluorophosphate glass appear to reflect the chemical

Fig. 7-66. Site dependence of the relative nonradiative-to-radiative transition rates for the fluorophosphate glass (see Fig. 7-65) as a function of laser excitation wavelength.

nature of the bulk. C. Brecher and L. A. Riseberg of GTE Laboratories have measured these properties under an LLL contract. Results of FLN studies of absorption and fluorescence spectra and fluorescence decay have been reported in previous annual reports. These measurements give strong indications of a considerable degree of site segregation in the mixed-anion glass, with those sites having predominantly fluoride coordination excited at the shorter wavelengths, and the predominantly oxidic sites excited at the longer wavelengths. Measurements of the site-dependent fluorescent intensity tend to corroborate this assertion.

By recording total fluorescent emission at any given excitation wavelength and normalizing it in terms of a constant number of photons actually absorbed by the specimen, it is possible to derive a site-dependent relative quantum efficiency.⁸⁷ Also, with the independent measurements of total decay time, it is possible to extract the site dependence of both radiative and nonradiative decay rates. This is shown in Fig. 7-66.

We find that the average nonradiative decay rates calculated for sites on the short wavelength side of the excitation range ($\sim 100 \text{ s}^{-1}$) are consistent with multiphonon relaxation rates typical of fluoride hosts. Those on the long wavelength side ($\sim 400 \text{ s}^{-1}$) correspond to rates in oxidic hosts, again indicating a segregation of sites.

The spectra, examples of which appear in Fig. 7-67, indicate that this site segregation is far from complete. Both the phosphate and fluoroberyllate show line-narrowed spectra typical of relatively well-ordered glasses. Such spectra have clean well-resolved Stark components that can be followed systematically across the excitation range.⁸⁷

In the fluorophosphate, however, the Stark components are quite broad and poorly resolved at all excitation wavelengths. Not even at the short and long excitation wavelength extremes, where the decay time data indicate the sites to be predominantly fluoride or oxide, do the spectra sharpen up to resemble those of the pure single-anion host.

Fig. 7-67. Site variation of the emission spectrum of Nd^{3+} in the fluorophosphate glass (at 4 K) when excited at 425 nm (bottom) and 429 nm (top). The broken curves show the spectra of Nd^{3+} in the fluoroberyllate (bottom) and the phosphate (top) at the same excitation wavelengths.

Thus, while the behavior of the decay time indicates segregation of the sites by excitation energy, the spectra show that even those sites that contain preponderantly fluoride or oxide coordinators still have enough of the other type to limit the site-selection process. Measurements on other ions (notably europium, Eu^{3+}) may help confirm the nature of such mixed-anion glasses; these are currently in progress.

Spectra resulting from laser-induced fluorescence line narrowing are sensitive to structural modifications. We have applied this technique under our OBES program to study simple alkali borate glasses. In this program, the relative num-

bers of network-forming BO_3 triangles and BO_4 tetrahedra and the existence of sublquids immiscibility depend on the mole fraction of alkali oxide. Previous investigations⁸⁸ of lithium borate glasses revealed large differences in the FLN spectra of Eu^{3+} for samples containing 10 and 40 mole % of lithium oxide (Li_2O). Whereas the spectra from the two samples were similar for laser excitation on the low energy side of an inhomogeneously broadened band, at high excitation energies added lines appeared in the spectra from the 10 mole % Li_2O glass. Among the possible causes of this behavior is phase separation into a lithia-rich and a borate-rich phase. To examine this possibility further, we, in

collaboration with J. Hegarty and W. Yen of the University of Wisconsin, investigated glasses with smaller Li_2O contents approaching the case of simple boron oxide (B_2O_3).

D. Blackburn (NBS) prepared the glasses. Europium ions could not be introduced into simple B_2O_3 glass in the absence of Li_2O . The network of $(\text{BO}_3)^{3-}$ units in glassy B_2O_3 is tightly bonded by bridging oxygens. Eu^{3+} does not enter this network substitutionally (because of size), nor, apparently, as a network modifier. If, however, a network modifier such as Li^+ is present, it disrupts the network and nonbridging oxygens occur. In the vicinity of the looser structure, Eu^{3+} may be incorporated as modifier ions.

Thus, we added Li_2O until a clear glass was formed with 0.1-mole % Eu_2O_3 and the remainder, B_2O_3 . The lowest concentration of Li_2O that would form a clear glass on cooling was 3 mole %.

Figure 7-68 shows the laser-induced FLN spectra from the $^5\text{D}_0$ state of Eu^{3+} to the $^7\text{F}_1$ and $^7\text{F}_2$ manifolds. These spectra are for 3- and 40-mole % Li_2O borate samples. Laser excitation energy (cm^{-1}) is at the left of each spectrum (the spectra are not normalized to constant excitation energy). The change in line positions in the FLN spectra with excitation energy arises from differences in the local fields. The low-energy excitation portions of the FLN spectra for the two samples are very similar, suggesting that they arise from Eu^{3+} ions having equal coordination and bonding. At high-energy excitation energies, however, extra lines appear in the 3% Li_2O spectra. These lines are identical to those observed previously in a 10% Li_2O sample. They are attributed to Eu^{3+} ions in sites having a different local environment (the lines are labeled 3, 4, and 7 in Fig. 7-68).

An increase in the Eu-O covalency reduces the Racah parameters, which, in turn, lowers the $^5\text{D}-^7\text{F}$ energy separation. We have observed a similar effect for Nd^{3+} in $x\text{Li}_2\text{O} \cdot (1-x)\text{B}_2\text{O}_3$ glasses, where the $^4\text{I}-^6\text{F}$ separation decreases with increasing Li_2O content for $0 \leq x \leq 0.45$. This is already apparent from the shift of the peak at the strong $^4\text{F}_{3/2}-^4\text{I}_{11/2}$ fluorescence band at 300 K. Thus, for Eu^{3+} , the low-energy side of the inhomogeneous $^7\text{F}_0$ -to- $^5\text{D}_0$ transition corresponds to sites with stronger Eu-O interaction and covalency.

The low-energy FLN spectra suggest that one phase is similar to that of the 40% Li_2O sample. On the basis of the nephelauxetic effect, such a phase is

likely to be the Li_2O -rich phase, where the concentration of BO_4 tetrahedra may be of the same order as in the 40% sample. The 3% Li_2O sample behaves identically to the 10% sample; but it is noteworthy that for a Li_2O concentration of 3%, the Eu doping was only 0.2%. Consequently, at such concentrations, the relative numbers of Eu ions and Li ions present are roughly similar to those of the 10% sample.

We also extended laser-induced FLN techniques to measure site-to-site variations in the spectroscopic properties of excited states of optically active ions in glass. The process was illustrated for Eu^{3+} in a lithium borate glass by exciting the $^5\text{D}_1$ state and observing $^5\text{D}_0 \rightarrow ^7\text{F}_j$ fluorescence. The measured crystal-field splitting of $^5\text{D}_1$ agreed well with that predicted from the splitting of $^7\text{F}_1$. Hegarty et al. published details of the conditions necessary for obtaining FLN in excited states.⁸⁹

To relate the results of FLN to glass structure, we are calculating glass structures by the Monte Carlo method. Although FLN experiments yield crystal-field parameters,⁹⁰ one cannot directly infer a unique distribution of structures of the rare-earth sites. A better approach is to calculate glass structure from first principles, compute the relative crystal-field parameters, then compare the results of the calculation with the experiment.

We are applying the Monte Carlo method of calculating fluid structures to glasses. As used in statistical mechanics, the Monte Carlo technique is a way of enumerating, with proper weights, the microstates of the canonical ensemble. This is done with no simplifying assumptions. Because a glass is a frozen liquid, the application of the Monte Carlo technique to glass structure is a reasonable extrapolation of a well-developed method.

To apply the Monte Carlo method, one places the desired number of particles in a cube, specifies the interatomic potential, and generates a series of "snapshots" of the fluid. Each snapshot, called a *configuration*, is determined by the position of all the particles. Usually between 0.25 million and 5 million configurations are generated.

With the technique used to generate configurations, one chooses a particle at random and gives it a random but small displacement in an arbitrary direction. Thus, a new configuration is generated that differs from the old in the displacement of a single particle. Let V_i and V_f be the internal energies

of the fluid in the initial and final configurations, respectively. One then chooses a random number, say TEST, between 0 and 1. If

$$e^{-\beta(V_f - V_i)} > \text{TEST} , \quad (11)$$

the move is accepted and the new configuration is accepted. If, however, we find

$$e^{-\beta(V_f - V_i)} < \text{TEST} , \quad (12)$$

then the move is rejected, the particle returns to its previous position, and the new configuration is the

same as the previous one. The result is that the configurations are generated in such a way that the fluid is in thermal equilibrium. That is, let the probability of appearance of two configurations i and j of total energy E_i and E_j be p_i and p_j . Then in the limit of an infinite number of steps, above, it can be proved that

$$\frac{p_i}{p_j} = e^{-\beta E_i / e} e^{-\beta E_j / e} \quad (13)$$

and the system is in thermal equilibrium. The ensemble averages of statistical mechanics, which gives the relevant quantities of an equilibrium fluid, are given by an average over all the configurations.

For an ionic system, the elementary volume is replicated periodically so that edge effects are minimized. Further, the Coulomb force is evaluated as the Ewald sum.⁹¹ The Monte Carlo technique is feasible when the atomic constituents of the fluid interact by means of two-body potentials. This is the case for alkali and alkaline earth fluorides, highly ionic materials for which the dominant interionic interactions are the Coulomb potential and a short-range repulsion. In particular, the method would be suitable for computing the crystal-field distributions at rare-earth sites in vitreous BeF_2 and various fluoride glasses.

As an example of some results, the radial distribution function $g(r)$ for BeF_2 is shown in Fig. 7-69. This is the average density of F^- ions a distance r away from a given Be ion. Also shown is the total number N of F^- ions within a shell of radius r of the Be ion. This latter is the volume integral of $g(r)$ from $r = 0$ to r . It is seen that in the fluid, Be^{2+} is four-fold coordinated by F^- ions at an average separation of $1.6 \text{ \AA}$. For this particular run, we have used 162 particles in a cube of edge $L = 12.9 \text{ \AA}$. The temperature was 1500°C .

References

83. M. J. Weber, J. A. Paisner, S. S. Sussman, W. M. Yen, L. A. Riseberg, and C. Brecher, "Spectroscopic Studies of Rare Earth Ions in Glass Using Fluorescence Line Narrowing Techniques," *J. Luminescence* **12/13**, 729 (1976).
84. T. Kushida and E. Takushi, "Determination of Homogeneous Spectral Widths by Fluorescence Line Narrowing in $\text{Cu}(\text{PO}_3)_2:\text{Eu}^{3+}$," *Phys. Rev. B* **12**, 824 (1975).
85. T. Kushida, *J. Phys. Soc. Japan* **34**, 1318 (1973).
86. W. E. Martin and D. Milam, "Direct Measurement of Gain

Fig. 7-69. Radial distribution function $g(r)$ of F^- ions at a distance r from a Be^{2+} ion and the total number N of F^- ions within a sphere of radius R about the Be^{2+} ion.

Recovery in a Saturated Nd-Glass Amplifier," *Appl. Phys. Lett.* **32**, 816 (1978).

87. C. Brecher, L. A. Riseberg, and M. J. Weber, "Line-Narrowed Fluorescence Spectra and Site-Dependent Transition Probabilities of Nd^{3+} in Oxide and Fluoride Glasses," *Phys. Rev. B* **18**, 5799 (1978) and *J. Luminescence*, in press.
88. M. J. Weber, J. Hegarty, and D. H. Blackburn, "Laser-Induced Fluorescence Line Narrowing at Eu^{3+} in Lithium Borate Glass," in *Boron in Glass and Glass Ceramics* (Plenum Press, New York, 1978), p. 215.
89. J. Hegarty, W. M. Yen, and M. J. Weber, "Spectroscopic Properties of Excited States of Ions in Glass Measured using Laser-Induced Fluorescence Line Narrowing," *Phys. Rev. B* **18**, 5816 (1978).
90. C. Brecher and L. A. Riseberg, "Laser-Induced Fluorescence Line Narrowing in Eu Glass: A Spectroscopic Analysis of Coordination Structure," *Phys. Rev. B* **13**, 81 (1976).
91. L. V. Woodcock, *Advances in Molten Salt Chemistry*, Vol. 3, J. Braunstein, Ed. (Plenum Press, New York, 1975).

Authors

M. J. Weber
S. A. Brawer

7.3.3 Laser Damage Program

Introduction. Damage to optical components limits the energy output from Argus, Shiva, and

Nova. The antireflection (AR) coatings used on lenses throughout Argus and Shiva are particularly vulnerable, because they experience the highest fluence and have the lowest damage threshold. The Nova design uses bare (uncoated) optics at critical locations. This increases the system's damage immunity by more than a factor of 2 and uniformly stresses coated and uncoated surfaces.

The range of optical damage thresholds in laser components is illustrated by comparing bulk, bare-surface, and coated-surface average damage thresholds for 1-ns, 1064-nm, linearly polarized laser pulses. The widely used BK-7 glass has a bulk damage threshold of 40 to 50 J/cm². Polished surfaces of BK-7, of other common optical materials, and of laser glass incur damage at about 15 to 20 J/cm².

Average damage thresholds at 1 ns for present production silicon dioxide (SiO₂)/titanium dioxide (TiO₂) thin-film coatings range from 6 to 8 J/cm² for high-reflectance (HR) coatings and polarizers and from 5 to 7 J/cm² for AR coatings. While examples of each surface with up to 100% higher thresholds have been measured in research coatings, current commercial practice yields the above averages. Our goal is to raise coating damage thresholds of production coatings to those of the better present-day research coatings.

We have conducted numerous experiments to improve the damage thresholds and to provide empirical scaling laws needed for laser design. Our experiments include

- Accurate measurement of the damage thresholds for different substrates, surface preparations, coating materials, and coating designs.
- Determination of the causes of damage.
- Identification and further development of the most promising techniques.

The Lawrence Livermore Laboratory (LLL) measurement techniques are discussed in detail in Ref. 92.

Cause of Damage. Optical damage results from absorber, heating, and finally local melting or cracking of the substrate surface or coating material. The most important sources of 1064-nm absorption by nominally transparent dielectric materials are homogeneous absorption arising from stoichiometric deviations, from defects and impurities, and, under intense laser irradiation, from absorbing plasmas initiated by avalanche breakdown.

Fig. 7-70. Absorption coefficient experienced by laser pulse in passing through film, interface, and substrate.

Measurement of absorption coefficients for thin films and surfaces has recently become possible with the development of sensitive calorimetry that can detect absorption of 1 part in 10⁵. Typical bulk absorption coefficients at 1064 nm for optical materials are 10⁻³ cm⁻¹ for BK-7 to 10⁻⁴ cm⁻¹ for fused silica. Absorption coefficients of transparent, dielectric thin films range from 1 to greater than 10³ cm⁻¹. Surface layer absorption is estimated to be in the range of 10² to 10⁴ cm⁻¹ based on a surface layer thickness estimated from ellipsometry data. Note that surface layers and thin films have about 10⁶ higher absorption than the bulk of good optical materials (Fig. 7-70 illustrates this effect). The damage thresholds of high-reflectance coatings are limited by absorption coefficients of the film materials or by the coefficient at the outermost film interface. The lower damage thresholds of AR coatings arise from high absorption coefficients in the interface between the substrate and first coating

(a)

(b)

(c)

Fig. 7-71. Damage morphology of four-layer Shiva Al. coating (TiO_2 against substrate then SiO_2 , TiO_2 , and SiO_2). The har is 1.0 m long. (a) Incipient spall occurred on the surface-coating layers. (b) The surface layers lifted from the substrate. (c) Melting residue appeared on substrate after thin-film layers were removed.

layer. Initial support for this conclusion comes from the observation that damage thresholds of AR films are generally less than the thresholds of HR films of the same materials. This is so even though the layers in HR stacks experience larger standing-wave intensities than do the layers of AR films. The fact that the electric field does not penetrate to the substrate interface of HR coatings is thought to account for this threshold difference.

Also, we have shown that undercoat layers of SiO_2 , which change the interface properties, also increase the thresholds of AR films. The second result is consistent with the concept that the interfaces are always highly absorptive. Thus, the interfaces are responsible for short-pulse damage, which depends on the local absorptivity of the material. Calorimetry, which provides an integrated measure of the combined energy loss in the less absorptive bulk of the film and the absorptive interface, thus

may not be a useful tool for predicting a coating's damage threshold.

Recent experiments have demonstrated that AR thresholds

- Increase slowly with pulse duration for pulse widths between 1 and 3 ns.
- Only weakly correlate with the measured total absorption in the film and interface together. The first of these observations suggests that linear absorption is the mechanism of damage in AR films.

Finally, the damage morphology in AR films strongly supports the conclusion that interface absorption is responsible for the damage. Short-pulse damage in AR films produces micropits, which are individually visible by optical microscopy or collectively visible by eye as a haze. The electron microscope photographs⁹³ in Fig. 7-71 show the evolution of these micropits. In low-flux regions,

the damage consists of raised areas that may exhibit centrally symmetric cracking of the outer film layers [Fig. 7-71(a)]. In higher-fluence regions, a disk-shaped area is loosened [Fig. 7-71(b)] and may be blown away, exposing areas that show evidence of substrate melting [Fig. 7-71(c)]. These stages suggest the progressive expansion of small absorbers at the film substrate interface.

Recent Results. These concepts of film and interface absorption suggest explanations for the three most outstanding, 1-ns damage results obtained in 1978:

- SiO_2 overcoat layers on HR coatings,⁹⁴ yielding $15\text{-J}/\text{cm}^2$ threshold mirrors.

- Gradient refractive-index AR surfaces with up to $12\text{ J}/\text{cm}^2$ threshold.

- SiO_2 /tantalum pentoxide (Ta_2O_5) AR coatings with thresholds of $13\text{ J}/\text{cm}^2$.

SiO_2 overcoat layers increased the damage thresholds of two research HR coatings by factors of between 1.5 and 2. Recent calorimeter absorption measurements on single and multiple SiO_2 and titanium dioxide (TiO_2) layers showed that the absorption of a TiO_2 layer, exposed to the atmosphere with no overcoating, was 10 times greater than that when a TiO_2 layer was covered by an SiO_2 layer.⁹⁵ A second possible explanation was that the columnar TiO_2 crystallite layer was weak under shear stress and was strengthened by the overlayer of amorphous SiO_2 .

Gradient-index coatings have been made by leaching away, from the surface, one phase of a specially prepared two-phase glass. This process results in an index gradient (at the air-glass surface) that can lead to a low-reflection surface. We think that the increased damage threshold in this system is associated with the elimination of the thin-film interface, because the index gradient is part of the original substrate material.

Finally, the $\text{SiO}_2/\text{Ta}_2\text{O}_5$ AR coating succeeds possibly because Ta_2O_5 has a lower absorption and greater strength than presently used TiO_2 films. We are actively examining Ta_2O_5 coatings at present.

We are optimistic about developing improved surfaces for laser systems. We have received excellent support from many laboratories and vendors who are already placing the discoveries made in this program into commercial practice. We especially thank our colleagues at

- Optical Coating Laboratories, Inc.
- Battelle Northwest.

- NWC China Lake.
- Design Optics.
- Spectra Physics.
- Corning Glass Company.
- Owens-Illinois Glass Company.
- Hoya Glass Company.

Laser Damage Experiments. Most damage experiments of the past year were designed to study the issues of interface and coating absorption. These experiments included variations of substrate materials and surface preparation, coating design and deposition process, and coating materials. This section reviews the experiments and results.

Several experiments have shown that thresholds of AR films depend on the characteristics of the substrate surface:

- Thresholds for AR films on small witness samples are frequently greater than the thresholds of films simultaneously deposited on large optical elements.

- Significant threshold variations occur within sets of AR films simultaneously deposited on nominally identical substrates.

- Low thresholds are observed when AR films exhibit obvious incorporation of cleaning residue.

A wide variety of chemical and mechanical processes had been suggested as the cause of the substrate influence on coating thresholds. To test the effect of the polishing procedure, we prepared substrates of fused silica and BK-7 by conventional and bowl-feed polishing, using available cerium dioxide abrasives. We then coated the substrates with identical AR films. Damage thresholds, given in Table 7-32, were the same for either material polished by one method and higher in both materials on the bowl-feed surfaces.

The increased relative threshold of films on bowl-feed surfaces is not due to a higher threshold of the surfaces themselves; thresholds for bare conventional and bowl-feed surfaces are the same for a pulse width of 3.0 ns. The difference in film thresholds probably arises from a variation in surface chemical interactions and may be related to the relative difficulty of cleaning.

The compounds used to polish optical surfaces were an obvious source for absorbing surface-layer impurities. We chemically analyzed a wide variety of common polishing compounds and pitch lap materials. The results in Table 7-33 showed a high concentration of metallic impurities. Surface

Table 7-32. 1064-nm damage thresholds of AR coatings with and without undercoats.

Coating material	Substrate material		Polish Super (bowl- feed)	Undercoat		Damage threshold at 1 us (J/cm ²)
	Fused quartz	BK-7	Conventional	Yes	No	
SiO ₂ /TiO ₂	X		X	X		5.4 ± 0.5
		X	X	X		5.0 ± 0.5
	X		X	X		9.3 ± 0.7
SiO ₂ /Al ₂ O ₃		X		X		8.8 ± 0.7
	X		X	X		6.6 ± 0.5
		X		X		6.0 ± 0.5
	X		X	X		6.3 ± 0.7
		X		X		10.7 ± 1.0
	X		X		X	4.0 ± 0.5
SiO ₂ /ZrO ₂		X			X	4.0 ± 0.5
	X		X		X	4.9 ± 0.5
		X			X	4.7 ± 0.5
		X	X		X	8.2 ± 1.0
		X		X	X	4.6 ± 0.4
		X	X	X		8.5 ± 1.5
SiO ₂ /Ta ₂ O ₅		X		X		7.7 ± 1.0
		X	X			13.0 ± 1.5
		X	X		X	11.0 ± 1.0
		X	X			6.0 ± 1.0
		X	X	X		6.0 ± 1.0

chemical analyses of substrates polished with these compounds gave evidence that the polishing compound impurities transferred to the glass surface. High-purity polishing materials were identified and are being used to polish glass surfaces whose damage threshold will be measured.

We evaluated a single variation in the cleaning procedure before coating. This was the use of a mild acid etch, but no threshold improvement resulted. We are studying other cleaning procedures.

We studied the effects of other undercoat and overcoat layers on thin-film damage thresholds in collaboration with Optical Coating Laboratory, Inc. Thresholds of SiO₂/TiO₂ AR coatings, with undercoat layers of SiO₂ or aluminum oxide (Al₂O₃) between the substrate and first AR coating layer, were measured. Table 7-32 shows the results. From these data and other unpublished measurements, the median threshold for undercoated films is 30% higher than the median threshold without the undercoat. The variation in threshold is large in both cases, however. We think this statistical improvement with undercoats is associated with the different chemical or impurity environment.

SiO₂ overcoat layers improved the damage thresholds of two research HR coatings by factors

of between 1.5 and 2. We gave the suggested explanation for this improvement earlier.

Single half-wave coatings have damage thresholds of one-half the bulk threshold or less. It is of interest to determine how little material may be deposited on the surface before the damage threshold is reduced. To this end, we have deposited single layers of TiO₂ and SiO₂, with thickness between 2 and 50 nm, on conventionally polished BK-7. Damage thresholds for these very thin coatings could not be determined by the usual method of observing light scattering. However, based on light emission, which may not be reliable, the thresholds of very thin films appear to be high compared with thicker films. Flash evaporation of silver on the surface should increase the damage site visibility and allow accurate threshold determination.

We have conducted a program, in collaboration with Battelle-Pacific Northwest Laboratories, to determine damage threshold dependence of sputtered TiO₂ films on crystallite grain size, phase composition, and stoichiometry. The results to date (Table 7-34) indicate that damage thresholds improve as the grain size is reduced. But, there is no apparent dependence on phase composition.

Table 7-33. Impurities in polishing compounds as determined by emission spectrometry.^a

Impurity elements	MgO Code 920	SnO AV-116	Liquid 85	ZOX CE-89	Al ₂ O ₃ Microgrit 30T	Al ₂ O ₃ Microgrit 9T	Reagent grade ZnO
Al	300	<5000	_b	_b	Major	Major	<100
Cu	6	1	10	10	4	_b	3
Si	600	1000	_b	_b	1 wt%	1 wt%	<2
Fe	200	600	>1000	1000	1000	1000	_b
Ca	3000	100	2000	20	3000	3000	<2
Zn	<30	100	_b	<1	<30	<30	Major
Ni	10	60	_b	<1	5	5	<3
Cr	<10	30	_b	1000	<10	<10	<10
Ag	<1	<1	_b	_b	<1	3	<1
Sr	10	<1	>1000	1000	100	1000	<1
V	<10	<10	_b	_b	40	20	<30
Pb	<10	<10	600	60	<30	<30	<10
La	_b	_b	_b	>10 wt%	_b	_b	_b
Ba	<100	<10	>1 wt%	5000	<30	<30	<100
Nb	<30	<30	>1000	300	<30	<30	<100
Mn	10	<1	30	20	5	5	<10
Mg	_b	_b	>1000	10	500	500	<1
Na	<300	_b	100	3000	3000	_b	_b
Ti	10	_b	_b	800	800	_b	<10
Ga	_b	_b	_b	30	30	_b	_b
Zr	<10	_b	>1000	_b	_b	_b	_b

^aMeasurements made by R. L. Landingham, A. W. Casey, and R. O. Lindahl, Lawrence Livermore Laboratory. Y and Th level at 100-1000 according to x-ray fluorescence. Note the high levels of iron in most polishing compounds; Fe³⁺ and Fe²⁺ absorb 1.06-μm light.

^bNot detected.

A range of oxide and fluoride film materials was deposited in single and multilayer coatings to determine whether any of these common materials easily offer improved damage thresholds.

The oxide films studied were SiO₂, TiO₂ and multilayer combinations of the low-index SiO₂ with one of the high-index films TiO₂, Al₂O₃, zirconium oxide (ZrO₂) and Ta₂O₅. Damage thresholds were

Table 7-34. Damage threshold and coating grain size for Battelle-PNL sputtered TiO₂.^a

Sample number	Phase composition (% rutile/% anatase)	Grain size (A rutile/A anatase)	Damage threshold at 1 ns, 1064 nm (J/cm ²)
054	100/0	115/-	5.2 ± 0.8
057	100/0	150/-	3.9 ± 0.6
067	100/0	620/-	1.1 ± 0.3
056	85/15	120/120	<2
055	65/35	109/125	4.1 ± 0.7
068	60/40	100/100	2.3 ± 0.5

^aSamples supplied by W. T. Pawlewicz.

all nearly equal. However, our experience with Ta_2O_5 illustrated the danger of quickly rejecting a material and the general difficulty of improving damage thresholds with such coatings. Two $\text{SiO}_2/\text{Ta}_2\text{O}_5$ AR coatings had damage thresholds of 11 J/cm^2 without undercoat and 13 J/cm^2 with undercoat. A second run designed to repeat these results gave coatings with thresholds of 4 to 6 J/cm^2 . No difference in deposition procedure is presently known that could account for this difference.

Trials of fluoride films were motivated by

- A single example of a moderately high threshold for 150-ps pulses of 6 J/cm^2 .

- The ability of a sodium fluoride (NaF)/ Al_2O_3 multilayer to withstand high repetition-rate uv exposure.

- The expectation that low-index, wide-band-gap films should ultimately have the highest thresholds.

We tested single layers of magnesium fluoride (MgF_2), NaF , cryolite (Na_3AlF_6) and multilayers of MgF_2 /thorium fluoride (ThF_4), $\text{MgF}_2/\text{PbF}_2$, and ThF_4 /zinc sulfide. All these films had 1-ns damage thresholds less than 4 J/cm^2 , which demonstrated that without further development and careful parametric studies, these materials offer no improvement over presently used oxide films.

The mixed fluoride-oxide combination $\text{MgF}_2/\text{Al}_2\text{O}_3$ is being studied because it can be removed from the substrate by an acid solution. After damage, the coated part can be stripped and recoated without need for optical surface refinishing. The potential problem of damage extending into the substrate surface requires further study.

A gradient refractive index surface on Corning Code 7740 Pyrex glass was found to have reflectivity comparable to multilayer AR coatings and a damage threshold about two times greater. This result stimulated efforts to develop an optical quality glass capable of forming gradient-index surfaces. Samples supplied by Corning Glass and Owens-Illinois had damage thresholds between 5 and 12 J/cm^2 . The surfaces of all samples scattered a great deal of light compared with well-polished surfaces, which made detection of threshold damage difficult. This light scattering was believed due to subsurface polishing defects exposed by the leach-etch process that forms the gradient index surface.

Laser-induced damage thresholds generally depend on the laser pulse width. Bettis et al.⁹⁶ have suggested the empirical scaling law that damage threshold increases as the square root of the pulse width. They have presented a heuristic argument for such scaling, based on the intensity dependence of inverse Bremsstrahlung plasma absorption. Because this scaling law has come to be used indiscriminately, a clear statement is needed that it has limited theoretical basis. Furthermore, and more important, LLL measurements of damage thresholds at 0.17, 1.0, 1.6, and 3.2 ns show the square root increase to be an upper limit met only by some bare surfaces. Coating thresholds increase much more slowly and some, particularly AR coatings, are nearly independent of pulse width between 1 and 3 ns.

Figure 7-72 shows the pulse width dependence of damage thresholds for conventional and bowl-feed polished bare surfaces, an HR coating, and an AR coating. In each case, the solid line corresponds to a square root pulse width dependence.

The most promising results of the past year have been

- Overcoat layers on HR coatings.
- Gradient refractive index surfaces.
- $\text{SiO}_2/\text{Ta}_2\text{O}_5$ AR coatings.

These results demonstrate that significant increases in coating damage thresholds are possible. However, the numerous experiments to date reduce the possibility that a simple change of process or material will produce a large, consistent increase in threshold. The lack of reproducibility of damage thresholds illustrates that physical and chemical parameters important to thin-film damage remain unidentified and uncontrolled. Progress is likely to result only from careful parametric studies of the processes and materials that now appear most promising.

Special Applications. We began three special application studies in 1978:

- Epoxy-coated debris shields whose surfaces are replicas of optical flats.
- Strippable AR coatings for debris shields and spatial-filter lenses.
- AR coatings that can be applied at low temperature to thermally sensitive, fluorophosphate glass.

Debris shield surfaces are damaged by target debris in the normal course of an experiment. The

Fig. 7-72. Damage threshold vs. pulse duration for (a) polished BK-7 glass, (b) mirror, and (c) AR coating.

shield is a polished glass window with anti-reflection coatings. When damaged, the shield must be repolished and recoated. Surfaces with good optical quality can also be formed by replication. A sandwich consisting of a glass window with epoxy on both surfaces is pressed between two polished surfaces to form optically flat epoxy surfaces.

Replicated debris shields with strippable coatings offer significant cost reduction over the optical polishing and coating now required to recycle a shield. Two companies, Acton Research Corporation (ARC) and PTR Optics (PTR), have produced epoxy, replicated debris shields. Damage thresholds exceeding 5 J/cm^2 at 1.0 ns have been measured on samples supplied by each vendor.

ARC provided shields of optical-quality glass, with both sides replicated, that have a transmitted-wave front distortion of $\lambda/6.5$ at 1064 nm (Fig. 7-73a). PTR produced a similar debris shield with wave front distortion of $\lambda/4.8$. PTR also fabricated epoxy replica surfaces on two pieces of commercial glass of debris-shield size; the wave front distortions were $\lambda/2.7$ and 2λ . The reduced wave front flatness was largely due to inhomogeneity in the commercial glass used as the substrate.

Four epoxy, replicated debris shields were anti-reflection-coated on both sides with cryolite and then tested in the Argus target chamber. The first test pair used debris shield substrates of normal optical quality whereas the second test pair used commercial quality glass as a substrate. Energy transmission of the commercial quality glass debris shields was about the same (i.e., within 1%) as the transmission of the optical-quality glass debris shields. With both test sets, all the incident energy was transmitted through a $150\text{-}\mu\text{m}$ -diam pinhole.

To AR-coat the debris shields, we have found that single-layer cryolite (Na_3AlF_6) films that reduce reflectance to 0.9% have a damage threshold of 5 J/cm^2 for 1-ns pulses. Such films have been used successfully on Argus and Shiva debris shields. Submersion in water removes the debris-damaged coating.

A strippable three-layer coating of MgF_2 and Al_2O_3 has been deposited at room temperature on fluorophosphate glass rods and other substrates. The coating has a damage threshold of $\sim 5.5 \text{ J/cm}^2$ and a surface reflectivity of 0.1%. It can be removed from BK-7 by an acid bath without damaging the substrate.

Facilities. The variable-pulse laser described in §2.5.3 of the 1977 Annual Report was used extensively for the study of laser-induced damage in optical coatings and glasses as well as gain saturation in laser amplifiers. We designed the system with sufficient flexibility to accommodate four to six stages of amplification with Faraday rotator isolation. Further isolation and pulse shaping from 1 to 30 ns

(a)

(b)

Fig. 7-73. Wave-front distortions. (a) Acton Research Corp. epoxy-replicated debris shield. Both the horizontal distortion of the first figure and the vertical distortion of the second illustrate 633-nm interference patterns. (b) PTR Optics replicated commercial glass. The first figure shows total transmitted wave-front distortion and the second, distortion using oil on the plate to eliminate surface contributions.

was provided by a Pockels cell shutter. Typically, the laser produced 1064-nm, 1-ns pulses with energies up to 1 J.

We made several modifications of the system to improve laser output reliability. The major change was the replacement of the original oscillator with one incorporating Shiva oscillator technology with improved single axial-mode control.

Frequency control is accomplished by a front-reflector composed of a two-plate fixed resonant-reflector coupled to a third, angularly adjustable, single-plate etalon.⁹⁷ The oscillator generates 5-mJ pulses with 70-ns full width at half-maximum at a 5-pps repetition rate. The system is aligned with these high-repetition-rate pulses. An optically triggered spark-gap, Pockels-cell arrangement carves out a

portion of the initial pulse, which is then amplified. Damage measurements are now normally made with 1-ns pulses. We have also installed a vacuum spatial filter. The vacuum cell is closed by plane parallel windows, and the lenses are not attached to the cell. This allows ample freedom in choice of beam size and divergence.

We add two new diagnostic devices to help provide rapid threshold measurements. The vidicon data-acquisition and analysis system (DAAS)^{98,99} monitored the target-plane spatial energy-profile; a Nomarski microscope with camera allowed pre- and post-shot examination of a damage site. The goal of the DAAS was to provide quantitative energy density on target for each shot. Figure 7-74 shows the results for a series of shots from the vidicon compared with the accurate, but very time consuming, hard film densitometry. We are investigating how to resolve the problems caused by electrical noise, background level drift, and incident-intensity effects.

After considering a wide variety of possibilities, we concluded that Nomarski microscopy of the irradiated site was the most sensitive and reliable method to detect laser-induced surface damage. However, irradiating the sample and then trying to find the site was laborious, requiring patience and experience to do properly. To eliminate that part of the process, we engineered a mechanical device that moved the sample from the laser beam line to a Nomarski microscope to put the irradiated site automatically in the field of view. Using kinematic holders, a sample could be mounted rapidly at any desired incident angle. Damage sites could then be located precisely for the experiment and again later, if necessary, for further examination.

It is particularly useful to photograph an irradiation site before and after damage. Comparing the photographs gives rapid, unambiguous determination of damage. It allows us to see if the damage is associated with a surface defect. Comparing "before and after" pictures also allows us for the first time to establish damage thresholds of non-smooth surfaces with confidence. Examples are shown in Fig. 7-75.

References

92. D. Milam, *Measurement and Identification of Laser-Damage Thresholds in Thin Films*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-80629 (1978); also *Optical Coatings-Applications and Utilization II*, Vol. 140, Society of Photo-Optical Instrumentation Engineers, Special Publication (1978).
93. G. F. Carrier, Corning Glass Works, did the electron microscopy.
94. J. Apfel and C. Carniglia, Optical Coating Laboratories, Inc., Santa Rosa, Calif., suggested investigation of such coatings.
95. T. Allen, Optical Coating Laboratories, Inc., Santa Rosa, Calif., Private communication (May 1979).
96. J. R. Bettis, R. A. House II, and A. H. Guenther, "Spot Size and Pulse Duration Dependence of Laser-Induced Damage," in *Laser-Induced Damage in Optical Materials: 1976* (National Bureau of Standards, 1976), NBS Special Publication 462; available from U.S. Government Printing Office, Washington, DC.
97. H. F. Hahlein and G. Schollmeier, "Analysis and Synthesis of Periodic Optical Resonant Reflectors," *Appl. Opt.* 8, 1197 (1969).
98. *Laser Program Annual Report—1977*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-50021-77 (1978).
99. W. L. Smith, A. J. DeGroot, and M. J. Weber, "Silicon Vidicon System for Measuring Laser Intensity Profiles," *Appl. Opt.* 17, 24 (1978).

Authors

W. H. Lowdermilk
D. Milam
G. R. Wirtenson
F. Rainer

Major Contributors

W. L. Smith
R. L. Landingham
A. J. DeGroot
S. Paluso
G. E. Murphy

(a)

(b)

Fig. 7-75. Graded-index, surface site (a) before irradiation and (b) after irradiation. The damage sites are circled.

7.4 Theory and Design Analysis

The Theory and Design Analysis group concentrated on propagation, damage, and pumping issues for the Nova project.

We carried out an in-depth analysis of the impact of gas-filled beam transport tubes to extend the work reported last year. An assessment of the propagation effects of stimulated Raman scattering was made using a propagation program and an accurate estimate of the cross section. Broullion and turbulence effects were negligible.

Statistical analysis of surface damage data was carried out to delimit the possible mechanisms responsible for failure of coatings and bare surfaces. We achieved considerable insight and developed a useful technique for determining failure confidence bounds.

Detailed experimental, calculational, and analytical efforts resulted in a good understanding of pinhole edge loadings effects and in a viable

pinhole strategy for Nova. This problem was difficult because of the complicated interaction of the effects of noise sources, apodization, nonlinear propagation, filter stripping of high spatial frequencies, and spatial-filter image relaying. We proved many of the developed methods on Argus and Shiv.

We heavily used the full-diffraction laser system simulation program Malaprop in investigating the performance of various Nova chain layouts. The use of this powerful tool permitted us to

- Develop an understanding of the various interacting factors that influence chain performance.

- Produce a combination of filter lengths, interfilter distances, and pinhole sizes that maximize Nova performance within the constraints of building size, peak fluence levels, and far-field beam quality (focusability).

Reflector design in disk amplifiers is important to amplifier performance; high-efficiency reflectors reduce the required bank size and cost. Undertaking a computational approach to reflector analysis, we have used normalization of its results to experimental data to

- Increase our understanding of amplifier operation.

- Support our selection of optimum amplifier configurations for Nova.

Author

J. B. Trenholme

7.4.1 Propagation in Long Air Paths

The wave front of an intense laser beam propagating through a long air path is distorted by the linear process of random refraction by density fluctuations (turbulence and acoustic waves). It is also distorted by the nonlinear processes of self-focusing and stimulated Raman scattering. Although these effects are expected to be small in a low-density medium such as air, they may be significant in Nova because of the long air-path lengths involved. The linear process is potentially a problem with laboratory air, depending on the local sources of disturbances. In quiescent air in enclosed beam pipes, however, experience with the alignment beams on Shiva¹⁰⁰ shows clearly that the fluctuations are small enough to be negligible. The well-known scaling laws for refractive effects then predict that this will also be the case for Nova.

Turning to the nonlinear phenomena, let us consider self-focusing in air. The electronic contribution to the nonlinear index may be estimated from measurements of second and third harmonic generation¹⁰¹ in gases at 684 nm. We expect the nonlinear susceptibility of dry air to be independent of its frequency arguments in the near infrared, because the first excited states of nitrogen and oxygen are near 10 eV. Thus, we estimate the electronic nonlinear index to be

$$\gamma_{\text{el}} = 9_{-5}^{+3} \cdot 10^{-19} \text{ cm}^2/\text{W. Amagat} . \quad (14)$$

We have calculated the rotational contribution to the nonlinear index at $1 \mu\text{m}$, assuming that the linear susceptibility satisfies the equation

$$\chi_{11} = \chi_{22} = \sigma \chi_{33} \quad (15)$$

and that all self-diagonal elements (ξ_{13} , etc.) are zero. The rotational contribution is quite sensitive to the parameter σ , which has been measured in optically induced birefringence and has been calculated in a number of formalisms. Theoretical results, summarized by Brandt,¹⁰² agree with experiments to within 10%. The best value is

$$\sigma = 0.68 \pm 0.07 , \quad (16)$$

which gives

$$\begin{aligned} \gamma_{\text{rot}} &= 2.39 \cdot 10^{-18} [3(1 - \sigma)/(1 + 2\sigma)]^2 \\ &= [3.96 \pm 0.4] \cdot 10^{-19} \text{ cm}^2/\text{W. Amagat} . \end{aligned} \quad (17)$$

Rotational relaxation time equals transverse relaxation time for stimulated Raman scattering. This has been estimated to be 2 ns at atmospheric pressure. For pulse lengths longer than 2 ns, the nonlinearity of air might perhaps be 50% larger than its value at 100 ps.

Table 7-35 presents the contribution to the total chain B-integral from the air in a nominal Nova arm for the full range of design pulse widths. The rotational contribution certainly freezes out below a certain pulse length; but, in view of the uncertainty in relaxation time, it has been fully included in each row. In Table 7-36, contributions from the air between spatial filters are compared with those from the glass for the baseline Nova design. The effect of the nonlinear index appears to be substantial. In Shiva, a final air path B-integral of $B \sim 1$ is sufficient to increase the growth of irregularity peaks by 50%. This increase is unusually large because of the combined effects of long propagation path and medium nonlinearity. Figure 7-76 shows typical peak intensity growth of a typical Shiva beam (as modeled by Malaprop) as it propagates from the final δ -amplifier to the target lens, a distance of some 24 m. In Nova, however, this effect is weaker due to improved relaying, as shown in Fig. 7-77.

Finally, we have estimated the effects of stimulated Raman scattering. The line shape of the Q-branch of nitrogen at 1 atm contains both

Table 7-35. Air B-integrals for Nova chain.

Pulse length (ns)	B(e2)	(Be2+rot)	Fraction of B (air) experienced in final air path
0.1	2.99	4.30	0.592
0.3	2.92	4.20	0.549
1	2.00	2.88	0.509
3	1.11	2.60	0.468
10	0.42	0.60	0.459

Table 7-36. Ratio of B(air) to B(glass).

Chain elements	B(air)/B _g	B(e2+rot)/B _g
1-7	0.0522	0.0751
8-14	0.0677	0.0974
15-21	0.0744	0.107
22-26	0.0933	0.134

homogeneous and inhomogeneous portions,^{103,104} with the high angular momentum lines comprising the inhomogeneous part. Because the Raman gain

Fig. 7-76 Peak intensity growth of Shiva beam over the distance from the amplifier to the target lens, as modeled by Melagrop.

under bandwidth-limited conditions sensitively depends on the line widths of both portions, and because the transverse-relaxation times of each are widely disparate (0.05 and 2 ns, respectively), we must calculate the approximate gain exponents for

Fig. 7-77 Peak intensity growth of three lines. The effect is neither linear nor expected result.

Table 7-37. Homogeneous Raman gains.

Pulse length (ns)	Total gain	Final air path
0.1	25	15
0.3	39 ^a	21
1	39 ^a	20
3	23	11
10	9	4

^aIndicates potential for observing significant Stokes energy.

both homogeneous and inhomogeneous lines. Tables 7-37 and 7-38 present these estimates. The actual exponent lies between these two extremes, depending on the details of line shape and pulse length.

If spatial filters limit Stokes radiation entering the final air path to less than 1 W/cm², as seems likely at present, there is insufficient Raman gain to cause a problem. In any case, the Stokes wave may be suppressed either by pumping the final air path down to 100 mb or by filling with helium or even with argon, which has a similar nonlinear index but no Raman lines at 1 μ m.

In conclusion, long air paths cause self-focusing, excitation of parasites, and random refraction. Both of the nonlinear processes, if present, may be controlled either by pumping the final air paths down to ≥ 100 mb or by filling them with an inert gas, such as helium.

References

100. E. S. Bliss, Lawrence Livermore Laboratory, Livermore, Calif., private communication.
101. G. H. C. New and J. F. Wurd, *Phys. Rev.* **185**, 57 (1969)
102. M. A. Brandt, D. A. Truhlar, and F. A. Van-Catledge, "Electron Scattering by Nitrogen Molecules: Theory and Application to Elastic Scattering and Rotational Excitation at 30-75 eV," *J. Chem. Phys.* **64**, 4957 (1976)
103. B. E. Kincaid and J. R. Fontane, "Raman Cross-Section Determination by Direct Stimulated Raman Gain Measurements," *Appl. Phys. Lett.* **28**, 12 (1976)

Table 7-38. Inhomogeneous Raman gains.

Pulse length (ns)	Total gain	Final air path
0.1	12	7
0.3	24	13
1	38 ^a	19
3	49 ^a	23
10	49 ^a	23

^aIndicates potential for observing significant Stokes energy.

104. A. M. Maker and R. P. Terhune, *Stimulated Raman Scattering*, Ford Motor Company, Detroit, Mich., unpublished report (1964).

Author

D. Eimerl

7.4.2 A Statistical Analysis of Absorptive Laser Damage in Dielectric Thin Films

The output energy of high-energy fusion lasers (such as Nova) is limited by damage to coated optical components in the beam. An increase in the damage resistance of the coatings is thus reflected in an increase of the laser's output. To increase the damage level, LLL has assumed technical direction of an extensive program in coating research.¹⁰⁵

Understanding the underlying physical processes of damage is important to the production of more resistant coatings. Also, analysis of damage data is a useful source of information on damage processes.

We thus studied possible damage mechanisms and did a statistical analysis of damage data in an attempt to delimit possible damage sources. A useful secondary result of this effort was an accurate mathematical description of damage statistics. This would allow coating users and vendors to describe coating quality and to set confidence limits.

Two physical mechanisms are most likely responsible for initiating breakdown of solid dielectric thin films and bulk materials when irradiated by a laser: the avalanche and multiphoton ionization processes.¹⁰⁶ This subsection deals with how to deconvolute such presumed breakdown dependence on both mechanisms.

We statistically analyzed time-to-damage and intensity-to-damage data compiled in Ref. 107 for various sputtered thin-film dielectric samples of SiO₂, ZrO₂, and Al₂O₃. These samples were damaged with temporally square pulses obtained by switching out the central portion of the output from a single-longitudinal-mode, single-transverse-mode Q-switched laser. For a given base pulse intensity I , the time delay to damage t_d , was measured from the width of the transmitted pulse. These values were obtained to $\sim \pm 2.5\%$ accuracy.

The failure data are analyzed with the Weibull distribution, a distribution previously found to fit the failure data of electrical components and of dc-material breakdown.¹⁰⁸ It is one of a class of distributions derivable from the probability theory of

extreme events, that is, the statistical theory of maxima and minima.¹⁰⁹ For minima, this is predicated on a "weakest link" concept. This presumes that there exist flaws in a body that weaken it. If the flaws are distributed inhomogeneously, they will provide a distribution of strengths as a function of material position. Each position requires a different degree of force to produce breakdown. When the actual material performance is dominated by its "weakest" segment, the use of minima statistics is in order.

The Weibull distribution function is given by the formula¹¹⁰

$$F(y) = 1 - e^{-(y/\alpha)^\beta} \quad y \geq 0, \quad \alpha, \beta > 0, \quad (18)$$

where y denotes the random variable

$$y = \lim_{n \rightarrow \infty} y_n = \lim_{n \rightarrow \infty} \min \{X_1, \dots, X_n\}, \quad (19)$$

comprised of the minimum of a large number of independently distributed damage random variables, X_j , with distributions

$$F(X_j) = 0 \quad X_j < 0 \\ = (X_j/\alpha)^\beta \quad 0 \leq X_j \leq \alpha. \quad (20)$$

The parameters α and β are respectively defined as scale and shape parameters with α being a characteristic failure coefficient. Plots of the density function $\delta(y)$

$$\delta(y) = \beta/\alpha (y/\alpha)^{\beta-1} e^{-(y/\alpha)^\beta} \quad (21)$$

appear in Fig. 7-78.

In plotting failure data $y_i, i=1, \dots, N$, to (1), we rank the y_i 's from smallest to largest and assign values to $F(y_i)$ as

$$F(y_i) = \frac{i}{N+1}, \quad (22)$$

Fig. 7-78. Weibull density function $\alpha = 1$.

and α and β can be determined either directly from a plot on Weibull graph paper¹¹¹ (Fig. 7-79) or from a least-squares-fit to

$$\ln \ln [1 - F(y)]^{-1} = \beta \ln y - \beta \ln \alpha. \quad (23)$$

A statistical ensemble to which Eq. (18) is fit is obtained by ranking all survival times t_d for specific values of I_B . Or, alternatively, the ensemble is obtained by ranking all I_B for specific values of t_d . Typical deductions from least-squares-fitting these data to these distributions are summarized as follows:

- The least-squares correlation coefficients r indicate that the fits of thin-film damage data to the Weibull distribution are excellent.

- Increasingly larger values of I_B lead to decreasingly smaller values of t_d .

- Increasingly larger values of t_d lead to decreasingly smaller values of I_B ; this is true because the sample experiences the damaging pulse for longer times.

- The β coefficients will in general lead to much narrower distributions for $F(I_B)$ than for $F(t_d)$.

- In some cases, the variances σ^2 are not sufficiently broad to distinguish statistics from experimental error.

Fig. 7-79. Determinations of β and $F(t_1)$ from Weibull graph.

● There may be a stabilization on the range of β values as a function of sputter bias and sputtering gas concentration (Tables 7-39A and 7-39B). More data are needed to investigate this point.

If we now plot for each sample category the median I_B values as a function of $(t_d)^q$ and least-squares-fit the result to

$$\ln I = q \ln \bar{t}_d + C_0, \quad (24)$$

the ensuing results for q and r^2 are presented in Table 7-40. By arguing that breakdown occurs when a fixed amount of heat Q_B is deposited per unit volume of the sample, the relevance of these q values can be discerned from the heuristic expression

$$Q_B = K I_B g(t_d), \quad (25)$$

where K is an effective multiphoton absorption coefficient and where the function $g(t_d)$ may be expressed as¹⁰⁷

$$g(t_d) = \begin{cases} \bar{t}_d^{-q} & \text{absence of thermal diffusion} \\ \bar{t}_d^{-2q} & \text{for thin films or long laser pulse durations in the presence of thermal diffusion} \end{cases} \quad (26)$$

Thus, for the samples studied and in the absence of thermal diffusion, breakdown caused by pure multiphoton ionization leads to a *maximal* 5-photon process. This upper limit is reduced in the presence of diffusion to a 2-photon process. The true picture is probably somewhat less than these upper limits. This is due to the availability of conduction electrons from avalanche processes or from

Table 7-39A. Weibull time-to-damage statistics for silica thin films.

N		β	$\alpha = \bar{t}_d$	r^2	μ	σ^2
No bias, no O₂						
7.4 < I _B < 7.8	7 < t _d < 19 (15)	9.27	17.93	0.938	17.00	4.83
9.6 < I _B < 10.0	6.2 < t _d < 11.2 (15)	6.28	9.36	0.983	8.70	2.61
10.0 < I _B < 10.4	2.7 < t _d < 9 (13)	1.74	7.78	0.865	6.92	7.44
11.8 < I _B < 12.2	3.3 < t _d < 4.8 (13)	8.90	4.40	0.977	4.16	0.31
Bias-sputtered						
6.4 < I _B < 6.8	7.7 < t _d < 10 (7)	9.19	8.10	0.922	7.68	1.00
6.7 < I _B < 7.1	7.4 < t _d < 9 (11)	17.89	7.81	0.915	7.58	0.27
9.4 < I _B < 10.2	3.4 < t _d < 4.5 (8)	12.20	4.18	0.935	4.01	0.15
Bias-sputtered, +O₂						
6.8 < I _B < 7.2	8.8 < t _d < 12 (11)	10.20	9.69	0.925	9.23	1.19
9.8 < I _B < 10.2	4.3 < t _d < 5.8 (11)	9.96	5.36	0.927	5.10	0.38
10.9 < I _B < 11.3	3.2 < t _d < 4.3 (10)	10.45	4.12	0.919	3.93	0.20
11.0 < I _B < 11.4	3.2 < t _d < 4.3 (9)	10.14	4.09	0.936	3.89	0.21
11.7 < I _B < 12.1	2.8 < t _d < 4 (11)	10.37	3.56	0.930	3.39	0.16

Table 7-39B. Weibull intensity-to-damage statistics for silica thin films.

N		β	$\alpha = \bar{I}_B$	r^2	μ	σ^2
No bias, no O₂						
3 < t _d < 3.3	11.3 < I _B < 13.3 (10)	19.32	12.89	0.912	12.54	0.64
3.6 < t _d < 4	11.8 < I _B < 12.4 (8)	45.68	12.24	0.895	12.09	0.11
7.8 < t _d < 8.2	7.2 < I _B < 10.7 (8)	25.51	9.92	0.951	9.71	0.22
Bias-sputtered						
3.8 < t _d < 4.2	9.4 < I _B < 10.7 (7)	20.24	9.55	0.834	9.30	0.32
7.7 < t _d < 8.4	6 < I _B < 7.2 (10)	18.26	6.97	0.737	6.77	0.21
Bias-sputtered, +O₂						
2.8 < t _d < 3.2	11 < I _B < 13.2 (11)	19.76	12.56	0.966	12.22	0.59
3.3 < t _d < 3.7	11 < I _B < 12 (8)	30.37	11.81	0.874	11.60	0.23
4.0 < t _d < 4.3	10.2 < I _B < 11.7 (10)	20.90	11.31	0.853	11.02	0.44
4.5 < t _d < 5.0	8.6 < I _B < 10.8 (9)	13.00	10.48	0.921	10.07	0.89

other excited states (excitons, for example). Because of this probable lesser limit, we feel that multi-photon events greater than 2 probably play an insignificant role in the damage process.

We also performed a similar analysis on gas breakdown for argon (Ar) at 500 psi. We obtained the same excellence of fit, but with the major difference that β was considerably less than those

Table 7-40. Breakdown intensity-pulse length scaling.

	$Q = KI_B g(t_d)$		Maximal multiphoton, no diffusion	Maximal multiphoton, diffusion
	q	r^2		
SiO_2 , no bias, no O_2	-0.325	0.992	3	1-2
SiO_2 , bias-sputtered, no O_2	-0.582	0.997	2	1
SiO_2 , bias-sputtered, + O_2	-0.532	0.993	2	1
ZrO_2 , no bias, Ar only	-0.350	0.966	3	1-2
ZrO_2 , 30% bias, no O_2	-0.221	0.950	5	2
ZrO_2 , 30% bias, + O_2	-0.232	0.740	4	2
Al_2O_3 , no bias, no O_2	-0.992	0.340	1	0
Al_2O_3 , 10% bias, no O_2	-0.442	0.973	2	1
Al_2O_3 , 10% bias, 10% O_2	-0.408	0.956	2-3	1

values reported here. This consequently led to a larger variance.

It is our contention that the Weibull distribution can be used to characteristically fit laser-induced breakdown of any material. We will wait for experimental verification of this conjecture.

To ascertain the correctness of previous physical or statistical models of breakdown, it seems fairly clear that, coupled with experimental nonobservability of higher than 2-photon absorption, $I_B (t_d)^{-q}$ fits seem to imply that the diffusion model or the avalanche mechanism or both are the most likely initiator of the plasma requisite for lattice meltdown. These fits also imply that the only other statistical avalanche mechanism for plasma creation, the lucky electron theory, is generally wrong. This is because this model predicts a failure distribution that varies on t and on the electric field $\mathcal{E} = I^{1/2}$ as

$$\Phi = 1 - e^{-\Gamma t / \tau_c}, \quad (27)$$

where

$$\Gamma = I e^{1/2 - k_1 I^{-1/2}}, \quad (28)$$

k being a constant greater than zero.* At damage threshold, this implies for a constant value of I_B a linear dependence on t_d in the exponent of (10). For a constant value of t_d , there is an exponential dependence on $I_B^{1/2}$ (Ref. 112). It seems fairly clear that the linear dependence on t_d is often incorrect. The exponential dependence of Eq. (28) on $I_B^{1/2}$, however, often seems to fit our Weibull description for the large values obtained.

The strong power-law dependencies exhibited here may be due to highly nonlinear microscopic mechanisms. In the macroscopic limit, these mechanisms are averaged out, once thermal diffusion is included, to produce near-linear absorption. Unfortunately, it is impossible from the analysis performed here to make any definitive predictions as to the exact microscopic mechanism, other than the improbability of high-order multiphoton ionizations.

We conclude by pointing out one practical diagnostic use of the Weibull distribution: statistical confidence bands for material survivability as a function of laser intensity and pulse length can be constructed.¹¹³

*The lucky electron theory as phrased by Bass and Barrett does not contain the exponential prefactor $I^{1/2}$ in Γ . A correct version of the lucky electron theory requires this prefactor. This statement will be the subject of a future article.

References

105. See, for example, T. J. Gilmartin, *Nova CP&D Final Report*, Lawrence Livermore Laboratory, Livermore, Calif., LLL-Misc-111 (1978), p. 88.
106. W. L. Smith, "Laser Induced Breakdown in Optical Materials," *Opt. Engr.* 17, 489 (1978).
107. R. H. Picard, D. Milam, R. A. Bradbury, and J. C. C. Fan, "Threshold Ambiguities in Absorptive Laser Damage to Dielectric Thin Films," in *Laser Induced Damage in Optical Materials: 1975*, National Bureau of Standards, Boulder, Colorado, NBS Special Publication 435 (1975), p. 272; available from U.S. Government Printing Office, Washington, DC.
108. J. H. K. Kao, "A Graphical Estimation of Mixed Weibull Parameters in Life Testing Electron Tubes," *Technometric* 1, 389 (1959); P. H. H. Fischer and K. W. Nissen, "The Short Time Electric Breakdown Behavior of Polyethylene," *IEEE Trans. Elect. Insul.* EI-11, 37 (1976).
109. E. Gumbel, *Statistical Theory of Extreme Values and Some Practical Applications*, National Bureau of Standards, Boulder, Colorado, Appl. Math. Series 33, (1954); available from U.S. Government Printing Office, Washington, DC.
110. G. J. Hahn and S. S. Shapiro, *Statistical Models in Engineering* (John Wiley and Sons, New York, 1968).
111. W. Nelson and V. C. Thompson, "Weibull Probability Papers," *J. Qual. Control* 3, 45 (1971).
112. D. Milam, R. A. Bradbury, and R. H. Picard, "A Statistical Analysis of Laser Induced Gas Breakdown—A Test of the Lucky Electron Theory of Avalanche Formation," in *Laser Induced Damage in Optical Materials: 1975*, National Bureau of Standards, Boulder, Colorado, NBS Special Publication 435 (1975), p. 347; available from U.S. Government Printing Office, Washington, DC.
113. A. B. Budgor and K. F. Luria-Budgor, "A Statistical Analysis of Absorptive Laser Damage in Dielectric Thin Films," in *Laser Induced Damaged in Optical Materials: 1978*, National Bureau of Standards, Boulder, Colorado, NBS Special Publication 541 (1978), p. 235; available from U.S. Government Printing Office, Washington, DC.

Author

A. B. Budgor

7.4.3 Intensity Loading of Pinholes in Vacuum Spatial Filters

Vacuum spatial filters are used in multiterawatt solid state laser systems to control and limit the peak intensity of the beam in the near field. To accomplish spatial filtering, one must repeatedly focus a high power beam through a small aperture (pinhole). If the pinhole is small enough, its perimeter will be ablated. The resulting plasma blowoff will block passage of the beam.

Figure 7-80 depicts the pinhole closure phenomenon. This figure shows a portion of the

Fig. 7-80. The pinhole closure phenomenon. A pinhole will remain clear of a refractive plasma if the beam incident upon its perimeter is 10^{11} W/cm² (1-ns pulse).

focused beam striking the perimeter of the filtering pinhole at a time early in the temporal pulse. This portion of the beam heats and evaporates material from the pinhole perimeter, creating a plasma that streams into the clear aperture of the pinhole. This plasma in turn scatters the beam (i.e., refracts the light) transmitted through the pinhole into angles larger than the acceptance angle of the output lens of the filter. Thus, it is possible for a large portion of the energy in the incident beam to be lost.

How does one avoid this problem? Succinctly stated, the answer to this question is *choose a large enough pinhole*. By this, we mean choose the diameter of the pinhole so the intensity of the light incident upon its edge is below the threshold for creating a plasma. Because the peak fluence of the near-field beam in the Nova system is 20 J/cm^2 in 1 ns, i.e., $2 \times 10^{10} \text{ W/cm}^2$, then this limit *must* be a conservative estimate for the ignition of plasma from a pinhole perimeter. Hence, we design the intensity loading on the pinholes to be between 2×10^{10} and $1 \times 10^{11} \text{ W/cm}^2$.

Let us now discuss the strategy used to ensure that the flux on the perimeter of a filtering pinhole is below the threshold for plasma ignition. Figure 7-81 summarizes the relationship between the "loading" on two consecutive pinholes in a sequentially filtered system. The lens pair located between pinholes n and $n + 1$ constitutes an imaging system. Thus, the intensity distribution appearing in the plane of the pinhole n will be imaged onto the plane where pinhole $n + 1$ is located. If (1) the imaging lens pair and the intervening space is "perfect" and

Fig. 7-81. Relationship between loading on two consecutive pinholes in a sequentially filtered system. There are three sources for light incident on the perimeter of a pinhole in a sequentially filtered system: the near-field aperture, small diameter scatters (dirt), and nonlinear beam effects.

(2) the clear aperture of pinhole $n + 1$ is slightly larger than the preceding pinhole, the intensity of the beam striking pinhole $n + 1$ would be zero. Thus, no refracting plasma would be formed. However, since this ideal situation never occurs in practice, some light will strike the perimeter of the downstream pinhole.

Figure 7-81 shows the three principal sources for this "stray" light. The first "imperfection" is the finite size of the clear aperture of the optical components located between filters n and $n + 1$. This hard aperture will truncate the near-field beam as it traverses those components, producing high frequency components in the focal plane of the downstream filter.

A second source for the stray light results from the nonlinear phase distortion that the beam accumulates while passing through the near-field optical components situated between the two filters.

The third source of "loading" on the downstream pinhole edge is any small scattering imperfections appearing in the region between the filters. Such scatterers include, for example, optical components damaged during previous firings, refractive

index inhomogeneities, and particulate matter in the beam line.

We have simulated the effects of the first two of these imperfections using a direct integration algorithm for the radially symmetric (Hankel) transform of the propagating wave front. Deferring for the moment a discussion of the mathematics involved, we present in Fig. 7-82 the calculational results that model the prototype Nova chain.

These figures show the intensity distribution in the pinhole plane and the intensity profile of the beam between filters. The calculations indicate that only moderate increases in the pinhole diameter are required to span the region for which the intensity on the perimeter of the pinhole is between 2×10^{10} to $1 \times 10^{11} \text{ W/cm}^2$. Hence, the strategy outlined here results in a high quality near-field beam and, barring too large a distribution of small scatterers, circumvents the beam-induced closure of spatial filter pinholes. We shall now comment on the methodology used in performing these computations.

We generated Figs. 7-80 to 7-82 by making use of circularly symmetric transform-pair relations

Beam profile

Filter No. 1
Power = 0.0363 TW

Filter No. 2
Power = 0.3034 TW

Filter No. 3
Power = 1.2569 TW

Filter No. 4
Power = 2.9148 TW

Filter No. 5
Power = 5.8880 TW

Pinhole irradiation

connecting a wave form $U(r)$ at the entrance plane of a lens and the wave form $U(\rho)$ on its back focal plane. Apart from phase factors, this relation may be written

$$U(\rho) = \frac{2\pi}{\lambda f} \int_0^a dr r U(r) J_0(\rho r 2\pi), \quad (29)$$

where r is the (near-field) radial coordinate, ρ is the far-field radial coordinate (scaled by a factor λf), λ is wavelength, f is lens focal length, and J_0 is the zero-th order Bessel function. This equation is the Hankel transform of $U(r)$. It is easily derivable, starting from the Fresnel-Kirchoff diffraction integral within the context of the Fraunhofer approximation.¹¹⁴

For a series of lenses, successive propagation from lens-to-focal plane-to-lens-to-focal plane-to-etc. is obtained by repeated application of Eq. (29). Defining the operation in Eq. (29) as $U_1 = H[U_0]$, one observes that the operation

$$U_2 = H^2[U_0] \quad (30)$$

takes us from input to output of a spatial filter with an established pinhole diameter at its focus. For each operation H , the limiting aperture (either pinhole or lens) is clearly defined [as the upper limit of the integral in Eq. (29), for example].

To simulate nonlinear propagation in the near field (i.e., between successive spatial filters), we make the ad hoc assumption* that the complex magnitude is modified by an intensity-dependent phase rotation B ;

$$U'_{2n} = \exp[iB|U_{2n}|^2] U_{2n}. \quad (31)$$

Beam propagation through a sequence of m spatial filters is thus modeled by the sequence of operations $H^2[U_0]$, repeated m -times.

To test the applicability of our approximation to image relaying by spatial filters, we compare

*This is equivalent to assuming that the propagation path between one spatial filter and the next is zero.

pinhole radii values with those calculated from the above prescription for the Nova prototype chain (Fig. 7-83) as predicted by Malaprop. This produces loadings $\sim 10^{11}$ W/cm². Assuming a uniphase, apodized wave form (as shown in Fig. 7-82, upper left) entering the first filter, the near- and far-field intensity profiles are sequentially calculated as shown in Fig. 7-82.

For the far-field graphs, the maximal abscissa values in each figure correspond to the 10^{11} W/cm² radius as computed by Malaprop. In order of pinhole number, these radii are 625, 660, 371, and 1347 μ m. They are to be compared with our predictions of 596, 518, 744, and 1169 μ m. The discrepancies are respectively -5, -22, -15, and -13%. Presumably, these differences result from the inclusion (by Malaprop) of small obscurations (§7.4.4) on the surfaces of the disk amplifiers and from sub-sequent growth of the resulting modulation.

Introduction of Gaussian-correlated amplitude fluctuations on the near-field amplitude did not significantly improve the agreement between models. Table 7-41 encapsulates comparisons between Malaprop and relay optics predictions for pinhole radii at the 10^{11} W/cm² loading baseline. One concludes that the present, simple algorithm underestimates pinhole radii by typically 20% for equivalent pinhole pin loading.

Table 7-41. Computed pinhole radii at 10^{11} W/cm^2 .

	Radii (μm)			
	Spatial filter 2	Spatial filter 3	Spatial filter 4	Spatial filter 5
Malaprop	625	660	871	1347
Relay optics (no noise)	596	518	744	1169
Error	-5%	-22%	-15%	-13%
Relay optics (with noise)	625	537	758	1184
Error	0%	-19%	-13%	-12%

In conclusion, we would like to delineate some trends to be expected from our pinhole loading calculations. Let us choose as input to the initial focusing lens a square pulse of unit intensity, which when Hankel-transformed into the far field, has the analytical form

$$I(\rho) = \frac{\pi^2}{4(f/2a)^2 \lambda^2} \left[\frac{2J_1(\rho)}{\rho} \right]^2, \quad (32)$$

where

$$\rho = \frac{\pi}{\lambda} \frac{r_0}{f/2a}. \quad (33)$$

Figure 7-84 compares far-field radial intensity profiles in the vicinity of a second pinhole, as a function of B , for a first pinhole radius of $50 \mu\text{m}$. The curves in white, yellow, violet, red, blue, and green represent B values of 0, 0.5, 1, 2, 4, and 8, respectively. There are several features worth mention.

First, the intensity at radii greater than $50 \mu\text{m}$, although small, is nonzero. Physically, this light appears from scattering at the (finite-aperture) entrance lens of the second spatial filter.

Second, the presence of a finite phase non-linearity B enhances larger angle components of the beam, thus increasing loading at any chosen pinhole plane.

Third, note the growth with increasing B of the intensity at the image radius of the first pinhole. This "sideband" frequency is characteristically generated by any band-limited filtering process; its growth (for small B) can be shown to be proportional to the multiplicative factor $(1 + \epsilon B^2)$, with ϵ a factor of order unity.

Finally, note the change in character around the region $B = 1$. Also note that the curves for $B < 1$ will have a 3-to-5 order of magnitude less loading on $100\text{-}\mu\text{m}$ pinholes than those curves for $B > 1$. In other words, for $B < 1$, a small change in pinhole radius produces a large change in loading. For $B > 1$, this trend is not so drastic.

Reference

114. M. Born and E. Wolf, *Principles of Optics—Electromagnetic Theory of Propagation, Interference and Diffraction of Light, Chapter VIII* (Pergamon Press, New York, 1970).

Authors

J. T. Hunt
A. B. Budgor

Major Contributor

W. W. Simmons

7.4.4 Modeling for Design of Large Laser Systems

Introduction. We have converted the fast Fourier transform (FFT) Malaprop code (discussed in detail in last year's Annual Report) to permit detailed beam-propagation simulation through spatially filtered amplifier chains. This has accurately accounted for the system performance of Argus and Shiva and has served to define spatial filtering for the larger Nova system being designed at LLL. The predictive success attained by this comprehensive code during 1978, discussed in several sections of the present report, is a direct result of two contributing factors:

- Multiple spatial filters, first used on Argus, repeatedly band-limit the propagating beam. This maintains the transverse scale of fluctuations within the spatial resolution of a reasonable computational grid.
- We have incorporated a spatial noise source that is both physically realistic and subject to independent observation.

During 1978, we installed output data and statistics characterizing the beam at callable inter-stage locations. This facilitated accurate analysis and comparison of various chain configurations. We expanded the two-dimensional version of Malaprop to a 256×256 array of grid points. The expansion permitted sufficient spatial resolution for a detailed modeling of chain amplifiers through the 34-cm disk apertures planned for Nova. The Seidel aberrations were also implemented, enabling detailed comparison of code predictions with focused-array camera data from Shiva.

Following a brief summary of the modeling procedure, we will discuss the obscuration model and each of the above implementations. Next, we will present an example Malaprop calculation illustrating the various physical effects that occur in a

typical real, nonlinear amplifier train. We will conclude with a detailed set of comparisons with Argus performance data gathered over the past three years.

Modeling Procedure. Malaprop¹¹⁵ sequentially calculates the evolution of a spatially profiled pulse as it passes through the various elements of a laser chain. Free-space propagation between elements and spatial filtering are accomplished by two-dimensional fast Fourier transform algorithms. Where nonlinear media (e.g., glass) are traversed, the appropriate paraxial differential equation¹¹⁶ is integrated using finite differences. Pinholes in spatial filters are modeled by aperture truncation in the Fourier transform plane of each spatial-filter entrance lens.

It is necessary to use the full two-dimensional version of Malaprop to realistically assess spatial noise growth and pinhole filtering. Thus, in modeling system performance where gain saturation is important, we first exercise the faster running one-dimensional version of the code. This procedure, by accurately treating gain saturation, determines individual amplifier gain settings for each time-slice of the pulse to be modeled with Malaprop II.

In practice, for fixed laser chain staging and input power, the code calculates the following set of outputs (as well as other information):

- Peak intensity at each lens in the system. This (near-field) information is important because spatial peaks must be kept below the fluence damage threshold of the lens (currently about 6 J/cm² at 1 ns for coated surfaces).
- Intensity at the perimeter of the spatial-filter pinholes. If this intensity exceeds 100 GW/cm², the plasma formed from the ablating pinhole edge can block the beam.
- Intensity distribution in the final (target) lens focal plane. This provides a measure of focusability in terms of the cumulative static aberrations acquired by the beam and the high-angle spreading caused by accumulated nonlinear phase retardation.

Knowledge of these parameters is crucial for quantitatively judging the relative merits of different spatial-filter staging strategies.

Obscuration Noise. Major laser systems such as Argus and Shiva are limited by growth in small-scale spatial fluctuations.¹¹⁷ The initial versions of Malaprop modeled this noise using stochastic amplitude and phase perturbations.¹¹⁵ Although

qualitative agreement with Argus experimental data was obtained with this noise model, the physical source of such noise remained unclear.

To facilitate the use of Malaprop as a predictive tool, we incorporated a second noise model using laboratory parameters to define randomly distributed obscurations on disk surfaces. This more physical noise model produced outstanding agreement with a wide range of Argus data.

The obscuration noise model consists of randomly setting points (or point clusters) on the Malaprop grid to zero, thus representing an opaque particle. The number of points in a cluster represents the particle size; the total number of clusters represents the total number of particles on the surface.

From laboratory examination of disk amplifiers and other sources, one estimates a particle size distribution and total obscured fraction of each surface. The obscured surface fraction, the particle size, and the number of surfaces* determine the total number of obscurations N to be randomly distributed:

$$N = \frac{(\text{surfaces}) \times (\text{fraction obscured}) \times (\text{area/surface})}{(\text{area per obscuration})} \quad (34)$$

Distribution of obscurations is made using a random-number generator to select transverse coordinates. Obscurations may be restricted to a circle centered at (0,0).

In practice, computational results are insensitive to cluster (size) distribution, although they strongly depend on N. We have thus relied (in all our simulations) on the detailed disk-damage site-count data of Stowers et al.,¹¹⁸ which leads to a fractional obscured area per disk surface of 5×10^{-5} . This parameter statistically represents the disks currently used in Argus and Shiva.

Beam Statistics. Several near-field beam statistics are calculated at each callable chain location z to facilitate comparative analysis and sensitivity studies. Table 7-42 is an example printout

*Amplifiers are generally modeled as a single glass element, with half the surfaces before and half after.

Table 7-42. Example of near-field beam statistics printout from Malaprop analysis.

P R O P 2

**ANALYSIS OF SATURATION REGION
IN SMALL SCALE SELF FOCUSING**

2 DIMENSIONAL INPUT

VERSION PROPP

ARGUS78 1.8TW .5NS AT -.15 NO DAMAGE, THIRD FILTER NOV064

09/08/78 13:43:30

INITIAL PROFILE

Z = 0.

INTENSITY STATISTICS

RADIUS 1.6554E + 00

MEAN 2.1166E + 00

RING MIN 2.1168E + 00

OUTER MX 5.7277E - 01

RMS 3.3230E - 01

FULL MAX 2.2530E + 00

DISK MIN 2.1168E + 00

POWER 1.8383E + 01

RMS/MEAN 1.5700E - 01

PUNCTURE MAX 2.2530E + 00

PMAX TO DMIN 6.4372E - 02

BEFORE THIRD FILTER

Z = 1283.1000

INTENSITY STATISTICS

RADIUS 3.8533E + 00

MEAN 8.5673E + 00

RING MIN 8.3148E + 00

OUTER MX 2.3261E + 00

RMS 1.3057E + 00

FULL MAX 9.6600E + 00

DISK MIN 8.2384E + 00

POWER 4.0400E + 02

RMS/MEAN 1.5241E - 01

PUNCTURE MAX 9.6600E + 00

PMAX TO DMIN 1.6594E - 01

(taken from an intermediate lens position during an Argus modeling run). The most frequent referents are

- **Power:** total beam power at this location in GW.
- **Radius:** nominal beam radius at this location in cm.
- **Mean:** average intensity of beam in GW/cm².
- **Root mean square (rms)/mean and rms:** statistical estimates of the spatial beam noise (referred to intensity).
- **Full max:** peak beam intensity at this location in GW/cm² (components are most prone to damage from this peak).
- **PMAX to DMIN:** defines the "modulation depth" of the beam (intensity) noise at this location. Also, one may observe other parameters, such as Outer Mx, Puncture Mx, Disk Min, Ring Min.

These parameters are included as convenient checks against pathological or anomalous propagation results.

A Propagation Example. Let us use Malaprop to illustrate the various physical effects that occur during the sequential propagation of a beam through elements that typify a real amplifier chain. In the plane $z = 0(\text{m})$, we presume that a 10-cm diam, 1- μm wavelength beam, suitably profiled spatially, encounters small obscurations that locally reduce the electric field to zero.

Figure 7-85 illustrates nine neighboring slices through the intensity profile of such a beam. The foreground slice, along a diameter of the (circular) beam, happens to contain one obscuration; there is another in the sixth slice (counting toward the back). We shall keep track of the peak-to-average (P/A) intensity ratio; it is unity in this (obscuration) plane. Its evolution with distance z and the elements to be modeled appear in Fig. 7-86.

Fig. 7-85. Initial 10-cm test beam profile cross sections. A single point obscuration appears in the front section at $x = 2$ cm.

One meter downstream ($z = 1$), diffraction has caused the P/A ratio to increase (Fig. 7-86) to 1.075, as the shoulders of the first "Airy ring" now interfere constructively with the (main) background beam. In this plane, we suppose that a thin nonlinear element ($B = 1.9$) is encountered.

With further propagation, spatial modulation grows faster for nonlinear than for linear propagation. In effect, the slope of the P/A vs z curve has been increased by the presence of the B element.

Insert a confocal lens pair (of focal length 2.25 m and unity magnification) for image relaying, and skip downstream to the image plane of the obscurations ($z = 9$ m). The (P/A) ratio is again unity for $B = 0$, but the finite nonlinearity B has aberrated the image. $P/A \approx 1.10$ in this plane. In the image plane of the nonlinearity ($z = 10$), we observe that modulation depths are identical for both linear and nonlinear cases. Thus, the imaging properties of confocal lens pairs are insensitive to phase aberrations. (The power of the image relaying technique derives directly from this property; but, as we shall see, band limiting by means of pinholes remains essential to full-chain performance.)

Still further downstream ($z > 10$ m), modulation depth in both linear and nonlinear cases has increased; the nonlinear case grows faster. In both instances, this growth is governed by diffraction. In terms of the obscuration scale length a ,

$$\left(\frac{P}{A}\right) \approx 1 + \left[\frac{(z - z_1)^2}{ka^2}\right]^2, \quad (35)$$

where z_1 is the obscuration image plane. When the beam encounters nonlinear elements, the growth rate is changed;

$$\frac{d\left(\frac{P}{A}\right)}{dz} \approx \frac{2}{(ka^2)^2} [(z - z_1) + B(z - z_2)] \quad (36)$$

beyond the nonlinear element image. [These equations are valid for $(z - z_1)$, $(z - z_2)$ less than the Fresnel length periodicity ka^2 .] Figure 7-87 shows

Fig. 7-86. Evolution of the peak-to-average (P/A) ratio with propagation along the z axis. The chart below the curves indicates component position and significant image planes. Note how the nonlinearity distorts the imaging properties of the relay element and enhances growth of P/A.

the nonlinearly modified beam profile at $z = 11.5$ m ($P/A = 1.45$).

In practice, amplifiers (and isolators) would be located in the space between the spatial filter and the image plane of its entrance lens, since the P/A ratio is smallest throughout this space. However, the P/A ratio at the output spatial-filter lens is very large (1:75). Figure 7-88 illustrates that the "valleys" created by obscurations have been turned into "peaks" by the phase-reversal effect of the image relay. The effect is quite real, and it undoubtedly accounts for occasions when output spatial-filter lenses have been damaged to a greater extent than input spatial-filter lenses.

Thus, image relaying must be abetted by low-pass filtering to protect the spatial-filter output lens.

Installing a 1.35-mm diam pinhole (acceptance angle $600 \mu\text{rad}$) results in a reduction of P/A from 1.75 to 1.02 at the output spatial-filter lens. The pinhole has filtered from the beam those high frequency Fourier components that otherwise interfere to produce spikes, as shown in Fig. 7-89. Furthermore, the P/A remains low throughout the imaging space, as shown in Fig. 7-90.

We observe that pinhole insertion changes the effective scale length of obscurations from a to Λ , where

$$\Lambda = \frac{\lambda f}{r_p}, \quad (37)$$

with f the spatial-filter output lens focal length. The

Fig. 7-87. Test beam profile cross section at $z = 11.5$ m. Diffraction and nonlinearity have conspired to severely modulate the originally smooth beam profile of Fig. 7-85.

Fig. 7-88. Test beam profile cross section emerging from the relay ($z = 6$ m). The "valleys" created by the original obscurations (Fig. 7-85) have been intensity-inverted to "peaks" by the B-element and the phase-reversal action of the relay element.

Fig. 7-89. Test beam profile cross section emerging from the spatial filter ($z = 6$ m). Comparing this figure with Fig. 7-88, the pinhole has removed those high-frequency components that interfered to produce the "peak" in that figure. Beam quality is therefore greatly improved.

P/A ratio now grows with propagation according to the formula

$$\left(\frac{P}{A}\right) \approx 1 + \left[\Delta + \left(\frac{z - z_0}{k \Lambda^2} \right)^2 \right] (1 + B), \quad (38)$$

where Δ represents edge modulation arising from low-pass Fourier truncation of the whole beam by the pinhole. (This effect is responsible for the radially symmetric "ring" modulation always observed on band-limited beams in the near field.) Δ can be estimated from the formula

$$\Delta \approx \frac{2\sqrt{2}}{\pi^2} \frac{(2\lambda f/\#)}{r_p}. \quad (39)$$

For the numbers we have used above, $\Delta \approx 2\%$. For the present example, beam modulation arises predominantly from obscurations rather than from rings. A significantly smaller r_p would reverse this situation.

As a final point, note that introduction of the pinhole in the spatial filter causes the system to "lose track" of the best obscuration image plane. (P/A) is a monotonically increasing function of z throughout the image space. Thus, while the original idea of imaging a smooth, steeply edged profile all the way through the system applies to the whole beam (thus enabling high filling factors), it has little impact on small scale obscurations. Of more immediate importance is the downstream distance to the next spatial filter and the P/A ratio that can be tolerated at its entrance.

Malaprop and Argus. Here we shall discuss examples of the interplay between the normalization through comparison with operations data and the evolutionary improvement¹¹⁹ of Argus operational performance. This is due (at least in part) to the encouraging predictions of, first, Artemis¹²⁰ (as discussed in last year's Annual Report), and later, Malaprop.

As originally designed and implemented,¹¹⁷ Argus (from a propagation point of view) consisted of a series of five $f/10$ sequential spatial filters, with focal lengths and pinhole diameters as shown in

Fig. 7-90. Evolution of the peak-to-average ratio with propagation along the z axis, with and without band-limiting pinholes installed in the spatial filter. Compare with Fig. 7-86.

Table 7-43. Our earliest normalizing comparisons of near-field data with code predictions are shown, for example, in Fig. 7-91, for three short-pulse (typically 30 ps) shots at various powers.

For these computations, we selected spatial obscurations at the value $F = 5 \times 10^{-5} \text{ cm}^2/\text{cm}^2/\text{disk surface}$. This was in approximate statistical agreement with the damage site count data observed by Stowers et al.¹¹⁸ Figure 7-91 shows that P/A spatial intensity fluctuations, compared in the figure in a plane optically equivalent to the target focusing lens plane, are in mutual agreement. (At 2.8 to 3 TW, the spatial structures of the beam scans obviously do not agree. We suggest that this lack of agreement stems from severe self-focusing of the experimental beam prior to the final spatial filter, which perforce strips away highest frequency peak modulations and results in the scan line as shown.)

Hence, we conclude that Malaprop is capable of realistic estimates of peak near-field intensity at planes of interest throughout the entire laser chain. Figure 7-92 illustrates plots of such peak intensities as a function of position along the chain. It is seen by inspection that the target focusing optics are subject to the most severe flux loading for any power level above 2 TW.

To examine the effects of obscurations more quantitatively, we have run a series of Malaprop calculations, using Argus 76 staging and driving the system at a nominal intended output of 3-TW short pulse. As the parameter F is varied from 10^{-5} to 10^{-3} per surface (corresponding to very clean disk surfaces and very badly pitted disk surfaces, respectively), we find that the code runs make the following generalized predictions:

- The output power through the final spatial filter decreases monotonically from 3 to 2.2 TW

Table 7-43. Spatial filter parameters for Argus (1976).

Spatial filter	Exit beam diameter (cm)	f No.	Pinhole diameter (μm)
Rod-B	8.5	10	300
B-B	8.5	10	400
B-C	20	10	400
C-C	20	10	500
C-output	20	10	600

(the missing power has, of course, been stripped from the beam by the various system pinhole filters). This result agrees well with early Argus data when the south arm was temporarily equipped with disks transplanted from the Cyclops laser system.

For these disks, F was estimated at $\lesssim 10^{-3}$ /surface; maximum obtained power on target was 2 TW.

● The P/A intensity ratio at the target lens increases from typically 3:1 to greater than 5:1. The

calculated P/A variation is shown in Fig. 7-93 (again for an intended output of 3 TW).

- The angular intensity distribution of the beam in the target lens focal plane is severely modified for $F > 10^{-4}$, as shown by the computed curves in Fig. 7-94. For $F < 10^{-4}$, the focal spot "flare" arises predominantly from beam edge modulation and subsequent self-focusing.

The intent of reconfiguring was to realize the benefits accruing to full image relaying techniques.¹²¹ Table 7-44 shows the sequence of spatial filters implemented in the Argus 77 reconfiguration. Figure 7-95 shows predictions stemming from Malaprop, for a nominal power performance of 3 TW (pulse duration <100 ps). Two pinhole strategies ("open" and "tight") are shown as calculated in Table 7-44. We note the following points:

- More power for a fixed input drive is coupled through the final spatial filter in either of the relayed configurations.

- The highest peak fluence (at the target focusing optics) is substantially reduced by either of the relayed configurations.

- The final focus spot (at the target) is substantially reduced by either of the relayed configurations; hence, relaying improves beam brightness.

- Differences between the two pinhole configurations are not severe. We conclude that peak performance is not particularly sensitive to *exact*

Table 7-44. Spatial filter parameters for Argus (1977).

Spatial filter	Exit beam diameter (cm)	f No.	"Small" pinhole diameter (μm)	"Large" pinhole diameter (μm)
Rod-B	8.5	20	600	600
B-B	8.5	10	300	500
B-C	20	20	500	900
C-C	20	10	400	750
C-output	20	10	500	1000

Fig. 7-96. Malaprop estimates of new short-pulse peak intensity figures for spatial filter parameters.

choice of spatial-filter acceptance angle for image relayed configurations. These advantages have been borne out by experiment.

Careful examination of Fig. 7-95 leads one to the conclusion that a final beam-expanding spatial filter would significantly reduce the peak intensity, and thus the optical damage risk, at the target focusing lens. Accordingly, we implemented this change during the past year. Table 7-45 shows the Malaprop estimates for the new short-pulse peak intensity threat at 3 TW for the spatial filter

parameters, as shown in Fig. 7-96. Table 7-46 quantizes sequential improvement through these restaging modifications.

Finally, we have mounted an intense effort to reduce the spatial-noise source density through cleaning or replacement of all suspect components in the chains. The results of this campaign have been spectacular, as discussed in §2.5 and summarized in the last column of Table 7-46. Malaprop can simulate these performance results only by reducing the fractional obscured area parameter F

Table 7-45. Spatial filter parameters for Argus (1978).

Spatial filter	Exit beam diameter (cm)	f No.	Pinhole diameter (μm)
Rod-B	8.5	20	600
B-B	8.5	10	500
B-C	20	20	900
C-C	20	10	750
C-output	28	10	1000

Table 7-46. Calculated short-pulse improvements in Argus through restaging spatial filters.

Configuration	Power on target ^a (TW)	Calculated 80% included Power half angle ^b (μrad)	P/A intensity at target lens	
			Calculated	Experimental
Argus 76	3.0	80	3.7	3-4
Argus 77 (closed)	3.1	70	2.6	~2.0 ^c
Argus 77 (open)	3.3	70	2.8	
Argus 78	3.3	60	1.7	1.3 ^c

^aThese computations assume an obscuration parameter $F = 5 \times 10^{-5} \text{ cm}^2/\text{cm}^2/\text{surface}$ and constant fixed beam power and profile. Assumed pulse duration is 100 ps. The calculated B for all configurations ranges between 8.0 and 8.5 (excluding target optics).

^bStatic aberrations are assumed to be zero for this comparison.

^cWith super-clean optical surfaces at 2.5 TW.

to $<10^{-5}/\text{surface}$. In this case, Malaprop and Artemis predictions become indistinguishable, and beam edge self-focusing becomes dominant as the ultimate limitation to focusable power from a fixed aperture.

References

115. A. J. Glass and W. E. Warren, *Malaprop—Light Propagation in a Nonlinear Medium*, Lawrence Livermore Laboratory, Livermore, Calif., UCRL-80316 (1977).
116. L. A. Vainshtein, "Light Propagation Through a Nonlinear Medium," *Sov. Phys.—Tech. Phys.* 9, 157 (1964).
117. W. W. Simmons, D. R. Speck, and J. T. Hunt, "Argus Laser System: Performance Summary," *Appl. Optics* 17, 995 (1978).
118. I. F. Stowers and H. G. Patton, "Damage History of Argus," in *Proc. 9th Symp. Materials High Power Lasers*, Boulder, Colo., 1977; also Lawrence Livermore Laboratory, Livermore, Calif., UCRL-80419 (1977).
119. J. T. Hunt, E. M. Campbell, and F. Rainer, "Argus Performance at 5 TW," in *Proc. Topical Mtg. Inertial Confinement Fusion*, San Diego, Calif., 1978 (Optical Society of America, Washington, DC, 1977), p. TUB8-1.
120. P. A. Renard and J. T. Hunt, *Artemis: A Diffraction Model for Laser Light Propagation*, Lawrence Livermore Laboratory, Livermore, Calif., UCID-17381 (1977).

121. J. T. Hunt, J. A. Glaze, W. W. Simmons, and P. A. Renard, "Suppression of Self-Focusing Through Low Pass Filtering and Relay Imaging," *Appl. Optics* 17, 2053 (1978).

Authors

W. W. Simmons
W. E. Warren

Major Contributors

J. T. Hunt
J. B. Trenholme
A. Glass
W. F. Haggen

7.4.5 Reflector Optimization Calculations

Laser amplifier performance can be improved by using the best possible flashlamp reflectors to direct the light efficiently to the ions in the amplifier. There are two things a good reflector should do. First, it should take as many rays as possible issuing from the cylindrical periphery of the lamp and direct them toward the region of the laser material. Second, it should reflect as many rays as possible back toward the laser material once they have passed through the material from lamp-reflector units on the other side.

The above two requirements tend to be mutually contradictory, because any reflector that efficiently directs rays from a lamp toward the amplifier interior also efficiently directs rays coming toward it into the lamp. Lamps are efficient absorbers of light, especially at high current densities ($>1 \text{ kA cm}^{-2}$); and although they efficiently re-radiate much of what they absorb, there is always some unavoidable loss. Thus, a good reflector avoids sending rays back into a lamp either on their first pass from the lamp toward the interior or on subsequent bounces off the reflector after passing through the amplifier.

A reflector design that is first-pass-perfect in the sense that all rays leaving a lamp miss the lamp on the first pass has been devised¹²² as a solar collector. This "gull-wing" shape is the evolute of the lamp i.d., starting at the o.d. at the top (Fig. 7-97). As shown, it takes all rays that leave the lamp and directs them toward the amplifier interior without restriking the lamp, with an angular spread over a full 180° angle. Deeper shapes are possible that restrict the output angle.

The problem with this reflector design is that it is much wider than the width of a lamp. The distance from the edge of the reflector to the other is the lamp i.d. times

$$\pi + \sqrt{R^2 - 1} - \cos^{-1} \left(\frac{1}{R} \right), \quad (40)$$

where R is the ratio of o.d. to i.d. in the lamp. This is π for an infinitely thin wall and 3.219 for a wall with $R = 1.2$ (for example, a 15×18 lamp), so the width depends only weakly on the wall thickness. Because the Winston reflector requires us to space lamps at about 3.2 times their diameter and because lamps have an upper limit on their output energy, we are limited in the energy per unit area we can supply to the amplifier interior. If we have to pump to a higher level than can be achieved with Winston reflectors, we have to use a narrower reflector design. It is possible to modify the Winston reflector for narrower spacing (for example, by using a design appropriate to a smaller lamp than the actual one), but it is not clear that this leads to the best design for narrower spacing. We thus have undertaken a computational approach to the reflector design problem.

The computational approach is to put a reflector around a lamp and trace rays to find out how ef-

Fig. 7-97. The Winston double-cusp reflector directs all rays that leave the lamp toward the amplifier interior after zero or one reflection. No rays are returned to the lamp before making at least one pass through the amplifier.

ficient the system is. The reflector shape is then adjusted and a new efficiency calculated. We compare the two, choose the best, and do it again. After a number of iterations, we should have a pretty good reflector. We have produced a fast 7600 computer program to do just this.

However, there are problems. Because only a finite number of rays can be traced (due to limitations of time and money), the calculated efficiency is only an approximation to the true efficiency. The process is noisy. Thus, we may be making things worse when we think we are making them better if a poorer reflector is seen as better due to noise. This problem gets worse and worse as the best shape is approached, because efficiency improvement per unit shape change is slower there and the noise swamps the signal. The result is that we never get to the best shape; our reflectors will always be sub-optimal by a small but uncertain amount.

Another problem is transmission of rays through the lamp. If the lamp is not totally opaque to its own radiation (as it is not), then some rays may bounce off the reflector and get to the glass by going back through the lamp. This is especially important at low current densities, where the lamps are most transparent. The details depend on the spatial distribution of opacity in the lamp as a function of wavelength and current density. This is a poorly studied area.

We have copped out by assuming that the lamps are totally opaque. All rays striking them are absorbed. One might argue that this doesn't matter, because a reflector shape that gives high efficiency when the lamp is opaque will simply do better if it is partially transmitting; and in the limit of total transparency, almost any reflector is good. Despite the argument, uncertainties remain.

Fig. 7-98. Best reflector efficiencies found after computationally evaluating various reflector designs, while varying the ratio of lamp spacing to lamp bore.

A third problem is re-emission of absorbed radiation. If rays absorbed by the lamps are recycled with 100% efficiency, all energy gets out sooner or later, and the reflector shape is again unimportant. In the real-world situation of partial recycling, reflector efficiency is raised by an uncertain amount.

A fourth (and minor) problem is the reflectivity of the reflector surface. Presumably, reflector shapes will be different for different reflectivities. We have simply used 90% reflectivity (typical of silver) for most of the calculations, presuming that nothing worse than this will be used in actual amplifiers.

A fifth problem is that we have not calculated the effect of rays returning to the reflector from the amplifier. Although this is important, the spatial and spectral details of the returned rays depend strongly on the amplifier design; and their absorption and re-emission are uncertain for the reasons discussed above. Including returned rays makes the problem hopelessly difficult.

What then, are the results of our calculations? In Fig. 7-98, we plot the best reflector efficiencies we have found as a function of the lamp spacing (in ratio to the lamp bore). Lamps absorb any ray that hits them and re-radiate none. The reflectors are formed of flat plates, so a cross section of the system is a circle for the lamp bore (it can be shown that the

envelope has essentially no effect on things) and a series of straight lines for the reflector. The calculation is for an infinite number of infinitely long lamps, with identical reflectors (no end effects). Because of total absorption, no re-emission, the flat-plate shape restriction, and the noise present in the efficiency calculation, the efficiencies shown are lower bounds. We will always do better, by an amount that is uncertain. Note that the linear energy density (efficiency divided by lamp spacing) is roughly constant.

Figure 7-99 shows some of the optimal reflector shapes. The efficiency is very insensitive to shape when the lamps are closely spaced, but becomes more sensitive as the lamps are moved apart and the efficiency rises. None of these shapes should be used in an actual design, because the straight-line restriction and calculation noise make them highly suspect.

What can we learn from these calculations? Because unknown effects of absorption and re-emission were not included, we do not know how much better we can do with real lamps. Note, however, that the calculated best efficiency rises in a straight-line fashion as lamp spacing increases from close-packed to about 3.3 times the bore diameter. Consider further that the widest spacing leads to the use of Winston reflectors, in which no rays strike the lamp once they are emitted. These wide-spaced results are thus independent of any assumptions regarding lamp opacity (at least on the first pass). The greatest uncertainty comes at the closely-spaced end of the graph, where results are most independent of reflector shape. This means that an experimental point with almost any reflector shape can be used to normalize this part of the curve.

We have used the extensive information available from amplifier gain tests at LLL to normalize and interpret these computational results. It is clear from the data that multiple-pass effects are important because the effectiveness of any reflector design depends strongly on the current density in the lamps. At high current densities, the lamps reabsorb strongly and efficiency drops. At low current densities, where reabsorption is low, one sees the large changes in efficiency with lamp spacing predicted by the one-pass computations. At high current densities, reabsorption is high and the differences are reduced. Using the combination of experimental and calculated reflector performance, we are now in a better position to understand the

Fig. 7-99. Various optimal shapes for a first-gas-perfect reflector. (a) Half-width 1.5. (b) Half-width 2.0. (c) Half-width 2.5. (d) Half-width 3.0. (e) Half-width 3.5. Coordinate values are given as a ratio to the nozzle bore radius.