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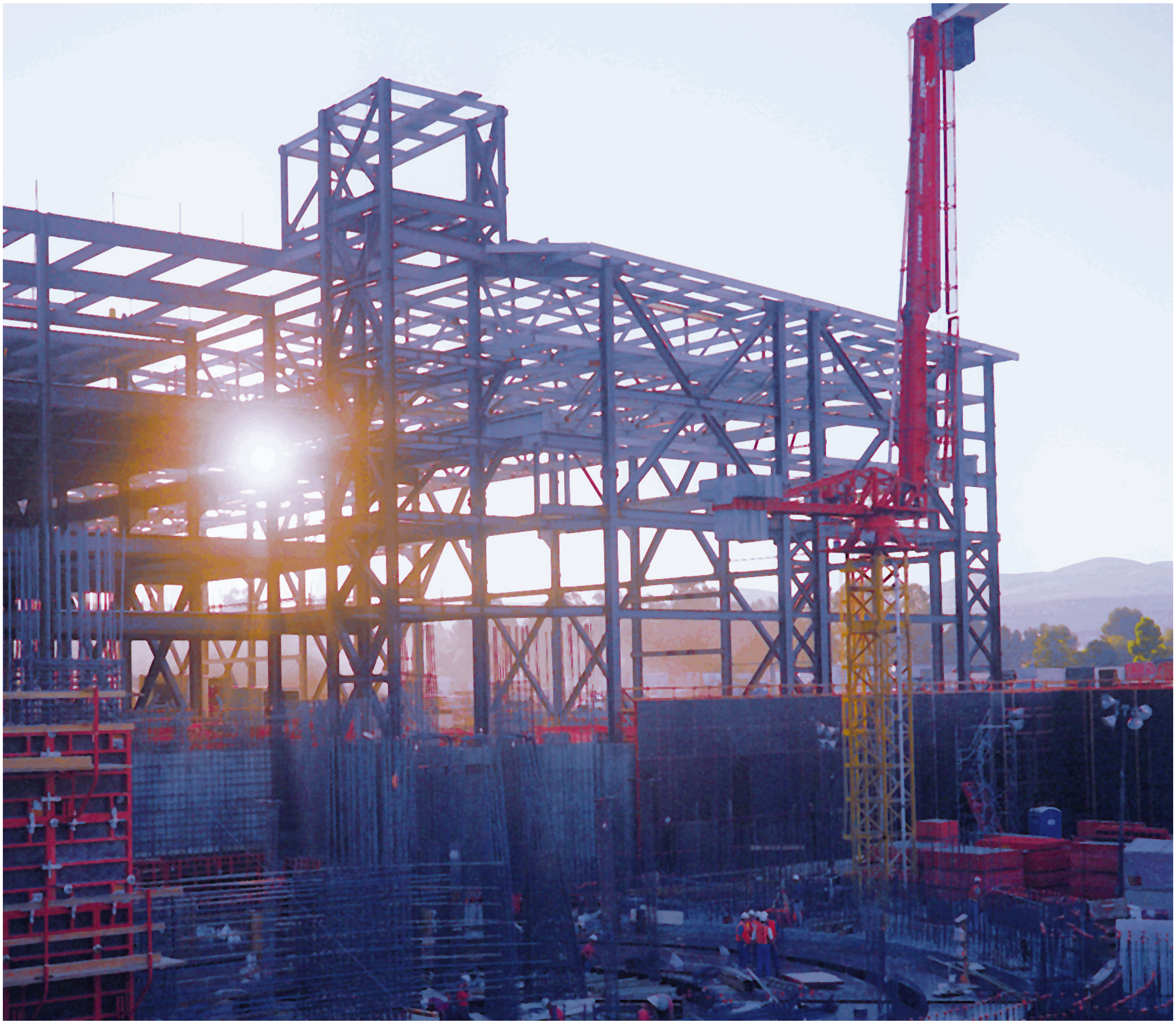

ICF Annual Report 1998

The Cover: The steelwork of the National Ignition Facility (NIF) rose in 1998. One of the missions of the NIF is to demonstrate thermonuclear fusion in the laboratory. Thermonuclear fusion, of course, is what powers the Sun and other stars; with the NIF, scheduled to be completed in 2003, comes the promise of studying many aspects of fusion currently unattainable on Earth.

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INERTIAL CONFINEMENT
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FOREWORD

The 1998 *ICF Annual Report* provides documentation of the achievements of the LLNL ICF/NIF and High-Energy-Density Experimental Science (HEDES) Program during the fiscal year by the use of two formats: (1) a summary of activity that is a narrative of important results for the fiscal year and (2) a compilation of the articles that previously appeared in the *ICF Quarterly Report* that year. In 1998, the compilation is being mailed separately in electronic format on a CD-ROM. The *Quarterly Report* and this *Annual Report* are also on the Web at http://lasers.llnl.gov/lasers/pubs/icfq.html.

The underlying theme for LLNL's ICF/NIF Program research continues to be defined within DOE's Defense Programs Stockpile Stewardship missions and goals. In support of these missions and goals, the ICF/NIF and HEDES Program advances scientific and technology development in major interrelated areas that include laser target theory and design (much of it in support of the stockpile program), target fabrication, target experiments, and laser and optical science and technology. The ICF program provides the experimental support for much of the core weapons program work on high-energy lasers in support of stockpile stewardship.

While in pursuit of its goal of demonstrating thermonuclear fusion ignition and energy gain in the laboratory, the ICF/NIF and HEDES Program provides research and development opportunities in fundamental high-energy-density physics and supports the necessary research base for the possible long-term application of inertial fusion energy for civilian power production. ICF technologies continue to have spin-off applications for additional government and industrial use. In addition to these topics, the *ICF Annual Report* covers non-ICF funded, but related, laser research and development and associated applications. We also provide a short summary of the quarterly activities within Nova laser operations, Beamlet laser operations, and National Ignition Facility laser design.

The LLNL ICF/NIF Program is one, albeit the largest, part of the National ICF Program. The program is also executed at Los Alamos National Laboratory, Sandia National Laboratories, the University of Rochester, and the Naval Research Laboratory. General Atomics, Inc., develops and provides many of the targets for the above experimental facilities.

Questions and comments relating to the technical content of the journal should be addressed to the ICF Program Office, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94551.

Jason Carpenter
Publication Editor

Joseph Kilkenny
ICF/NIF and HEDES Program Leader

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We thank Technical Information Department (TID) editors Jason Carpenter, Cindy Cassady, Pete Gaughan, Robert Kirvel, Al Miguel, and Jeff Morris for editing and managing the production cycle; designer Pamela Davis and artists Norm Calderon-Zablocki, Treva Carey, Al Garruto, Frank Marquez, Judy Rice, Toney Sanchez, and Frank Uhlig for providing expertise in graphic design, and Sandy Lynn for the cover design.

We appreciate the support of Michael Gallardo, the Government Printing Office coordinator, who worked with the Government Printing Office to obtain high-quality printing; and Mary Nijhuis of TID's Publications Services and TID's Print Plant for making sure that each publication was distributed with dispatch.

The talents and dedication of the ICF/NIF Program staff make the *ICF Annual* what it is for so many of its readers.

Robert L. Kauffman
Assistant DeputyAssociate Director
for ICF

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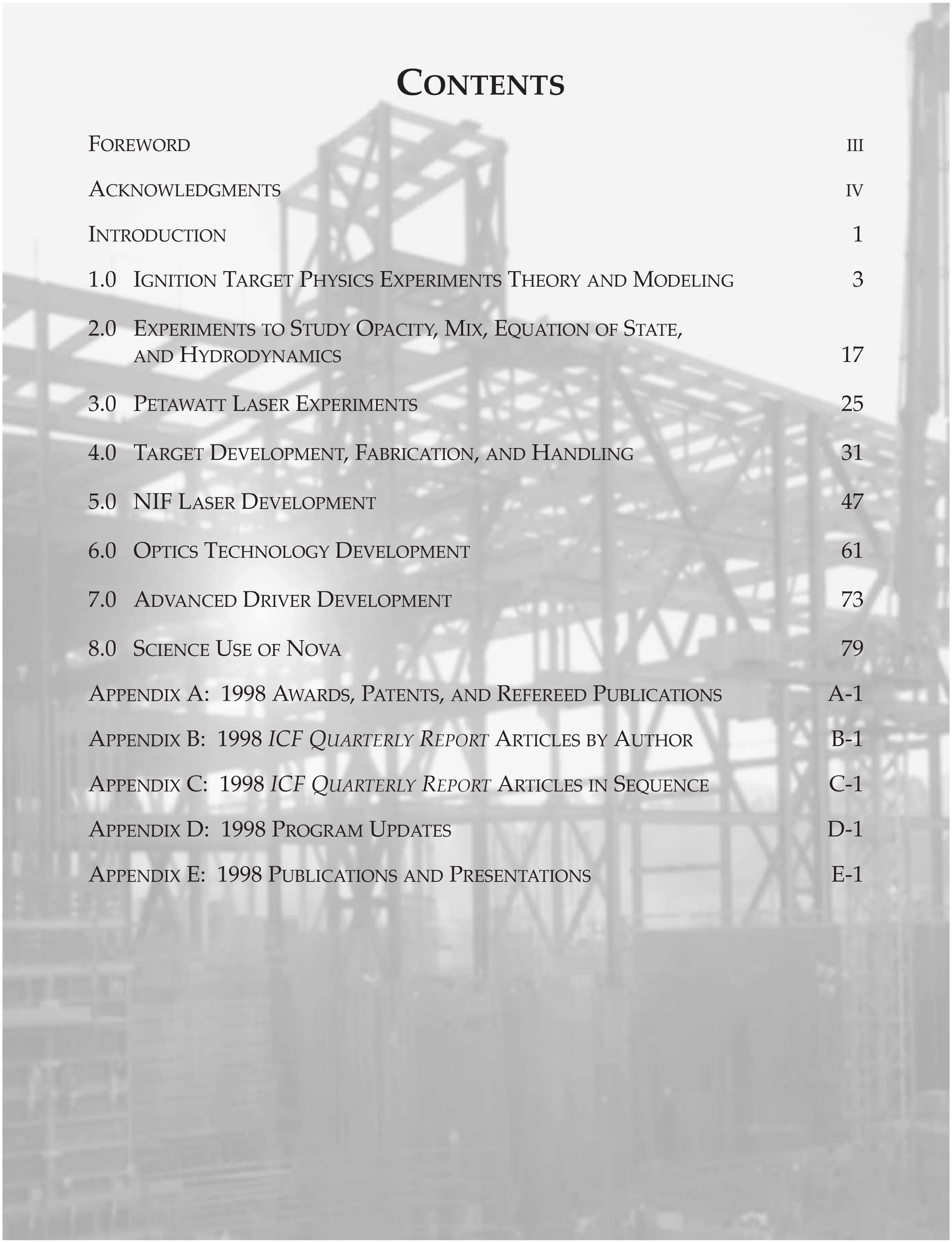
ICF/NIF and HEDES Program Leader



CONTENTS

INTRODUCTION

The narrative section of the 1998 *ICF Annual Report* is divided into sections reflecting major areas of program activities. There are sections on (1) ignition target physics experiments theory and modeling, (2) experiments to study other target-physics–related issues, (3) experiments using the Petawatt high-power laser modification to Nova, (4) target development fabrication and handling, (5) NIF laser development, (6) optics technology development, (7) advanced driver development, and (8) science/university use of Nova.

1998 was another outstanding year for the LLNL ICF/NIF Program.

- We met 58 of 60 of our DOE milestones for the program, including:
  - — 956 Nova shots, in excess of expectations.
  - — Completion of the Beamlet mission, closedown of the facility, and handover of the Beamlet laser equipment to Sandia National Laboratories (SNL).
  - — Completion of the Nova two-beam mission, closedown of the facility, and conversion to the Optics Processing and Development Lab.
  - — Near completion of the NIF laser technology program, a four-year joint program with the Commissariat a l'Energie Atomique (CEA).
  - — Qualification of the OMEGA laser at the University of Rochester for weapons physics use.
  - — Rapid growth of full-scale KDP and KD*P crystals for switching and frequency conversion in the NIF.
  - — Use of Accelerated Strategic Computing Initiative (ASCI) computers for major wave propagation and hydrodynamic codes in support of the ICF/NIF Program.
- We continued having a major impact on the weapons progam:
  - — 601/956 Nova shots and 31/60 OMEGA shots were used for the weapons program.
  - — We had a major success in measuring the equation of state of cryogenic hydrogen at pressures up to 3 Mbar and confirming new theories and equations of state of other materials.
  - — Radiography with the Petawatt laser explored as a possible strategy for the Advanced Hydro Facility.
  - — Two Weapons Program Excellence Awards.
- Major broad scientific impact and recognition:
  - — Continuing university outreach program.
  - — ~90 papers in refereed journals.
  - — Organized several international conferences.
  - — American Physical Society (APS) Division of Plasma Physics (DPP) Award for Excellence in Plasma Physics Research.
  - — Three APS-DPP Fellows.

1998 was the last full year of operation of the Nova Facility. The program is now transferring its focus from Nova experiments to preparing a program on the NIF. Major facility conversion started in 1998 and will accelerate in 1999. There will be major organizational changes in 1999. During the Nova–NIF hiatus, ongoing experimental effort will continue principally on the OMEGA laser at the University of Rochester and on other DOE Defense Programs facilities (Z, Trident, Nike).

1.0 IGNITION TARGET PHYSICS EXPERIMENTS THEORY AND MODELING

The primary activities within the Target Physics Program are target ignition physics (experiments, target design, and target fabrication), weapons physics experiments, and advanced code development.

During the past year, the technical path to ignition on the National Ignition Facility (NIF) has been further developed and refined by the National Ignition Planning Groups, made up of representatives from the national laboratories—Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory, Sandia National Laboratories—University of Rochester Laboratory for Laser Energetics, Naval Research Laboratory, and General Atomics. This plan has been incorporated into a work breakdown structure (WBS), divided into four subject areas:

1. WBS1: Hohlraum Energetics.
2. WBS2: Hohlraum Symmetry.
3. WBS3: Implosion Optimization and Shock Timing.
4. WBS4: Implosion Physics (Target Design and Fabrication).

We have used this plan internally to focus our effort on high-priority activities in target experiments, design, and fabrication, and for our resource planning and shot allocations on experimental facilities (Nova at LLNL and OMEGA at University of Rochester's Laboratory for Laser Energetics).

There have been significant advances this year in all four areas of the Ignition WBS. In the area of hohlraum energetics (WBS1), we completed a highly successful series of experiments examining the coupling of laser light, with NIF-like beam smoothing, to targets that emulate the conditions in NIF ignition hohlraums. We also validated a new x-ray drive measurement technique, which demonstrated excellent agreement with LASNEX modeling. In the area of hohlraum symmetry (WBS2), we continued to develop techniques for symmetry measurement and control, and demonstrated an ability to achieve the accuracy required for NIF ignition. Using these advanced methods for symmetry control, we have begun implosion experiments at higher convergence than previously possible. In the area of implosion optimization and shock timing (WBS3), we have begun detailed experimental studies of candidate NIF capsule ablator materials to ensure accuracy of our ignition designs. Finally, there has been excellent progress in the area of implosion physics (WBS4). Target design has focused on increasing our understanding of the requirements for the baseline targets (point design), and on developing target designs that work on the edges of ignition-parameter space. Progress on target fabrication has occurred on all fronts, with advances in capsule development and cryogenic layering and control. (For more details about our target fabrication work this year, see Section 4, "Target Development, Fabrication, and Handling" on p. 31)

Advanced hydrodynamic code development remains a key component of the target physics portion of the National Ignition Plan. During the past year, we have made significant advances in the capabilities of the 3D code HYDRA and have continued important algorithm development and maintenance for LASNEX.

Target physics work on high-energy-density Stockpile Stewardship Program experiments and Petawatt laser fast-ignitor assessment is reported in Section 2 on p. 17 and Section 3 on p. 25, respectively.

NIF-like Symmetry Control with Foam Balls

For x-ray-driven ignition to succeed on the future NIF facility, P_2 and P_4 flux asymmetries imposed on the imploding capsule, averaged over any temporal window τ, must be maintained below levels of ~[20/τ(ns)]%. For example, the maximum tolerable average asymmetry is 10% over any 1-ns interval. NIF hohlraums will provide time-dependent low-asymmetry mode control by varying the power ratio between at least two sets of beam rings. Two recent campaigns conducted at the OMEGA and Nova laser facilities have demonstrated time-dependent control of P_2 and P_4 flux asymmetries to 5% over any 1-ns interval, below the levels required for ignition. Both campaigns used 2-mm-scale, 200-eV hohlraums driven by 2.2-ns-long pulse-shaped beams with peak powers of 10–20 TW. Time-dependent flux asymmetries were inferred from the shapes of shock-driven backlit surrogate foam balls. Out-of-round shape deviations at the few-microns level were decomposed into Legendre moments, which could be differentiated in time to extract flux-asymmetry moments.

At Nova, NIF-like time-dependent symmetry control was achieved[1] by sending different pulses down each half of each beamline (i.e., "beam phasing") and by defocusing beams, creating two rings of illumination with a time-varying power ratio but with limited adjustability in ring separation. A comparison of the inferred P_2 asymmetry with and without beam phasing showed a 3× reduction in the P_2 asymmetry swing to levels below 5%/ns.

The most recent OMEGA campaign used a NIF-like multiple-ring illumination with adjustable ring separation.[2] The results from the measured second- and fourth-order foam-ball distortions are plotted in Figure 1. Also plotted here is the distortion for a 5%/ns swing in P_2 or P_4, showing that we have controlled the asymmetry swings to better than 5%/ns, as predicted by LASNEX simulations. In addition, Figure 1 shows that the final a_2 and a_4 are zero within the ±1-μm measurement accuracy, implying the average P_2 and P_4 asymmetry has been limited to 2%. This is to be compared with larger 20%/ns P_2 swings and 4% average P_4 inferred from traditional single-pulse, single-ring illumination.

Notes and References

1. S. G. Glendinning et al., *Rev. Sci. Instrum.* **70**, 656 (1999).
2. O. L. Landen et al., to be published in *Phys. of Plasmas*, May 1999.

Symmetric Implosions Using the OMEGA Laser in a NIF-Like Multiple-Cone Geometry

As a test of the improved time-dependent symmetry provided by the multiple-ring OMEGA hohlraums described in the above subsection, a series of moderate- (9×) and high- (16×) convergence implosions were achieved in a NIF-like hohlraum illumination geometry.

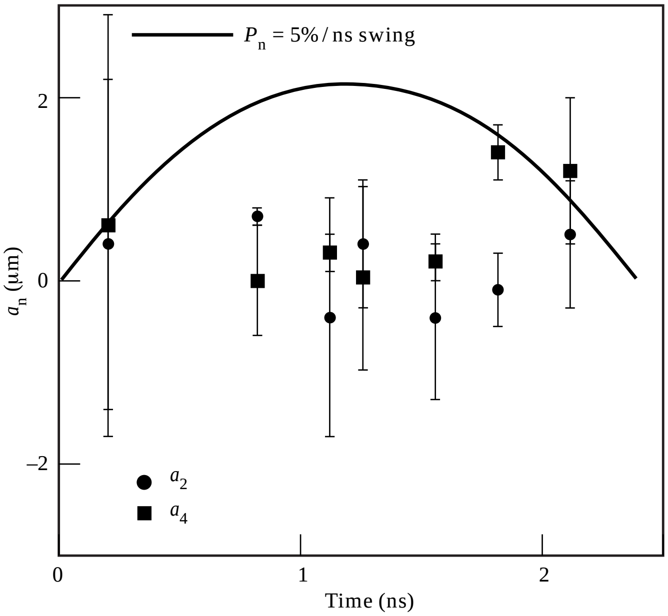


FIGURE 1. Measured second- (dots) and fourth- (squares) order Legendre distortions on foam balls driven by NIF-like multiple-ring hohlraum. Also plotted is distortion predicted for 5%/ns asymmetry swings. (08-00-0299-0198pb01)

The convergence ratio was varied between 9× and 16× by changing the initial fuel-fill pressure from 50 to 10 atm D_2. Both low-growth-factor plain plastic and high-growth-factor 1% Ge-doped plastic capsule ablators were used. The laser-drive pulse shape (6:1 contrast over 2.2 ns) was chosen for comparison purposes, because it is identical to that used for earlier high-growth-factor Nova implosions (HEP4).

As shown in Figure 2, the measured x-ray core image ellipticities were close to round (average a/b = 1.1 ± 0.1), which agreed with simulations. Because the multiple-ring hohlraum seeks to balance large but opposite-sign P_2 flux-asymmetry components from the inner and outer rings, the excellent agreement in time-integrated symmetry between data and simulations is noteworthy. The convergences, as measured by a secondary fusion reaction and x-ray core image size, were within 10% of calculated.

For the moderate-convergence, high-growth-factor implosions, the ratio of measured neutron yields to yields calculated from 1D LASNEX simulations were 65%–80% for the NIF-like multiple-ring OMEGA illumination, compared to 15%–40% for the older single-ring Nova illumination. For the 16×-convergence OMEGA implosions, this ratio is 20%–50%. Moreover, the yield degradation due to the intrinsic even-order asymmetries is calculated to be negligible (<5%) for the multiple-ring OMEGA implosions. The degradation in

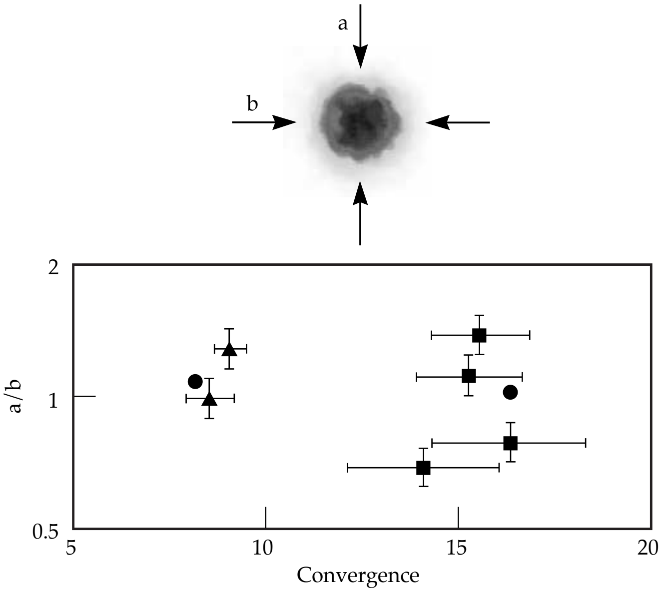


FIGURE 2. Measured (triangles and squares) and calculated (dots) core image distortions as a function of measured convergence ratio for Ge-doped capsules imploded in a NIF-like multiple-ring hohlraum geometry. (08-00-0299-0199pb01)

OMEGA yields compared to 1D predictions are currently ascribed equally to P_1 asymmetries resulting from beam-to-beam power imbalances and from mix at the pusher-fuel interface.

Laser-Entrance-Hole Drive Measurement

For several years experiments have been carried out on Nova[1,2] and on other facilities[3] to measure radiation flux, or drive, in laser-heated hohlraums. The principal experimental technique was to measure absolute x-ray flux emerging from a diagnostic hole in the side of the hohlraum using an array of filtered, absolutely calibrated x-ray diodes known as "Dante"; we now refer to these measurements as "traditional Dante." The earliest experiments with traditional Dante demonstrated the fundamental scaling of drive with laser energy, pulse duration, and hohlraum dimensions.[2] We used the traditional-Dante data to test the ability of detailed numerical simulations to model the time-dependent hohlraum drive. Unfortunately, the experimental measurement was consistently less than simulations at times greater than 1 ns.[2] We suspected that this disagreement was not due to fundamental errors in our 2D modeling but due to the 3D nature of our measurements.[4–6] In particular, we suspected that a plume of cold plasma might be emerging from the hole at later times, scattering x rays from out of the diagnostic's collimated line of sight. Because of this we tried, in 1996, a new diagnos-tic line of sight that measures absolute x-ray flux emerging from the laser entrance hole (LEH) at a polar angle of ~25–35 degrees.[4]

Initial OMEGA experiments showed very good agreement between this new line of sight and modeling.[4] In 1997 a compelling series of Nova experiments jointly performed by CEA (French Atomic Energy Commission) and LLNL demonstrated that, in situations where there is gross disagreement between traditional Dante and modeling, the LEH line of sight indicates that the hohlraum is in fact performing as expected.[6] This sequence of experiments provided the strongest evidence to date that there is something wrong with the traditional Dante line of sight at later times, when the hohlraums fill with plasma. Drive measurements made through the LEH proved to be very close to our expectations throughout the pulse and even after the pulse.[6]

The gross difference between findings from the two views has led to the LEH line of sight becoming the preferred drive diagnostic for virtually all experiments and our baseline line of sight for NIF. However, we were concerned that the results being close to our expectations didn't guarantee that they were right.

In an effort to validate the LEH line of sight, we performed two types of experiments to assess drive at the hohlraum center. In one, we measured burn-through time of thin gold foils covering holes in the center of our second series of "build-a-pulse" (BAP) hohlraums. The thicknesses were chosen so that the burn-through times would readily distinguish which of two grossly different drives was more likely correct. The observed burn-through time was very close to the times expected from LASNEX simulations using supertransition array (STA) opacities and the LEH drive.

Complementing the burn-through measurements, we also have made a few measurements on "half-hohlraums." We cut a hohlraum in half, irradiated it through only one end, and used the LEH drive diagnostic to measure the x-ray emission through the open, unirradiated end. Figure 3 is a comparison of simulated and measured radiation flux versus time from a scale-1.41 hohlraum irradiated by an 8-ns long drooping pulse. A large amount of plasma evolution exists in the simulated hohlraum; this evolution moves the laser deposition region progressively closer to the LEH throughout the pulse. Nevertheless, the flux exiting the midplane of this half-hohlraum is quite close to what we expect, indicating again that the LEH line of sight provides a valid measure of late-time drive.

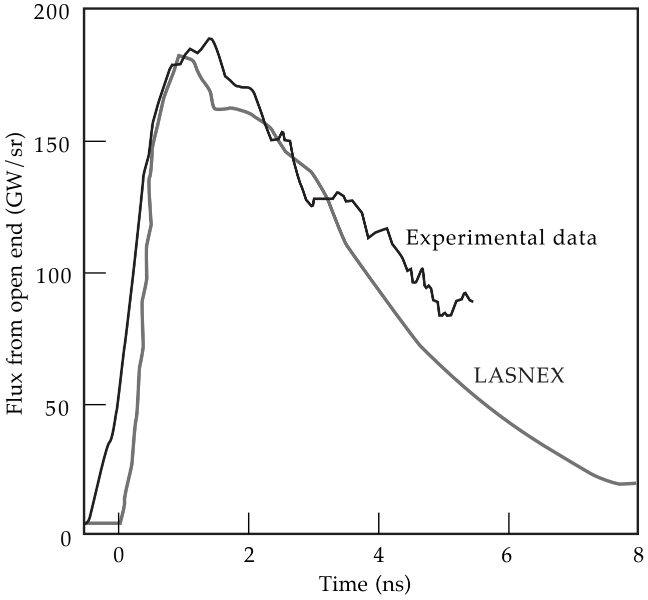


FIGURE 3. Radiation flux emerging from the midplane of a half-hohlraum irradiated by a very long pulse. This indicates that a real hohlraum midplane will not have a radiation flux that is significantly different than that expected from radiation hydrodynamic simulations. (08-00-0299-0200pb01)

Notes and References

1. R. L. Kauffman et al., *Phys. Rev. Lett.* **73**, 2320 (1994).
2. L. J. Suter et al., *Phys. Plasmas* **3**, 2057 (1996).
3. R. Siegel et al., *Phys. Rev.* **A 38**, 5779 (1988).
4. C. Decker et al., *ICF Quarterly Report* **8**(1), 1, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-LR-105821-98-1 (1998).
5. C. Decker et al., *Phys. Rev. Lett.* **79**, 1491 (1997).
6. L. J. Suter et al., *ICF Quarterly Report*, **8**(4), 171, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-LR-105821-98-4 (1999).

Indirect-Drive Experiments with NIF Ablators

The WBS3 program element is primarily devoted to developing techniques for measuring timing of the ablatively driven shocks on the NIF. A secondary goal of this project is to test and improve the physical-characteristic databases of the ablator materials and fuel to improve the precision of target designs. During FY98 we began a series of ablator characterization measurements—1D hydro, Rayleigh–Taylor (RT), shock breakout, and burn-through—to test our predictive capability for candidate NIF ablators, in particular beryllium doped with copper (Be/Cu). We have collected a small database for Be ablators that will be used to benchmark LASNEX over the next few years.

Ablator Materials Testing

Measurements of the 1D hydro and RT growth of preimposed surface modulations used ~50-μm-thick Be/Cu foils accelerated by scale-1 hohlraums. Foil trajectory measurements indicate that the Be/Cu is somewhat more efficient as an ablator than predicted by simulations: the foil begins to move slightly earlier (by ~200 ps) and farther (~20–30 μm) than predicted. RT-growth measurements of 30-, 50-, and 70-μm wavelengths, with initial amplitudes of 1, 2, and 2 μm respectively, were analyzed to determine the Fourier amplitudes (in optical depth) of the fundamental and second harmonic of the initial wavelength; Figure 4 shows some example results. LASNEX simulations of the modulation growth reproduce the data fairly well when we use accurate opacities calculated using detailed atomic configurations (HOPE code). Modeling with the more approximate opacity code XSN does not reproduce the data as well.

Typical shock breakout times for nominally 1% Cu-doped Be, using 1-ns pulses into hohlraums of scale 1.3, 1, and 0.75, are in agreement with modeling. Preshock signals suggest that preheat may be somewhat higher than predicted by current modeling. Burn-through times versus Cu doping (3.7% Cu, 22 μm, and 4.7% Cu, 16 μm) in scale-1 hohlraums are in approximate agreement with simulations. The x-ray burn-through rise time from a spectral band centered at 700 eV is well modeled (Figure 5). A band at 475 eV is much slower than predicted, which could result from

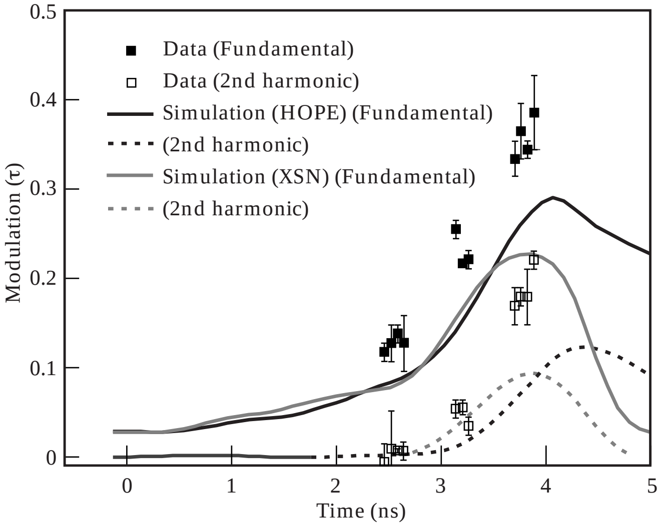


FIGURE 4. 50-μm wavelength data from two shots, fundamental and harmonic. LASNEX simulations using XSN (gray) and HOPE (solid) opacities are shown. (08-00-0299-0201pb01)

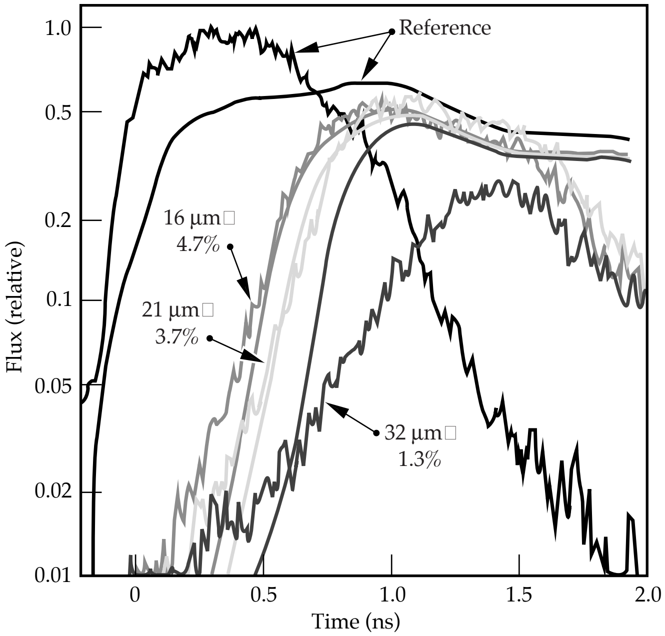


FIGURE 5. Measured and simulated x-ray burn-through of Be/Cu foils in the 700 eV channel for shot 28092414. The jagged lines are data, smooth lines postprocessed simulations. (08-00-0299-0202pb01)

leakage of energy from higher orders off the grating used to select the spectral band.

Pulse-Shape Measurements

A primary goal of WBS3 is to develop a technique for ensuring that a particular laser pulse shape is properly timed to drive a NIF ignition capsule. We have identified a candidate technique which relies on VISAR (Velocity Interferometery System for Any Reflector)[1] or high-resolution radiography for accurately measuring shock propagation in liquid deuterium. We apply the candidate pulse shape to a flat sample of the ignition capsule ablator, driving a series of shocks into liquid or solid deuterium so that the first three all coalesce at a single specified depth in the deuterium. Beyond the third shock, spherical convergence plays a more significant role, and modeling of the difference between spherical and planar geometry may be required. In the coming year we will address such details as how well VISAR will work in a NIF hohlraum, how the pulse shape should be adjusted, and what differences exist between the drive temperature at the wall and at the center of the hohlraum.

The WBS3.1 tasks include assessments of our sensitivity to errors in pulse shape, equation of state, opacity (or preheat), and so on. Simulations with variations in pulse shape indicate that the polyimide ignition target can tolerate ±15% variations in flux or ±300-ps variations in shock timing and still give 90% of nominal yield. We have also done simulations with a new deuterium–tritium (DT) equation of state (EOS), which causes an increase of about 25% in the predicted yield of our NIF capsule designs compared to previous modeling with the QEOS code. Also, performance cliffs are shifted, showing more robust performance generally with the new EOS. These comparisons help us estimate the sensitivity of the performance to EOS variations.

Notes and References

1. G. W. Collins et al., *Science* **281**(5380), 1178 (1998); P. M. Celliers et al., *App. Phys. Lett.* **73**(10), 1320 (1998).

Laser–Plasma-Instability Target Physics Issues Relevant to NIF Underdense Plasmas

We made significant progress in FY98 in advancing our experimental and theoretical understanding of the laser–plasma instability (LPI) target physics issues relevant to NIF underdense plasmas. This work was divided into three milestones. First, we measured the scaling of stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) as a function of plasma density and focal spot intensity for a smoothed interaction beam (subsection below). These experiments utilized smoothing by spectral dispersion (SSD) with a high-frequency modulator (17 GHz) and kinoform phase plates (KPP). We found that SBS is saturated from intensities of 2.5×10^{15} W/cm^2 to nearly a factor of 10 below this. Also, the measured SRS scaled somewhat weaker with intensity than the calculated scaling.

In addition, we tested the effect of polarization smoothing (PS), with and without SSD, on reducing the scattering levels (see subsection "Beam-Smoothing Effect on SRS and SBS"). We found that, in hohlraum targets and open-geometry gasbag targets, SSD significantly reduced SBS levels, and the addition of PS further reduced the scattering. In hohlraum targets, SSD also reduced SRS significantly. In gasbag targets, the addition of PS brought total scattering in most cases to less than 6% at the time of peak electron temperature.

Also, we experimented on and modeled the effect of NIF-like beam smoothing on beam propagation through underdense plasmas (see subsection on "Beam Propagation"). The addition of SSD reduced beam spray by about a factor of 5, and addition of PS to the SSD further reduced beam spray by an overall factor of 6 to 8. NIF baseline ignition simulations using beam spray, ranging from the maximum that we have measured in our experiments to about twice that value, show reduced fusion yield compared to simulations without beam spraying, but these calculations also show that one can easily recover high fusion yield by adjusting the relative laser power in the inner and outer beam cones to retune the symmetry. Overall, we now have experimental measurements of the intensity and density scaling of SRS and SBS, and we have demonstrated that SSD and PS significantly reduce backscattering in both open- and closed-geometry targets and reduce beam spray in open-geometry targets. The simulations also show significant reductions in SBS and SRS with addition of PS and SSD.

The majority of the data for all of these experiments was obtained during a series of experiments in which we converted one Nova beam to a NIF-like $f/8.5$ focusing geometry. This beam was used as an interaction beam to drive instabilities, and all measurements of backscattered and forward-scattered (transmitted) light were made on this beam. The intensity of this beam ranged from 3×10^{14} to 5×10^{15} W/cm^2, and various types of smoothing (KPP, SSD, and PS) were applied. The other nine Nova beams had an $f/4.3$ focusing geometry and were used to heat either an open- or closed-geometry target. The open-geometry target, a gasbag, consisted of two membranes, one on either side of a thin Al washer, that were inflated with a C_3H_8 and C_5H_{12} gas mixture at close to 1-atmosphere pressure to produce an almost spherical gas volume. Nearly symmetric irradiation by the nine heater beams produces a 6% to 15% critical-density plasma, with 1- to 2-mm scale lengths and a peak central $T_e = 3$ keV. The closed-geometry targets used scale-1 gas-filled hohlraums heated with 27 kJ of 3ω laser light from the 10 beams of Nova.

Intensity Scaling of SBS and SRS

In FY 1998, campaigns were carried out to study the dependence of SBS and SRS backscatter in NIF-like plasmas on the laser intensity and plasma density. In the theory and simulations of SRS and SBS, reflectivity increases exponentially with the linear gain exponent until nonlinear saturation occurs. The saturation may be caused by several processes that limit the amplitude of the plasma waves. For a perfectly uniform laser beam, nonlinear saturation can occur for gain exponents of greater than ~20. Because of the intensity hot spots in real laser beams and the effects of self-focusing, nonlinear effects and significant reflectivity may occur for much smaller gain exponents. In Figure 6, the reflectivity versus gain exponent is shown using a simple model of the effects of hot spots and the simulation code F3D. These show nonlinear effects occurring for gain exponents above 5. Our experiments— illuminating mm-scale gasbags filled with CH gases to ionize and heat the plasma—have been described in the previous subsection and elsewhere.[1] The experiments have two distinct phases: "early," when the plasma is hot as it is being heated by the 9 other Nova beams; and "late," when the plasma is cooling. The gain exponents in the 10% critical density experiments spanned the range between 4 and 40 in the early period (depending on intensity) and between 3 and 26 in the late period. This range should be adequate to see a "knee" in the response where the reflectivity drops for low gain.

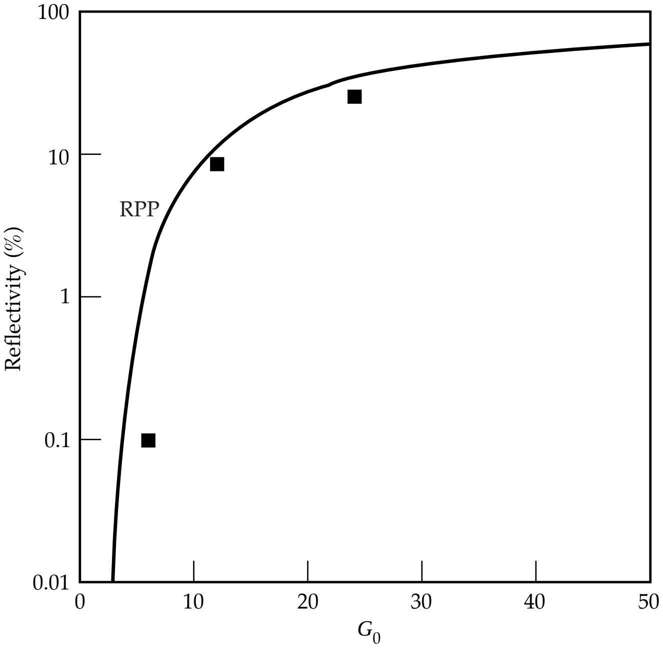


FIGURE 6. Predicted SRS reflectivity obtained from F3D simulations (solid boxes) and from a simple model. (08-00-0299-0203pb01)

The SRS data (Figure 7) show that the reflectivities averaged for the early and late time periods both show a reduction in SRS as intensity is reduced below 2×10^{15} W/cm^2 (the average intensity in the NIF point-design focal spot), similar to the simulations shown in Figure 6. The measurements of SBS from the same experiments show that the SBS reflectivity is primarily from the early time period, when it is ~3% and nearly independent of intensity. SBS scattering remains saturated at intensities as low as 2.2×10^{14} W/cm^2, which is 9 times less than in the NIF point design, wheras SRS reflectivity decreases as much by a factor of ten in some cases, so that designs with reduced laser intensity will couple substantially more energy to the hohlraum.

Further experiments were carried out with higher intensity beams and in higher density plasmas ($\leq 5 \times 10^{15}$ W/cm^2 and ≤14% critical). Both early- and late-time SRS reflectivity from an RPP smoothed beam under these conditions increased by only ~3% of the total energy, when compared to the value at 10%

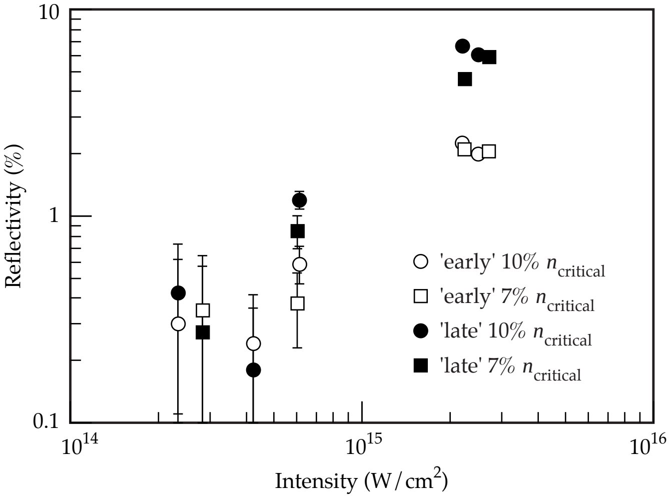


FIGURE 7. Measurements of SRS reflectivity versus intensity in gasbag targets. (08-00-0299-0204pb01)

critical and 2 × 10^{15} W/cm^2, but SBS reflectivity dropped by ~5%. The effectiveness of both SSD and polarization smoothing was shown to be substantial under these conditions as well, reducing the SRS by more than 2× and the SBS by more than 4×. These results indicate that levels of scattering may be manageable even in targets with higher intensities and plasma densities than those expected in the NIF-baseline target design.

Notes and References

1. S. H. Glenzer, C. A. Back, K. G. Estabrook, B. J. MacGowan, D. S. Montgomery, R. K. Kirkwood, J. D. Moody, D. H. Munro, and G. F. Stone, *Phys. Rev. E* **55**, 1 (1997).

Beam-Smoothing Effect on SRS and SBS

Recent calculations have shown that filamentation, stimulated Brillouin scattering (SBS), and stimulated Raman scattering (SRS) can all be reduced with temporal and spatial smoothing, specifically smoothing by spectral dispersion (SSD) and polarization smoothing (PS).[1] These simulations show a particular benefit to combining SSD with PS because the latter instantaneously reduces the power at very high intensity in which instabilities grow too fast for SSD and because SSD is effective in controlling the self-focusing of lower-intensity speckles, which PS does not affect.

For example, power in the speckles with intensity greater than five times the mean is an order of magnitude smaller with PS (0.3%) than with a KPP only (4%). F3D simulations of SRS and SBS are shown in Figure 8 for a mean intensity of 2 × 10^{15} W/cm^2 and an intensity gain exponent of 12 for SRS and 10 for SBS, about a factor of two less than in the experiments. The competition between SRS and SBS is not included in this figure but filamentation is. Note the strong reduction in SBS and SRS when both SSD and PS are included.

We tested the effect of PS and SSD employing scale-1 gas-filled hohlraums. The experiments show that NIF-like SSD with a 17-GHz frequency modulator significantly reduces scattering losses for laser intensities of 2 × 10^{15} W/cm^2 (NIF standard) and 4 × 10^{15} W/cm^2. Figure 9 shows the total time-integrated scattering losses due to SBS and SRS backscattering and near backscattering measured into the lens of the *f*/8-laser beam and onto a scattering plate mounted around the lens.

We also studied the effect of beam smoothing (SSD, KPP, and PS) on scattering from open-geometry gasbag targets. Figure 10 shows the stimulated Raman and Brillouin scattering reflectivity that were measured from gasbag targets. Most of the data shown is for intensities of ~2 × 10^{15} W/cm^2; all targets with density above 13% critical and one point at about 8% critical with PS and 3 Å of SSD used a higher interaction

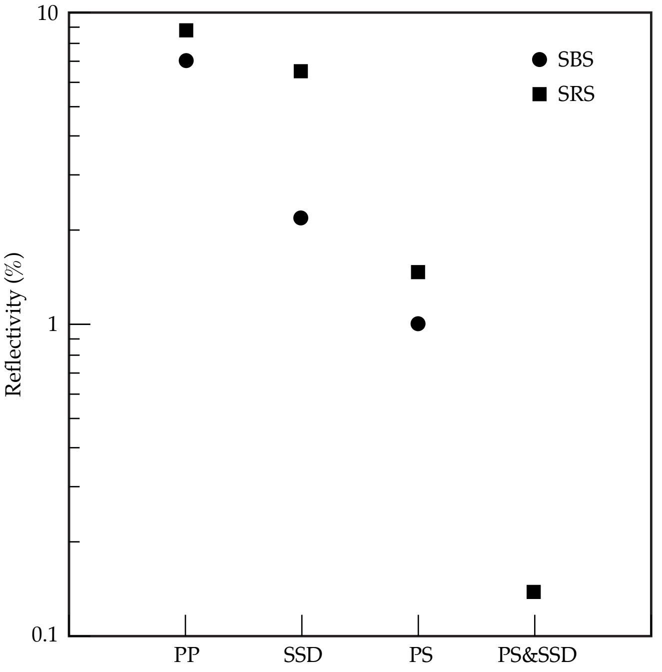


FIGURE 8. Calculation (F3D) of the SBS and SRS expected from a 10% n_{crit} low-Z (CH) plasma at 3 keV, irradiated with a beam of intensity 2 × 10^{15} W/cm^2. The calculations model a RPP alone, in combination with SSD with 3 Å of bandwidth at 1ω, with polarization smoothing, or with both. These plasma and laser conditions correspond to the NIF inner beam and the 300-eV NIF point-design hohlraum. (08-00-0299-0205pb01)

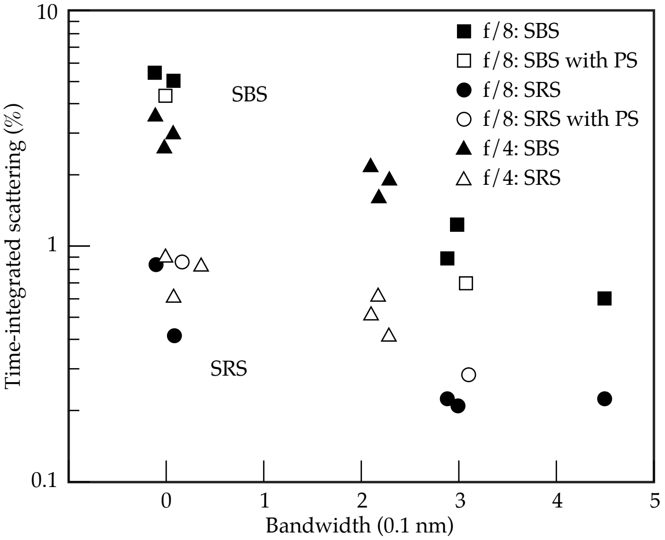


FIGURE 9. Total time-integrated scattering losses due to SBS and SRS backscattering from scale-1 methane filled hohlraums, for the standard NIF laser intensity of 2×10^{15} W/cm^2. (08-00-0299-0206pb01)

intensity of ~5×10^{15} W/cm^2. These high-intensity experiments were intended to explore the conditions expected in a higher-radiation-temperature, NIF-hohlraum design. Most of the data points show that, although PS reduces scattering, the reduction is not as significant as when it is combined with SSD; the combination gave the most effective beam smoothing ever observed in Nova gasbag experiments. These results indicate that NIF could benefit from PS of the inner beams. We propose to further test PS on NIF itself by adding a piece of wedged KDP crystal in the diffractive optics cassette of the final optics assembly.

Notes and References

1. E. Lefebvre et al. *Phys. Plasmas* **5**, 2701–2705 (1998); S. Huller, P. Mounaix, and V. T. Tikhonchuk, *Phys. Plasmas* **5**, 2706–2711 (1998); R. L. Berger, et al., *Phys. Plasmas* **6** (in press, April 1999).

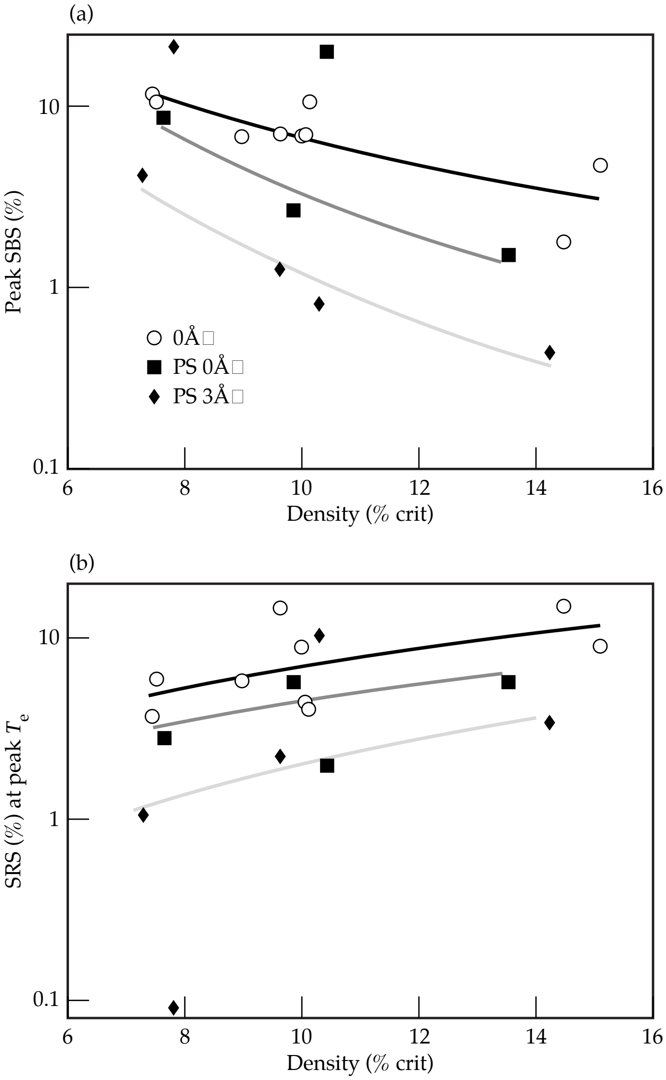


FIGURE 10. (a) Peak SBS reflectivity and (b) SRS reflectivity at peak T_e ($t = 1$ ns), for gasbag plasmas. Most of the data are at an interaction beam intensity of 2×10^{15} W/cm^2. (Experiments above 13% n_{crit}, and one data point at 8%, used an RPP in place of the KPP and were at an intensity of 5×10^{15} W/cm^2.) (08-00-0299-0208pb01)

Beam Propagation

We performed experiments and measurements to model the effects of NIF-like beam smoothing (SSD, PS, and KPP) on beam propagation through underdense plasmas. These studies focused on the angular spread of the transmitted 351-nm probe beam through the gasbag plasma. Beam spray leads to a larger spot on the wall of a hohlraum, subsequently affecting the symmetry of the x-ray radiation. It is important to either reduce the beam spray so it is insignificant or to be able to predict it on a shot-to-shot basis in order to maintain control on capsule symmetry. Our studies of beam spray showed that spray was reproducible and could be reduced by a factor of 6 to 8 with the addition of PS and SSD. We performed simulations of a NIF-ignition hohlraum using beam spray on all 192 beams equal to, and at twice, the measured beam spray and found that the fusion yield dropped significantly. Redistributing the same total energy between the inner and outer beam cones recovered high fusion yield. We conclude that beam smoothing can reduce beam spray significantly, and the combination of simulations with measured beam spray show how to tune the NIF beam energy distribution to maintain high yield even with fairly significant beam spray.

Laser-driven instabilities, background fluctuations from heater beams, or hydrodynamic plasma evolution can cause beam spray. Forward-scattered light from the probe beam exhibited both small-angle spreading (from background fluctuations) and large-angle spreading (from probe-driven fluctuations). Spectral measurements made at several angles outside the $f/8.5$ transmitted beam cone showed light that was red-shifted and spectrally broadened, indicating that the scattering physics was predominantly stimulated Brillouin forward scattering (SBFS). We found a two-part spectrum of background plus SBFS-generated density fluctuations, which, when used in our Monte Carlo scattering model, gave a calculated angular distribution of the forward-scattered light that agreed with the measured angular distribution. We confirmed the background part of the fluctuations with forward-scattered light from a low-intensity, nonperturbative 263-nm probe. The correlation length (l_c) of the background fluctuations is estimated to be $l_c/\lambda_0 \geq 40$, and the probe-driven part is $l_c/\lambda_0 \geq 4$. The amplitude, $<|\delta n/n|^2>^{1/2}$, ranged from the background level of 0.05 to the probe-driven level of 0.08. Addition of temporal beam smoothing reduced the probe-driven fluctuations to 0.06, almost recovering the background level. The 351-nm forward scattered-light measurement, compared with a Monte Carlo model of laser propagation through a turbulent plasma, is shown in Figure 11.

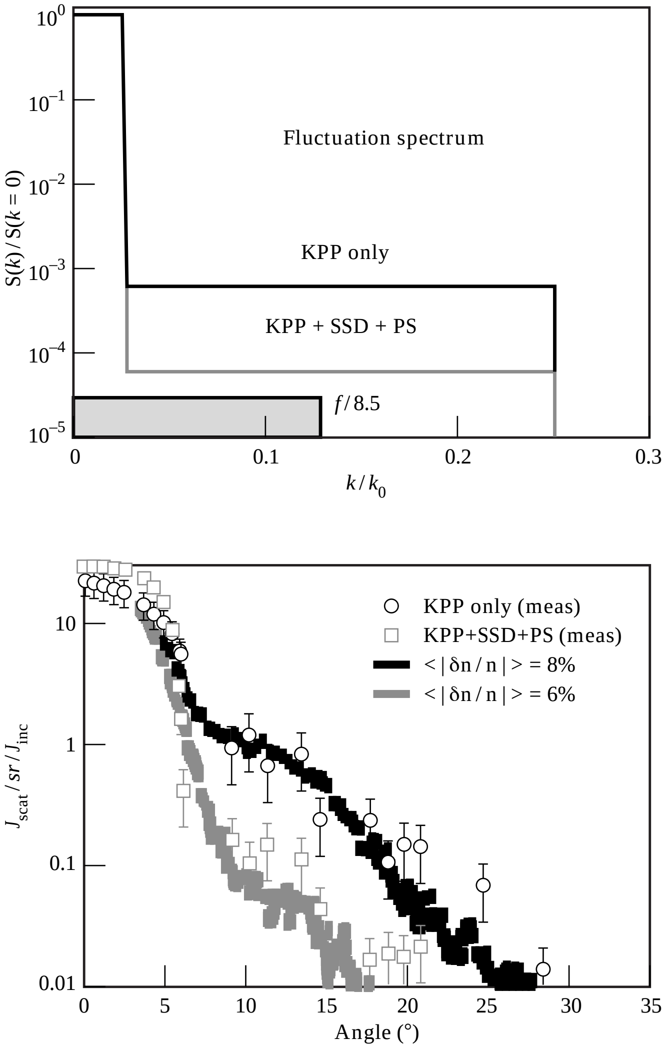


Figure 11. Measured and calculated angular spread for the 351-nm, $f/8.5$ probe. (08-00-0299-0209pb01)

NIF Target Design

Significant progress was made this year in several areas of NIF target design. Work on the baseline target has increased our understanding of its requirements, and work on targets at the edges of ignition-parameter space has increased our understanding of the issues we may encounter if we need to move away from the baseline.

The parameter space characterizing NIF ignition targets is shown in Figure 12. The shaded region shows the powers and energies at which ignition is expected according to current modeling, with the region bounded at high power by laser–plasma instabilities and at low power by hydrodynamic instabilities. Most of our modeling has concentrated on the point labeled PT, at power and energy inside the ignition space but with some margin below the laser operating curve. The point at 1.8 MJ and 500 TW is the expected nominal performance of the NIF laser. The other points shown in Figure 12, around the edges of the ignition space, are other areas of active consideration in this work area.

We completed a comparison of three ablator materials, all driven at the baseline drive temperature of 300 eV.[1] This work included 3D simulations of the Rayleigh–Taylor instability growth on these targets; we inferred that each of the ablator materials would ignite and burn well, with initial ablator-surface finish similar to the best achieved to date on a Nova capsule ablator and with DT ice surface smoothness similar to that achieved in characterization of natural beta-layered DT ice. This work is being extended to include hohlraum asymmetry and larger solid angle. Code development (now complete) was necessary to perform this task, as it involves the use of massively parallel computing algorithms; however, the computer hardware needed to extend the simulations to significantly more solid angle has not become available as soon as expected. We are also improving our modeling of the hohlraum asymmetry to ensure that these very large, expensive, implosion simulations use the most accurate possible estimate of the asymmetry in the capsule irradiation.

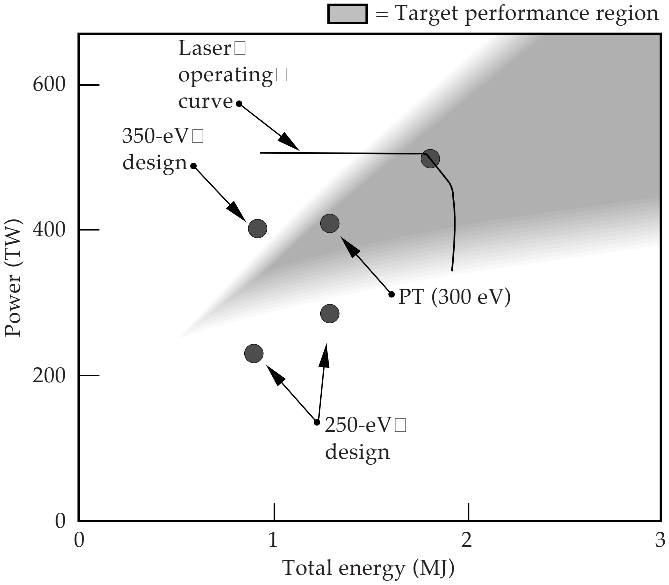


FIGURE 12. The parameter space characterizing NIF ignition targets, showing the points at which work has recently been done. (08-00-0299-0210pb01)

We completed design work on lower-intensity 250-eV capsules.[2] This included a very small capsule that would require only 900 kJ of laser energy, although this capsule requires surface finishes at the limit of plausibility. Work on 250-eV capsules has been extended to consider somewhat larger capsules, and another ablator material, polyimide. The ablator materials were compared at 1.3-MJ scale, still relatively small for performance at 250 eV but large enough that surface-roughness requirements will not be quite as tight as at 900 kJ. The trend identified at 300 eV—that beryllium is superior to polyimide but either material would work—is extended to 250eV, although for both ablator materials surface-roughness requirements are quite a bit tighter than at 300 eV. The roughness requirements are a strong function of capsule energy, and where most of the work was done (1.3 MJ) the requirements are about a factor of two looser than at 900 kJ. At the largest plausible energies—approaching 1.8 MJ—the 250-eV designs are expected to work with surface-roughness requirements almost the same as for the 300-eV designs at the 1.3-MJ/400-TW PT point.

Work on small laser energy capsules has also considered the other side of parameter space: the 350-eV design point indicated in Figure 12. Here the principal issues are laser–plasma instabilities and hohlraum physics. The capsule designed for these parameters performs well, although we have not yet done quantitative surface-roughness simulations. A very low aspect ratio for the capsule suggests that hydrodynamic instabilities will probably not grow very much and that surface-roughness requirements will be relatively loose. Laser–plasma conditions do indicate high plasma densities, and detailed modeling of the stimulated scattering is in progress. Experiments are also being done on the Nova laser to explore the stimulated scattering in this regime, as described in the subsection, "Intensity Scaling of SBS and SRS," on p. 8. The target-design work has raised several interesting issues, most notably a need for a higher initial gas density in the hohlraum. At 350 eV this gas density begins to affect the implosion hydrodynamics, and higher temperatures would probably not be acceptable even if laser–plasma instabilities turn out not to be the limiting factor. The size of the spot achievable on NIF is another limiting factor, as the hohlraum temperature increases, because laser entrance holes become relatively more important due to both the small target size and the higher intensity of x-ray loss out the holes.

Work on the point design—1.3 MJ and 400 TW—has been done in two areas. First, we did a full analysis of long wavelength modes to provide full quantitative specifications for target asphericity. Specifications are now available for each spherical harmonic mode number in the long-wavelength regime (mode number <10) and for each surface in the capsule: the DT ice inner surface, the ice/ablator interface, and the ablator outer surface. Requirements are similar to preliminary estimates and will be achievable but demanding for target fabrication.

Second, we have begun extensive analysis of the diagnostic requirements for ignition implosions. Figure 13 shows a simulated neutron image for a failed ignition shot, in which only the hot spot gave any burn. The structure of the perturbations that cause the failure is only a few microns across, and resolution of 5 microns or less will be very valuable to help us understand in detail the implosions of ignition targets. We have also simulated x-ray images. The x-ray images of failed ignition implosions look very similar to neutron images if the x-ray energy is above about 10 keV; below 8–10 keV, absorption becomes important and x-ray images become more difficult to interpret. Resolution requirements for x-ray and neutron images would be similar.

Notes and References

1. M. M. Marinak et al., *Phys. Plasmas* **5**, 1125 (1998).
2. T. R. Dittrich et al., *Phys. Plasmas* **5**, 3708 (1998).

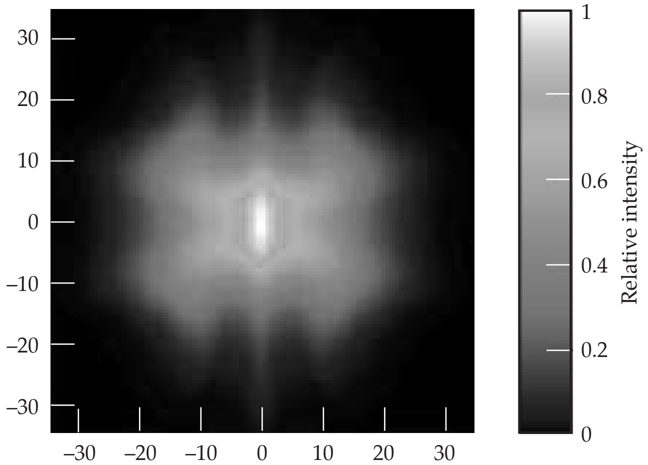


FIGURE 13. A simulated neutron image for a possible NIF implosion shot. For diagnostic optimization, we have considered this implosion which did not ignite and burn well (27 kJ of yield, at a burn-weighted ion temperature of 4.8 keV). The structure that we would like to see in such an image is only about 5 μm across, indicating a need for very high-resolution imaging technology. (08-00-0299-0211pb01)

"Platform-Independent" Laser–Plasma Interaction Postprocessor for LASNEX

A new postprocessor, NEWLIP, has been developed for use in the design and analysis of laser–plasma interaction experiments. It is based on the Yorick[1] interpreter, adding to it a large number of functions and scripts.

NEWLIP provides an intermediary between experiments, hydrodynamic simulations (with LASNEX), and laser–plasma interaction codes like F3D. With NEWLIP one can extract the plasma conditions on the interaction-beam path from a LASNEX simulation; these conditions are then analyzed to find regions in which plasma instabilities are predicted to grow. Detailed simulations of the instabilities (stimulated Brillouin scattering [SBS], stimulated Raman scattering [SRS], filamentation) can then be performed with F3D or other codes, incorporating the plasma conditions that have been isolated using NEWLIP. This multistep approach is necessary because simulations of the entire volume of a laser–plasma interaction experiment, resolving the plasma physics, is rarely feasible.

NEWLIP runs on platforms on which Yorick itself runs, which include most Unix workstations, Macintoshes, and Windows 95/NT machines.

As a stand-alone, it can be used as an "on-line plasma formulary." After entering the plasma conditions of interest (e.g., temperatures, electron density, material specifications, laser intensity), the user can readily calculate a variety of derived plasma quantities, such as thermal Thomson spectra, mean free paths, wave properties, and instability growth rates. The user can easily extend the package to calculate other quantities not directly provided.

Using packaged scripts, NEWLIP can be used to postprocess LASNEX output. Plasma conditions from LASNEX are interpolated onto a set of typical laser ray paths. The laser intensity along the rays is computed, accounting for laser focusing and inverse bremsstrahlung absorption. Linear gains for SBS and SRS are computed as a function of scattered frequency and time by integrating the local gain rate along the rays, taking into account any variation of material composition, such as from window material to gas to gold in a typical hohlraum. Averaging the gains over the ray collection creates "streaked spectra" that can be compared with experimental data.

We have begun testing NEWLIP predictions against experimental results obtained on Nova. Initial comparisons show good agreement between experiments and LASNEX/NEWLIP predictions. More in-depth testing of NEWLIP will be performed during the coming year.

Notes and References

1. Using the Yorick interpreted language, D. Munro, *Computers in Physics* **9**, No. 6 (November–December, 1995).

3D Full Wave Equation Solver for F3D

Experiments have shown that stimulated Raman scattering (SRS) grows to such nonlinear levels that linear convective saturation and pump depletion are inadequate models. The Langmuir decay instability is a probable mechanism for limiting SRS[1] because the SRS reflectivity is proportional to the ion wave damping in some NIF laser–plasma instability (LPI) scaling experiments, in agreement with theory and simulations of Langmuir turbulence.[2] Those simulations did not include important processes, such as filamentation and stimulated Brillouin scattering (SBS), that are known to influence SRS, and vice versa, and were limited in the spatial scale. Thus, we are motivated to implement this physics in F3D, which does model these in 3D and which we are developing as an LPI predictive computational tool. We followed two approaches: first, we treated the Langmuir waves in a paraxial approximation and accounted for the turbulence with anomalous damping coefficients, and then we developed a 3D second-order wave equation solver to treat Langmuir turbulence correctly. The latter capability will allow future improvements to the SRS saturation model and treatment of other NIF LPIs such as crossing-beam energy exchange.

F3D implemented a nonlinear damping on the amplitude of the Langmuir wave that Raman backscatters laser light in 1997. That model was successful in limiting the reflectivity of SRS once the Langmuir wave exceeded the threshold for the Langmuir decay instability (LDI),

$$\left|\frac{\delta n_{\mathrm{th}}^{\mathrm{LDI}}}{n_{\mathrm{e}}}\right|^2 = 16\left(k_{\mathrm{l}}\lambda_{\mathrm{De}}\right)^2 \frac{\nu_{\mathrm{e}}}{\omega_{\mathrm{l}}}\frac{\nu_{\mathrm{a}}}{\omega_{\mathrm{a}}} \tag{1}$$

where n_{e} is the local electron density, ν_{e} and ν_{a} are the damping rates for the Langmuir and acoustic waves, ω_{l} and ω_{a} are the Langmuir and acoustic wave frequencies respectively, k_{l} is the wave number of the Langmuir wave, and λ_{De} is the electron Debye length. In that model, the damping rate above the LDI threshold was an arbitrary fraction of the Langmuir wave frequency. In the improved model (based on scaling formulas from Langmuir turbulence studies[3]), the damping rate is proportional to the linear damping rate of Langmuir wave and the amplitude of the Langmuir wave relative to the threshold. In addition to this nonlinearity, the energy in turbulent Langmuir waves is accounted for. In the new model, the damping on the Langmuir wave is weaker, but new effects come into play. The ponderomotive force of the Langmuir waves is bigger because of the inclusion of the turbulent wave energy density that acts to detune the SRS rather than damp it. Simulations of single hot spots show an SRS reflectivity that increased with ion acoustic wave damping ν_{a}, because the threshold for LDI is proportional to ν_{a}. For a distribution of hot spots in which the mean intensity was reduced and a small percentage of the energy was at the same intensity, reflectivity would be much lower but the scaling with ion temperature would remain. This scaling of SRS with ion damping obtained with F3D is qualitatively in agreement with the experimental results that motivated this development.

F3D was extended to accommodate a 3D full wave (nonparaxial) Langmuir wave solver and associated 3D physics of secondary nonlinear processes affecting Langmuir waves and, hence, laser–plasma interactions. The new Langmuir-wave routine runs inside F3D and produces a solution that agrees with the old solver in a specified limit where the two should agree. Several subsidiary subroutines that were required to make this happen were developed, debugged, and successfully tested on the way. The new Langmuir solver will be used to run some other simple physics test cases.

Notes and References

1. R. K. Kirkwood et al., *Phys. Rev. Lett.* **77**, 2706–2709 (1996); J. C. Fernandez et al., *Phys. Rev. Lett.* **77**, 2702–2705 (1996).
2. D. F. DuBois et al., *Phys. Rev. Lett.* **70**, 2569 (1993).
3. D. F. DuBois, Los Alamos National Laboratory, Los Alamos, NM, private communication.

Postprocessing and Physics Packages in 3D Codes

Advanced hydrodynamic code development remains a key component of the target physics portion of the National Ignition Plan. Over the past year considerable effort has continued in the development of the three-dimensional arbitrary Lagrangian–Eulerian (ALE) code HYDRA and in development and maintenance of LASNEX, an essential ICF computational tool. This past year HYDRA has both built upon algorithms developed by the Department of Energy Defense Programs (DOE/DP) Accelerated Strategic Computing Initiative (ASCI) and provided algorithms for other codes being developed as part of the ASCI effort.

Hydrodynamic Algorithm Development

Improvements were made to both HYDRA's hydrodynamic and grid-motion algorithms. The hydrodynamic package has been modified to run predictor corrector, a numerical method for solving complicated ordinary differential equations in a fully self-consistent manner. New, more flexible, grid-motion algorithms, intended for Cartesian geometry simulations, were implemented and extensively tested. Two of these algorithms are extensions of the Winslow-Crowley 2D algorithms and were derived and implemented in both the finite-difference and finite element formulation. A new grid-motion algorithm was also implemented for use in 3D converging-geometry simulations. This algorithm was derived to include the effects of curvature of the specific mesh, preserve the symmetry of spherical and cylindrical meshes, and allow the user to control the local mesh orthogonality.

We have improved the ability to simulate both vacuum- and gas-filled hohlraums. These modifications have resulted in significant improvement in the hydrodynamic behavior for hohlraum simulations, particularly where near-vacuum regions exist.

Transport Algorithm Development

To treat diffusion on 3D grids composed of arbitrary hexahedrons, a 27-point finite element-coupling operator was installed and tested this year. In addition, the diffusion packages in HYDRA were modified to incorporate a finite element flux limiter prescription.

In the area of advanced radiation transport, work continued on the implementation and testing of implicit Monte Carlo (IMC) transport package, which is currently operational using a single block mesh. This configuration, which does not yet allow for (required) parallel operation, has allowed for testing of this package to begin. Initial testing of this package has reproduced analytic solutions to test problems. Initial tests on hohlraums have been conducted. During the coming year, we will improve the package with regard to the physics included and increase the efficiency of parallel performance, including domain decomposition of the IMC package.

Geometric Optics (Raytrace) Laser Deposition Package

A geometric optic (raytrace) laser deposition package was developed for use in HYDRA this year. This package is required for the simulation of hohlraums as well as direct-drive simulations. The package solves an eikonal equation for the ray path and treats energy deposition due to inverse-bremsstrahlung, both with second-order accuracy. The laser package operates on a domain-decomposed mesh, using threads to distribute tasks among processors within a box and the Message Passing Interface (MPI) library for communications across boxes. The laser package is currently being tested in distributed parallel memory operation on the LLNL IBM ASCI machine.

Parallel Code Development

The remainder of HYDRA’s existing physics packages were converted or improved to allow for efficient implementation on massively parallel distributed-memory machine architectures during this past year. These packages were converted to support multiblock meshes, a technique whereby a user can break up a large simulation into “blocks” for implementation on massively parallel platforms. The conduction, grid-motion, thermonuclear-burn, and charged-particle transport packages were among those adapted, using the MPI library. Initial studies were carried out to examine the efficiency of the parallel implementation. Detailed timing studies of HYDRA’s performance on up to 128 processors on the existing LLNL IBM ASCI machine showed that, for sufficiently large problem sizes having a fixed number of blocks, near-linear scaling of speed versus the number of processors is obtained.

Results from HYDRA’s parallel multiblock simulations can be postprocessed with our recently developed raytracing package HEX, an extension of our Yorick postprocessing tool. Figure 14 shows the mesh used for the simulation of a standard Nova gold hohlraum with 100% laser entrance holes (LEH) and a diagnostic hole on the side. The hohlraum was illuminated with 8 Nova beams. Figure 15 shows the simulated image of radiation temperature at 3.0 ns, viewed through an LEH at a 23° angle from the hohlraum axis. In addition to the laser spots, emission from plasma stagnating on the axis is apparent. This simulation, which used an earlier version of the laser package and multigroup radiation diffusion, was performed on 32 nodes of the LLNL IBM ASCI machine.

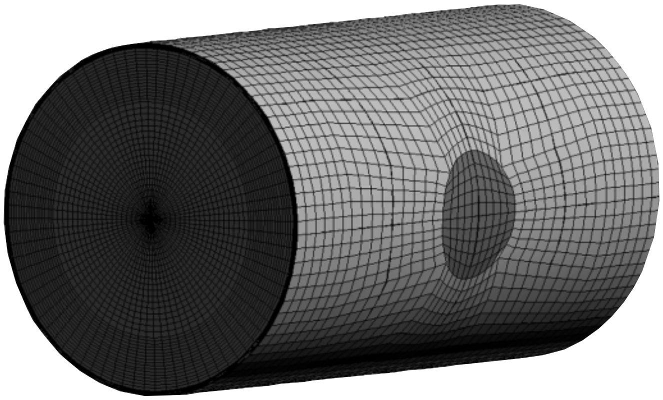


FIGURE 14. Mesh used for the simulation of a standard Nova gold hohlraum with 100% laser entrance holes (LEH) and a diagnostic hole on the side. The hohlraum was illuminated with 8 Nova beams. (08-00-0299-0502pb01)

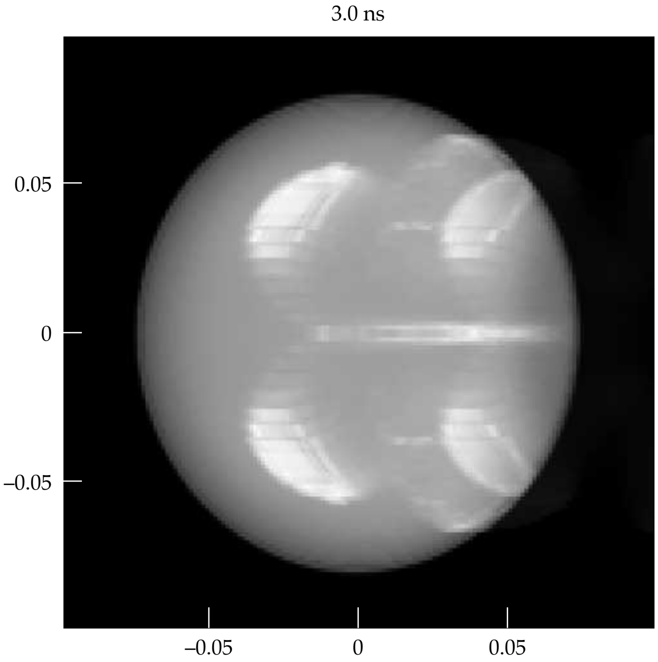


FIGURE 15. Simulated image of radiation temperature at 3.0 ns, viewed through an LEH at a 23° angle from the hohlraum axis. (08-00-0299-0503pb01)

LASNEX Code Development

During this past year LASNEX code development has focused on improvements to existing physics packages; testing of new, and potentially more computationally efficient, methods of treating nonlocal thermodynamic equilibrium opacities; parallelization; and code maintenance.

To conduct high-resolution integrated calculations important to the National Ignition Plan milestones and objectives, a significant effort was devoted to modifying LASNEX to run on massively parallel machines. This work made extensive use of the OpenMP standard for shared memory parallel (SMP) machines. Extensive testing of the new parallel version of the code was undertaken as part of this effort. Many of the major time-consuming packages in the code have now been modified to run in parallel.

2.0 EXPERIMENTS TO STUDY OPACITY, MIX, EQUATION OF STATE, AND HYDRODYNAMICS

The Lawrence Livermore National Laboratory (LLNL) researchers performed 304 shots on Nova in FY 1998, in the areas of opacity, radiation flow, equation of state, and hydrodynamics and radiation hydrodamics. Scientists also performed experiments on OMEGA and qualified the facility. This allows for a transition of these Nova experiments to OMEGA.

Hydrodynamics and Radiation Hydrodynamics

The experimental campaigns performed in this category cover five specific topics of study:

- Single- and double-shocked Richtmyer–Meshkov instability growth.
- Hydrodynamic features.
- Ablation-driven Rayleigh–Taylor instability.
- Radiation and material pressure hydrodynamics.
- Rayleigh–Taylor instability growth in the presence of material strength.

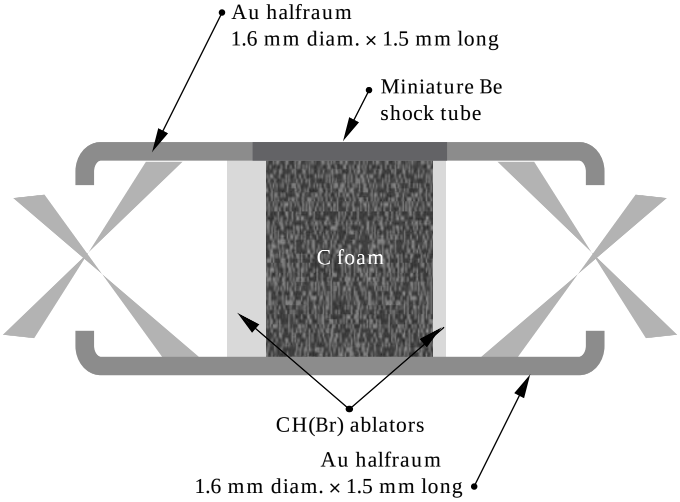


FIGURE 1. Geometry for double-shocked experiments. (08-00-0299-0487pb01)

A Novel Double-Shock Experiment on Nova

We have developed an experimental geometry (shown in Figure 1) to investigate hydrodynamic instabilities in a double-shocked system. Previous shock-tube experiments on double-shocked mixing layers indicate that the growth rate of the mixing region is greatly enhanced upon passage of the second shock, showing a rapid transition to turbulence. In Nova experiments, which achieve higher Mach numbers than shock tube experiments, four beams enter a half-hohlraum. The x rays ablatively launch a shock of approximately Mach 20 into a carbon-foam-filled Be miniature shock tube and across an interface. A second, counterpropagating shock is launched from the opposite end of the shock tube by a second half-hohlraum driver; the second shock strikes the interface region later than the first. By placing initial perturbations on the interface, the effect of the second-shock on the growth of the Richtmyer–Meshkov instability can be measured. In addition, by delaying the laser beams entering the second half-hohlraum driver, the relative timing of the second shock arrival can be uniquely controlled.

The half-hohlraum drive configuration was characterized. Shock planarity was measured by analyzing shock breakout from two steps of CH(Br), 250 μm and 300 μm thick (Figure 2). Interface decompression was measured via x-ray radiography. Experiments with perturbed interfaces will begin in FY 1999.

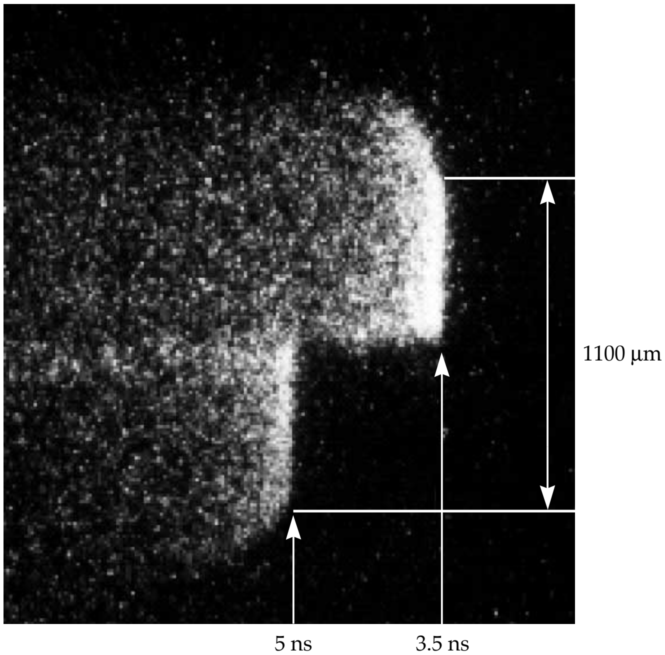


FIGURE 2. Shock breakout from a stepped carbon foam driven by a half-hohlraum. (08-00-0299-0488pb01)

Hydrodynamic Features

We are conducting two experimental campaigns devoted to understanding different aspects of the growth of hydrodynamic features. The first experiment, done in collaboration with Los Alamos National Laboratory (LANL) and Atomic Weapons Research Establishment (AWE), attempts to measure the generation and propagation of supersonic jets ($M \approx 8$). An ~190-eV temperature drive is generated using an 18-kJ, 1-ns laser pulse into a Nova hohlraum. This pulse ablatively produces a shock in a cylindrical Al target, as shown in Figure 3. The shock propagates through the Al and breaks out of the back surface of the Al, resulting in a jet of material at the interface of the Al and plastic. The jet is radiographed using a Ti backlighter generated by a 600-ps laser pulse and is pinhole-imaged onto film. Kelvin–Helmholtz rollup is evident, and the proximity of the bow shock to the jet tip is evidence of the high Mach number of the jet (Figure 4). These experiments are compared to code simulations and are used to validate the codes. Future experiments will record directly onto x-ray charge-coupled device (CCD) cameras to improve the image.

The second experiment attempts to measure the transition from 2D to 3D in a geometry that starts out with 2D symmetry. This experiment will be compared with 3D code modeling to verify the new generation of 3D codes being developed. A shock of Mach ~10 to 20, created by a 1-ns laser pulse into a hohlraum, propagates down a foam-filled Be shock tube and interacts with a

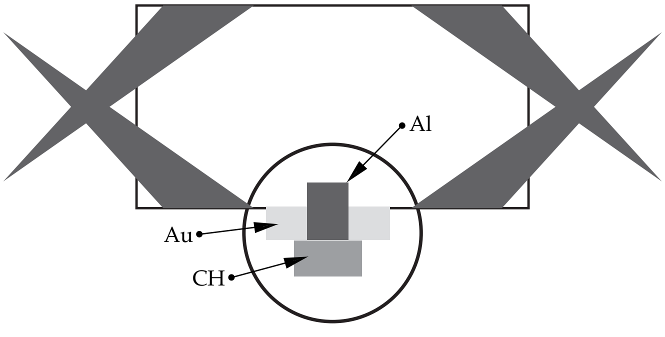


FIGURE 3. Geometry for supersonic jet experiments. (08-00-0299-0490pb01)

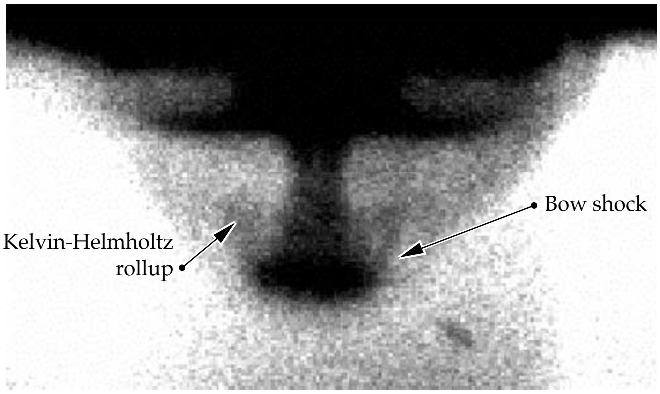


FIGURE 4. Radiograph of supersonic jet. (08-00-0299-0491pb01)

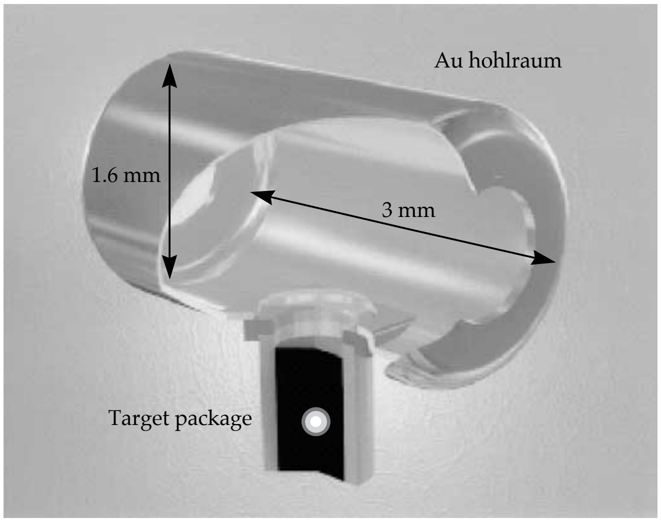


FIGURE 5. Geometry for 2D-to-3D shock study. (08-00-0299-0489pb01)

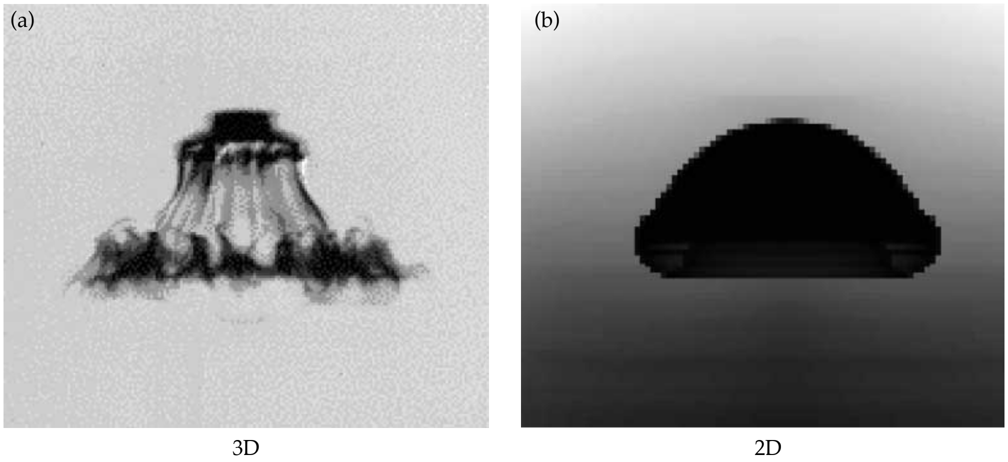
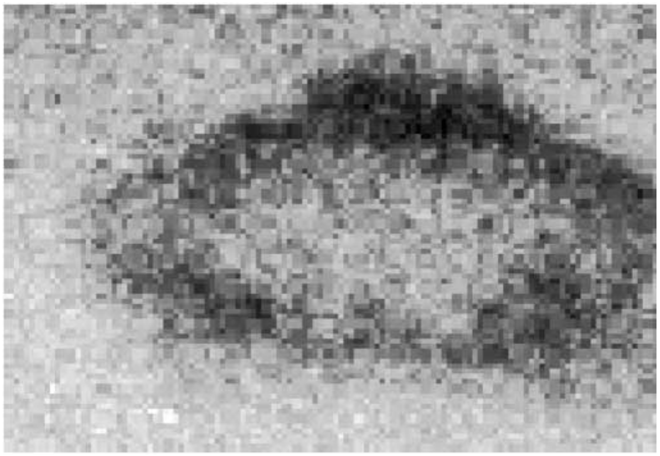


FIGURE 6. Code simulations of Cu deformation: (a) 3D model; (b) 2D model.
(08-00-0299-0492pb01)

spherical Cu ball placed downstream (Figure 5). This problem, initially 2D-axisymmetric, becomes 3D at late times when an azimuthal-bending mode instability (the Widnall instability) begins to develop at the back end of the crushed sphere. This 2D-to-3D transition is qualitatively predicted by 3D codes (Figure 6a) and not predicted by 2D codes (Figure 6b). X-ray radiographs are taken of the Cu sphere, and a central void within the sphere (illustrated in Figure 7) is measured, characteristic of the 3D fingering signaling the 2D-to-3D transition. To improve the image resolution, a half-hohlraum geometry was developed that uses a shock-tube diameter—and, thus, a sphere size—twice that of the hohlraum geometry. Future measurements will use direct imaging onto an x-ray CCD, and a parameter study will be done for differing foam-to-sphere density ratios.

Ablation-Driven Rayleigh–Taylor Instability

Experiments are being developed to understand foil breakup from ablation-driven Rayleigh–Taylor (RT) instability. The goal of these initial experiments is to make the first conclusive indirect-drive measurements of the ablation-front RT dispersion curve under steady-state conditions. A new drive was developed and characterized to generate a nearly constant acceleration for an extended period, at T_r (~100 eV). Figure 8 presents plots of T_r and laser power over time. Initial sinusoidal perturbations of wavelengths of 10, 20, 30, 50, and 70 μm and 1 μm amplitude were machined on the surface of a 25-μm-thick Al. This layer was placed on the side of a hohlraum, with low-density agar foam



$t \sim 3T_c$

FIGURE 7. Radiograph of void within Cu target ball.
(08-00-0299-0493pb01)

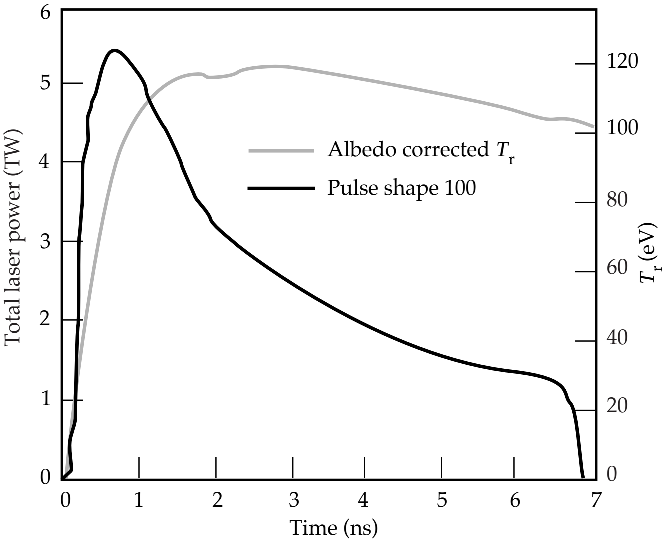


FIGURE 8. New pulse shape and radiation temperature.
(08-00-0299-0494pb01)

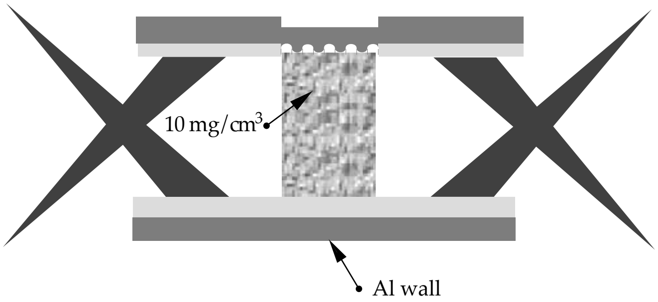


FIGURE 9. Experimental geometry to measure RT instability. (08-00-0299-0495pb01)

filling the central 1 mm of the hohlraum to keep the line of sight open (see diagram in Figure 9). The growth of the RT instability was measured via face-on x-ray radiography, using a Sc backlighter (4.3 keV). Experiments are planned to measure the wavelength region in greater detail near the cutoff on the dispersion curve (10 to 20 μm); work is under way to compare our experimental results with 2D numerical simulations and with the Betti ablation-front RT theory.

Radiation and Material-Pressure Hydrodynamics

A new source is being developed in collaboration with AWE for driving radiation-hydrodynamics experiments using an admixture of radiation ablation and material pressure. These experiments have concentrated on a configuration to study the hydrodynamics of a thin Au layer.

The driver is a single-ended, ~200-eV hohlraum driven by ~11 kJ of 3ω laser light in a 1-ns square pulse (Figure 10). The hohlraum radiation penetrates a low-density foam ($\rho \approx 0.1$ g/cm^3) supersonically, with a Mach number $M_R > 3$ to avoid generating significant compression in the foam as the radiation passes. The payload is a thin layer of Au on solid CH. The foam density controls the material-pressure component of the drive, P_f, and the radiation transported to the payload causes ablation P_a. For the upper density limit of ~0.15 g/cm^3, consistent with $M_R > 3$, for these experiments, $P_f \approx 15$ Mbar, and the ratio of foam-to-ablation pressure reaches approximately 3 (Figure 10).

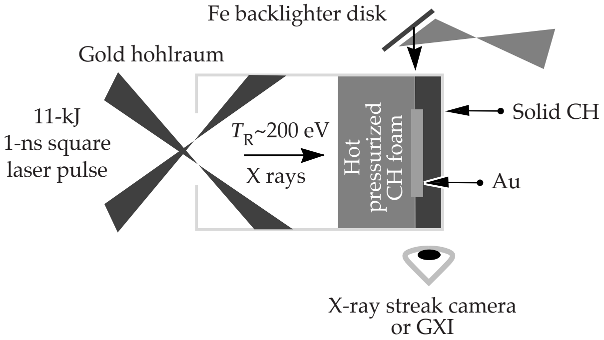


FIGURE 10. Geometry for new pressure source. The length of the foam section depends on the density. (08-00-0299-0496pb01)

The x-ray power history incident on and transmitted through the foam was measured on separate shots and was found to be in good agreement with 2D simulations. The trajectory of the Au layer was measured using streaked x-ray radiography at a photon energy of 6.7 keV from an Fe backlighter. Spatially resolved, 2D gated x-ray imaging confirmed that the package remained reasonably planar.

Figure 11 shows streaked radiographs of the Au layer in three regimes: freely ablating, moderately tamped ($\rho = 0.05$ g/cm^3; $P_f \approx P_a$), and strongly tamped ($\rho = 0.15$ g/cm^3; $P_f > P_a$). In the freely ablating configuration, the Au layer moves off towards the drive. In the moderately tamped system, this ablation is inhibited, whereas in the strongly tamped regime, the foam pressure dominates and acts like a plasma piston, accelerating the payload away from the hohlraum. Preliminary 1D simulations (Figure 11) reproduce the qualitative behavior of the targets. More detailed simulations of the

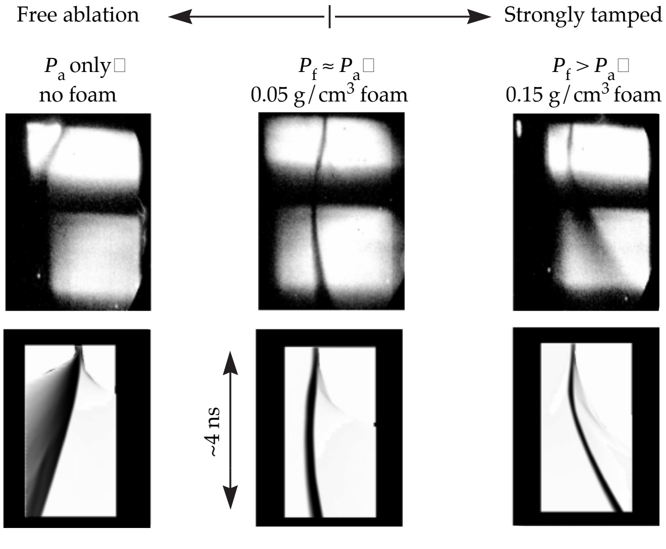


FIGURE 11. Streaked radiographs of the Au layer for different ratios of ablation to material pressures. Top images are experimental measurements; bottom images are 1D simulations. (08-00-0299-0497pb01)

Au layer dynamics are being performed using a 2D code to capture the effects of the RT instability, which is particularly important in the strongly tamped target and causes significant broadening of the layer compared with the 1D simulations.

In summary, a novel "plasma piston," which uses a combination of material pressure and x-ray ablation to drive radiation hydrodynamics experiments, has been demonstrated on Nova. The targets behave qualitatively as expected, and the experimental observations are reproduced qualitatively with 1D radiation-hydrodynamics code simulations. More detailed simulations to include the effects of the Rayleigh–Taylor instability are under way.

Rayleigh–Taylor Growth in the Presence of Material Strength

As a solid is compressed, its melt temperature is predicted to increase, based on the Lindemann melt law. As the pressure and compression increase, the strength of the material is also predicted to increase, based on the Steinberg–Guinan model of material strength. This strength should modify the rate of perturbation growth due to the RT instability. By measuring the RT growth compared to that expected in the liquid state, the strength of the metals at high pressure can be deduced. Experiments are being developed to examine the evolution of hydrodynamic instabilities at an unstable interface of metal in the solid state at Mbar pressures. An x-ray drive, PS56, has been developed to compress metal foils in the solid state by launching a series of staged shocks, reaching peak pressures of 3 Mbar and peak compressions of 1.5 to 2.0. The drive has been characterized by several techniques. In the $T_r = 20–90$ eV range the drive was characterized with the Dante diagnostic measuring the flux out of the hohlraum. The foot of the drive was measured with the Active Shock Breakout diagnostic (ASBO), and the overall hydrodynamics was characterized with side-on foil trajectory measurements at high magnification (~60×). Dynamic Bragg diffraction experiments are under development as a means to verify the solid-state compression. Experiments have been conducted to study growth of the RT instability in Cu foils at these 3-Mbar peak pressures. Preimposed modulations with initial wavelengths of 20 to 50 μm and amplitudes of 1.0 to 2.5 μm show growth consistent with simulations. Based on simulations with use of the strain-rate-independent Steinberg–Guinan strength model, the fluid and solid states of Cu are expected to behave alike in this parameter regime. Strength effects would be observable only for wavelengths shorter than ~10 μm, which would be difficult to observe.

A new experimental design was developed using an extended drive, such that small differences in RT growth rate would be observable due to larger overall growth. This drive uses 3ω laser pulses (as opposed to the 2ω laser pulses used in PS56), so that measured 3ω power profiles are more readily available. We also switched from Cu to Al, where the relative strength at peak pressure should be considerably larger. The drive requires staggered beams: 4-ns square pulses at total power of 0.8 TW in the foot, followed by a 1.5-ns ramp to a 3.0-ns peak at 2.8 TW total laser power. This leads to an 8.5-ns extended drive with a 200–300-kbar first shock, and a peak pressure in the Al of ~1.5 Mbar. For this design, significant strength stabilization effects are predicted (factors of 2 or greater) for wavelengths of 20 μm. For wavelengths of 10 μm and shorter, the RT instability is predicted to be nearly completely stabilized.

Initial experiments with the staggered beam design have been conducted, showing such a drive is straightforward to implement and characterize. We have measured Dante flux, and foil trajectories, and compared against drive models from a view-factor analysis and from a full 2D drive hohlraum simulation. All are reasonably consistent with each other, and we adopt the $T_r(t)$ from the 2D hohlraum simulation for our drive model. This design predicts that the Al interface will stay solid under compression throughout the experiment. Dynamic diffraction techniques are being developed to verify the compressed state.

Radiation Flow

The goal of the radiation-flow experiments is to experimentally characterize radiation transport in increasingly complex geometries. This year's experiments at the Nova and OMEGA facilities investigated the importance of high-Z walls in determining the radiation transport in a low-Z fill. The samples consisted of 10-mg/cm^3, SiO_2 foam cylinders surrounded by Au walls. The foam faces were irradiated from one end by an 80-eV, 12-ns, soft x-ray drive, designed to provide supersonic radiation flow.

An example of radially resolved, streaked radiation breakout data is shown in Figure 12. The data shows that the radiation wave takes about 2 ns longer to burn through at the edges of a foam than at the center, demonstrating the importance of wall losses in Nova- and OMEGA-scale radiation-flow experiments. Simple analytic models developed this year confirm this significant radiation-front curvature. Comparisons

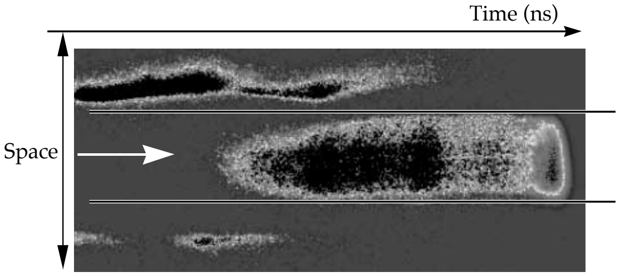


FIGURE 12. Radially resolved, temporally streaked image of radiation breakout from 10 mg/cm^3 SiO_2 foam. (08-00-0299-0498pb01)

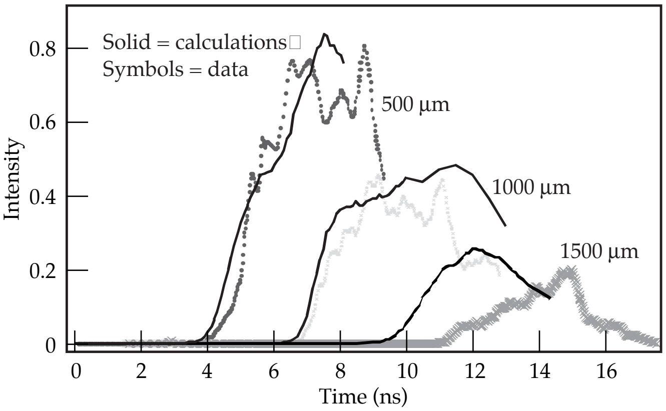


FIGURE 13. Measured and calculated radiation transmissivity vs delay at foam center for different length foams. (08-00-0299-0499pb01)

between measured and predicted breakout times at the center of the foam plotted in Figure 13 show extremely good agreement.

Analytic scaling laws have been developed to evaluate the relative merit of various size drivers for radiation flow. Specifically, if we take the figure of merit as the number of mean free paths propagated, it is a weak function of the driver energy E, varying as $E^{0.07}$ with lossy walls and $E^{0.26}$ with lossless walls.

Equation of State

A variety of successful EOS experiments were conducted with Nova in FY 1998. Final results were established for data on the high-energy-density EOS of polystyrene and beryllium. Absolute principal Hugoniot data were obtained for Be at 12 and 14 Mbar and CH between 10 and 40 Mbar. The Be data confirmed relative Hugoniot measurements made in underground tests. Although uncertainties were large, the CH data revealed the preferred LLNL EOS model for plastic was too soft above about 5 Mbar.[1]

Three Nova shots investigated the use of an egg-shaped halfraum to drive impedance-match EOS experiments. Excessive preheat was observed, possibly due to 11-keV radiation from the Au converter plate in the halfraum.

LiF and C-diamond were shocked by direct drive on an Al pusher. Most shots were an attempt to establish a uniform, unidirectional shock by overlapping several high-angle-of-incidence beams and a collection of available random phase plates and kinoform phase plates. Unpredictable beam smoothness and low number of beams made this extremely difficult. Preliminary data show both materials driven below and above the metallic phase, from 3 Mbar to about 10 Mbar.

Principal Hugoniot data on liquid D_2 from 300 kbar to 3.4 Mbar were obtained, confirming FY 1997 Hugoniot data. Shock temperatures were measured via optical pyrometry. Reflectivity data confirmed that the Hugoniot data spanned the metal-insulator phase transition.[2]

The ASBO diagnostic was implemented in a Michelson interferometer configuration for preheat tests and in a single-wavelength velocity interferometer system for any reflector for high-resolution shock breakout and shock uniformity measurements.

FY 1998 results led to five submissions to refereed journals in addition to those noted above, six proceedings articles, one plenary talk, and six invited talks. Four members of the team (Cauble, Celliers, Collins, Da Silva) received the 1998 American Physical Society Award for Excellence on Plasma Physics Research for the D_2 EOS experiments.

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Opacity Experiments

In FY 1998, the opacity project focused on three goals: validation of opacity modeling tools and databases, challenging the theory and models in new regimes, and ensuring successful application of NIF. Experiments tested the line broadening in open M-shell systems, effects of strong coupling, non-equilibrium plasma models, and the development of advanced backlighting and plasma characterization tools needed for very-high-temperature experiments on NIF.

In FY 1998, experiments were conducted on Nova, to test line-broadening mechanisms for high Z and high temperature systems. A quasi-isoelectronic open M-shell sequence of plasmas was studied: Cu at ~60 eV, Nb at ~100 eV, and Ag at ~120 eV. In addition, data of Nb plasmas at 60 eV was obtained. These experiments significantly extended the temperature range for spectroscopic measurements of Rosseland mean. This required the simultaneous measurement of emission and absorption spectra, using a double-slit extreme ultraviolet (XUV) gated spectrometer looking at a thin plasma target. The gated imaging grating spectrometer (IXUV) covers an x-ray energy range of 200 to 1200 eV. The plasma is produced by the Nova laser in a modified scale-1 hohlraum with lips and is in radiative driven thermal equilibrium.

New plasma diagnostics are needed for high-temperature plasmas when scaling up to the NIF. In FY 1998 we investigated two of these: a model-independent temperature diagnostic and a tool for measuring the equilibrium of a plasma employing the IXUV spectrometer looking at Au samples in emission and absorption (seven shots). Both of these diagnostics depend on the relative sensitivity calibration of the spectrometer that we determined by simultaneously measuring the back wall of a Au scale-1 hohlraum or Au foil in a scale-1 hohlraum with the IXUV and the Dante spectrometers (four shots). The temperature diagnostic uses the slope of the free-bound continuum of the plasma species. This is a model-independent diagnostic because it does not depend on line ratios or the plasma being in equilibrium. By applying Kirchhoff's Law to the sample, the plasma equilibrium is inferred by the quality of agreement between emission and absorption opacities.

Understanding the nonlocal thermodynamic equilibrium (NLTE) physics of highly ionized, high-*Z* materials is important in hohlraums, Z pinches and other devices where the radiation and matter are strongly coupled. Comparisons of current high-*Z* NLTE models show large discrepancies due to difficulties in treating complex processes such as dielectronic recombination. In FY 1998, experiments tested NLTE models of highly ionized high-*Z* materials on the Nova laser facility. Laser-heated Au microdots, centrally buried in a thin Be foil, reached temperatures of 2 keV and ionized into the M shell. During expansion, the tamped Au samples remained uniform and in near steady-state ionization equilibrium. The electron temperature was measured with time- and space-resolved Thomson scattering while the density was determined from time-gated x-ray imaging the expanded Au sample. The charge state distribution was derived from emission measurements of Au 5f–3d transition arrays in the wavelength range 3.3Å to 3.9Å using a quasi-coronal model, allowing the average charge to be determined with better than 2% accuracy. To our knowledge, this is the first accurate determination of Z^* in a well characterized, highly ionized, high-*Z* plasma. By comparisons with various NLTE codes, these results verify theoretical predictions that two-electron processes can significantly lower the charge-state distribution in plasmas in this regime. Similar experiments are under way to study other materials, such as Si and Se, which are predicted to ionize into the K and L shells, respectively.

In FY 1998, we designed high-density experiments to test models for ionization in a strongly coupled plasma and developed a temperature diagnostic for shock-heated targets. This extended previous experimental work on Al but tested L shell models for germanium at 30-Mb pressure. The design required making an EOS table for Ge, detailed calculations of the x-ray preheat (using LASNEX), and estimates of the anticipated absorption characteristics (using OPAL). The results were found to be a sensitive test of the EOS model used, suggesting the experiment would provide an excellent benchmark. A new spectrometer nose-cone was built to allow large diffraction angles needed for the Ge L-shell spectrum. The first shot has recently been taken, and the results look encouraging.

OMEGA Qualification

Two weeks of experiments were performed jointly with LANL and the Laboratory for Laser Energetics to prepare and qualify OMEGA for experiments. DOE approved modifications and certified OMEGA to perform classified experiments. Demonstrations were made of long-pulse capability, point-backlighting capability, and a facility capability for performing hydrodynamic, radiation-flow, and opacity experiments, fulfilling the original requirements for validation. These experiments were chosen to provide a stressful test of the OMEGA facility. We also successfully demonstrated the use of one leg of the OMEGA laser for long-time-delay backlighting as well as the use of two groups of backlighters separated by 5 ns.

3.0 PETAWATT LASER EXPERIMENTS

In FY 1998, the Petawatt laser, using one arm of the Nova facility at LLNL, reached its full one-petawatt power (1 PW equals 10^{15} or one quadrillion watts) in a pulse lasting 500 femtoseconds (1 femtosecond, fs, is 10^{-15} or one quadrillionth of a second) and delivered focused intensity up to 3×10^{20} W/cm^2. This performance, which is an order of magnitude higher than lasers elsewhere, has opened many paths of both basic and applied scientific interest.

The main goal of experiments in FY 1998 was to assess the viability of using petawatt-class lasers to generate sufficiently intense pulses of 2- to 6-MeV x rays to provide a technically advantageous and cost-effective x-ray source for next-generation radiography studies in the Stockpile Stewardship Program (Section 2). Study of the feasibility of fast ignition as an ICF ignition concept capable of significantly higher gain, and therefore interesting for inertial fusion energy, was continued from FY 1997 at a lower level of priority.

Underpinning both these applications is the efficient generation of a well collimated source of relativistic electrons. This aspect of the science is discussed next, leading into the subsections on the two applied science areas.

Relativistic Electron Sources Produced at Laser Intensities above 10^{20} W/cm^2

Relativistic electrons are electrons traveling at nearly the speed of light. Intense-beamed relativistic electron sources are required in the major applications that motivate research with the Petawatt laser.[1] A central objective in FY 1998 was, therefore, to characterize the source of relativistic electrons produced in the irradiation of solid targets at intensities above 10^{20} W/cm^2.

Control of the laser wavefront using adaptive optics was implemented for progress to higher intensities. A reproducible focal spot of 8 μm full width at half maximum intensity, with about 30% of the laser energy inside the first minimum, was obtained and gave peak intensity in vacuum up to 3×10^{20} W/cm^2 for 1-PW power in 0.5-ps pulses.

When 1-mm-thick Au targets were irradiated, two magnetic electron spectrometers, at 30° and 95° to the laser axis, recorded electrons emitted by the target in the energy range 1 to 100 mega-electron-volts (MeV). Electron energies up to 100 MeV were observed, and the angular pattern was forward peaked. Positrons from pair production by bremsstrahlung photons were also seen at the theoretically predicted flux level relative to the electrons.[2] (*Bremsstrahlung* is the radiation emitted by an electron that is accelerated in its collision with an atom's nucleus or a positively charged ion.) The quasi-Maxwellian slope temperature of the electrons for energies greater than 10-MeV energy was in the range 5 to 10 MeV, giving evidence of a hot tail in the distribution function with a temperature several times the ponderomotive potential. The angular pattern of electron emission was studied in detail using a detector comprised of nested conical sheets of radiochromic film sandwiched in 100-μm-thick layers of tantalum (Ta).[3] Targets were thin enough to freely transmit the electrons; examples of the angular pattern over the forward hemisphere are shown in Figure 1.

Figure 1a shows a highly directional beam of electrons, emitted normal to the rear surface of a 125-μm gold (Au) target. Similar results were obtained for 0° and 45° incidence, both for S or P polarization. There is also a weaker diffuse background of electrons, which is much less attenuated by the Ta layers. The directional is sharply bounded with less energetic electrons in its periphery. The diffuse source (Figure 1b) has a much wider-angle spread and a gentle maximum. CH targets of 100-μm thickness showed much more substructure in the angular pattern of diffuse emission and also

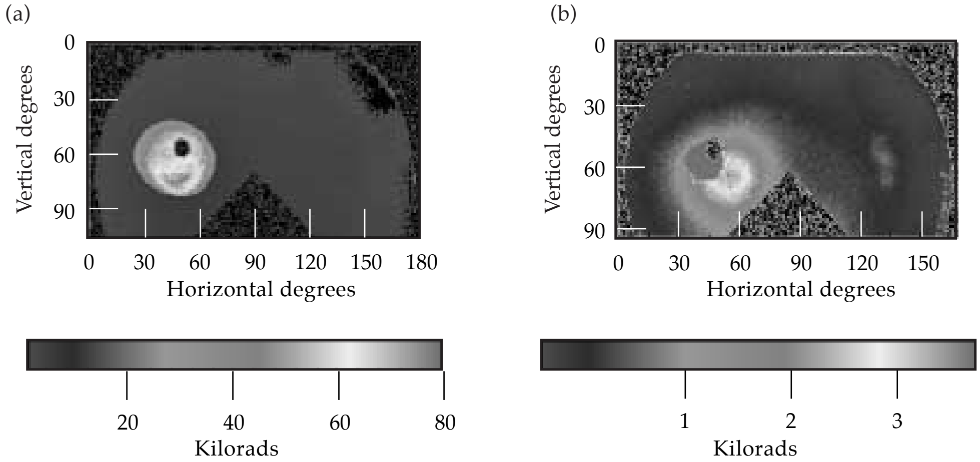

FIGURE 1. Radiochromic film data showing kilorads. Intensity scale is chosen to show (a) the directed beam (left, recorded via 200-μm Ta) and (b) the diffuse feature with the beam display saturated (right, via 600-μm Ta). The hole in the film transmits the beam to an electron spectrometer. (08-00-0299-0293pb01)

irregular and finer structure in the directional beam. From Monte Carlo simulations and the response characteristic and absolute calibration of the film, the slope temperatures of the two sources were estimated to be 0.6 and 3.5 MeV, and the total energies were calculated as 10 and 1 J. These total energies observed in vacuum represent a small fraction of the energy entering the target, even though the range of electrons is much larger than the target thickness. Escape of the electrons to vacuum is severely restricted by the buildup of positive potential and by the relativistic Alfven current limit for electron beams.

Particle-in-cell (PIC) simulations[4] and further data analysis are ongoing to understand better the physical processes influencing the electron source and, in particular, the significance of the observed directional beam. The modeling treats laser–plasma interactions in the regime that is complicated by relativistic self-focusing in the plasma atmosphere on the target surface, which is formed by precursor irradiation by amplified spontaneous emission. In the simulations, two principal sources of electrons have been identified. One is a quasi-Maxwellian source of mean energy similar to the ponderomotive potential ϕ_p, originating in absorption close to critical density. The other has a mean energy several times ϕ_p and is attributable to acceleration of electrons linked to relativistic self-focusing at subcritical density.[5] The latter source is consistent with the electron spectrometer measurements.

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Experiments to Assess the Viability of Petawatt Lasers for Radiography

Emission of MeV x rays is produced by bremsstrahlung of relativistic electrons in high–atomic-number (high-Z) targets. The x-ray emission for Lorentz factor γ is in a narrow cone angle of $1/\gamma$ around the direction of the electrons. Photon energies from 2 to 6 MeV are the most effective for radiography of dense high-Z objects and are produced most efficiently by electrons of a few times the photon energy. Pulsed-power machines, generating kilojoule pulses of beamed electrons at about 15 MeV, are presently used for stockpile-stewardship– related dynamic radiography in the 2- to 6-MeV range of photon energy. Multi-petawatt lasers generating multi-kilojoule pulses focused to 10^{21} W/cm^2 could produce a quasi-Maxwellian source of electrons with 10 MeV mean energy. Petawatt lasers therefore offer an advanced conceptual alternative with potential advantages in engineering flexibility, lower cost, smaller source size, and reduced pulse duration, provided that sufficient x-ray brightness can be achieved.[1] Investigation of the viability of this application was a priority activity in FY 1998.

Figure 2 illustrates the laser radiography capability. It shows a projection radiograph with well resolved millimeter-scale features photographically recorded through substantial thicknesses of lead (Pb) in a single exposure with the PW laser.[1]

Experimental effort in FY 1998 concentrated mainly on quantitative characterization of the x-ray source. The spectrum, angular pattern, and absolute intensity were determined for irradiation of 1-mm-thick solid Au targets. Data were recorded at normal incidence and best focus with minimum preformed plasma. The spectrum from 0.2 to 10 MeV was obtained from thermo-luminescent dosimeters (TLDs) in a multifilter assembly with up to 2-cm-thick Ta filters. From 10 to 50 MeV, the spectrum was deduced from multiple orders of (γ,n) photonuclear processes leading to nuclear activation of Au discs placed close to the target.[2]

The absolutely calibrated results showed a strongly nonthermal x-ray spectrum with a slope temperature of about 1.5 MeV at 2 MeV energy, rising steadily to more than 5 MeV at 20 MeV. The angular pattern of the emission was recorded with an array of 96 TLDs, which gave results similar to the diffuse pattern of energetic electron emission described in the previous subsection. The detectors were calibrated absolutely and used in filtered housings giving a flat spectral response above 1 MeV (modeled by Monte Carlo simulation). The emission pattern was largely confined to the forward hemisphere in a ±60° cone, typically with one or more irreproducible ±10° maxima. The maximum intensity of the source measured in this way reached a value of 2 rads at a distance of 1 m, in peaks of the angular pattern.[2] Measurements of γ,n nuclear activation with an array of up to 20 Au discs showed, with less resolution, the angular pattern of the photons of about 15 MeV energy,[2] which was broadly similar to the TLD patterns. Monte Carlo modeling was used to simulate the x-ray source, assuming that electrons behave independently (ballistically) and relating the energy spectrum and number of the electrons to the spectrum of laser intensity and the ponderomotive potential ϕ_p on the target. Fair agreement was obtained if it was assumed that relativistic self-focusing enhanced the measured vacuum intensity by a factor of 4 to 8.[3] Current work is directed to optimizing the source by varying key parameters.

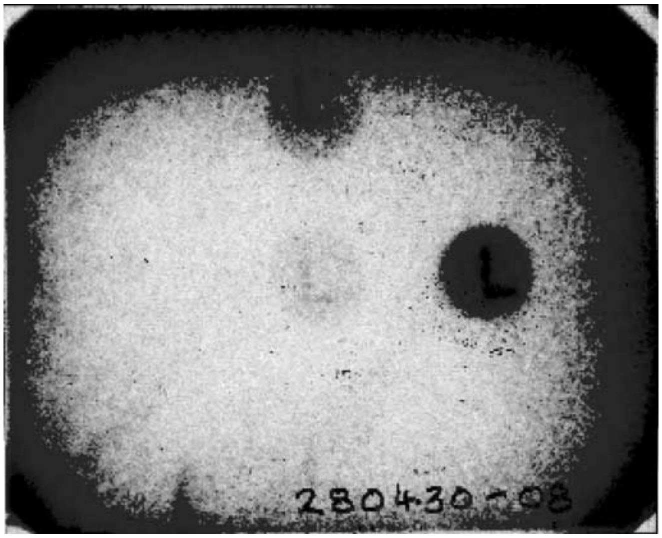


FIGURE 2. Radiograph showing 1.3-mm-wide, 15-mm-deep, L-shaped Pb features, recorded via 11.6 (right), 13.3 (top), and 14.5 cm (center) of Pb with a single laser pulse of 265 J on target. (08-00-0299-0292pb01)

Notes and References

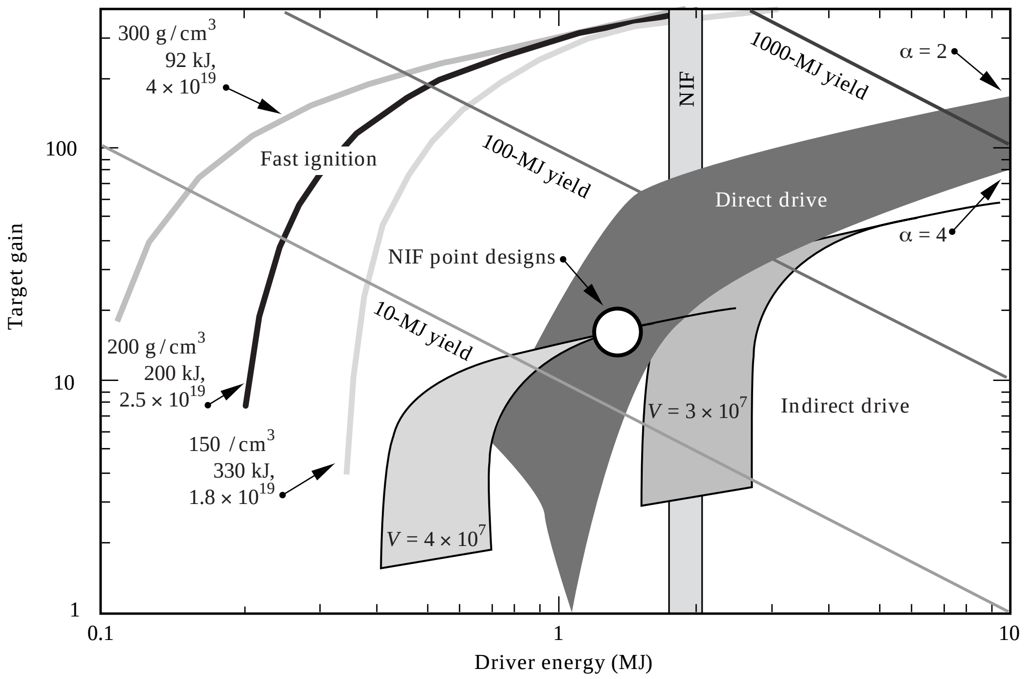
1. M. D. Perry et al., *Rev. Sci. Inst.* **70** (1), 265–269 (January 1999).
2. M. Stoyer et al., *Bull. Am. Phys. Soc.* **43** (6), 1556 (1998).
3. S. P. Hatchett et al., *Bull. Am. Phys. Soc.* **43**, 1656 (1998).

Heating of High-Areal-Density Matter by Hot Electrons for Pulse Energies up to 500 J, and Related Prospects for Fast Ignition

A potentially important long-term application of petawatt lasers is in fast ignition of a precompressed pellet of fusion fuel.[1] The main advantage of fast ignition is significantly higher gain, which opens up new possibilities for laser-driven inertial fusion energy. For example, a model scenario for fast ignition using the National Ignition Facility (NIF)[2] suggests that more than 300× gain could be obtained (see Figure 3), and the potential advantage relative to indirect and direct drive (DD) is evident. This assumes use of 10% of the NIF beams as igniters and 90% for compression of DT fuel to 200 g/cm^3. The second-harmonic-frequency igniter beams are focused to 10^{20} W/cm^2 ($I\lambda^2 = 2.5 \times 10^{19}$ W·cm^{-2}·μm^2) to provide the 1-MeV required mean energy of the electrons.

The main problem in this application is to achieve ignition by heating compressed fuel *via its surrounding plasma atmosphere* using laser-generated relativistic electrons. The ignition condition is $kT > 10$ keV in a region with density radius product $\rho r > 0.5$ g/cm^2. Study of the heating effect of Petawatt-laser–generated electrons has therefore been a prime objective of our fast-ignition research.

FIGURE 3. Calculated gain curves for laser-driven ICF targets. Fast ignition plots are labeled with density, ignition spark driver energy, and focal spot $I\lambda^2$. (08-00-0299-0294pb01)



Both x-ray spectroscopy[3] and neutron energy spectroscopy[2] have been used to assess the heating. Spectroscopy and imaging of emission from a layer of aluminum (Al) buried at 5 to 30 μm below the surface of a CH target showed temperature of 300 eV and density of 0.4 g / cm^3, from spectra illustrated in Figure 4. The spatial origin of the Al emission was resolved in x-ray pinhole camera images (Figure 4b) and was a ring of 120 μm diameter for Al layer depths less than 10 μm, changing to a circular spot of emission for depths greater than 20 μm. Numerical modeling with LASNEX suggests that the ring is caused by prepulse-induced decompression of the Al layer in the focal spot. Although the ring was absent in observations from greater depth, opacity of the CH plasma to the Al spectrum made the spectrum faint and the data

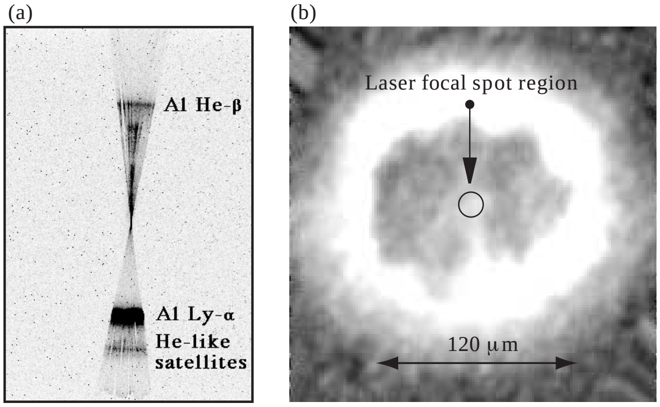


FIGURE 4. (a) Al spectrum recorded from 0.5-μm-thick layer, 10 μm beneath CH. (b) X-ray pinhole camera image filtered to show Al emission. (08-00-0299-0295pb01)

noisy in this limit. The spectral measurement, therefore, probably underestimated the heating in the center of the focal spot.

The depth at which neutron emission from DD fusion can be observed is not limited, and neutron spectra from targets with a layer of CD_2 were recorded with Lansa, a large array of high-resolution neutron time-of-flight detectors.[2] These measurements were complicated by the emission, in an 8-MeV-wide spectrum, of more than 10^8 neutrons from photonuclear processes. Thermal DD fusion, at its temperature threshold around 1 keV, has the signature of an 80-keV-wide peak in the neutron energy spectrum. Experiments showed that a maximum of 10^5 neutrons of thermal origin (with instrumental statistical certainty that the peak is not noise of 3000:1) could be detected, using 300 J of laser energy in a 5-ps pulse irradiating a target with 100 μm of CD_2 below a 10-μm CH layer. The yield, scaling as kT^5, implies that temperatures approaching 1 keV were produced. The experimental situation was, however, close to the threshold for observing the heating, because the thermal peak fluctuated in magnitude and was most often lost in the background of photoneutron emission.

These heating studies are nevertheless significant in the context of fast ignition because they show heating approaching 10% of the required temperature produced by less than 0.25% of the laser energy specified in the scenario discussed here for full-scale fast ignition at the NIF.

Notes and References

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2. M. H. Key et al., "Progress in Fast Ignitor Research with the Nova Petawatt Laser Facility," presented at the *17th IAEA Fusion Energy Conference*, Japan, November 1998 (to be published by IAEA).
3. J. A. Koch et al., *Lasers and Part. Beams* **16**, 225–232 (1998).

4.0 TARGET DEVELOPMENT, FABRICATION, AND HANDLING

To perform the first ignition implosion experiments on the National Ignition Facility (NIF), we will require ignition targets, fusion-based diagnostics to measure experimental results, and a NIF target chamber that is capable of handling the x-ray and neutron yields from igniting targets. This section of the *ICF Annual Report* summarizes the status of our efforts to provide these critical items.

The subsection “First Wall and Beam Dumps of the NIF Target Chamber” explains that the total debris generated from a NIF shot must be less than 2 g to meet the cleaning-frequency specifications for final-optics debris shields. One gram can come from the target, and the other from all other sources, including the beam dumps. This subsection describes tests of a beam dump design that minimizes generation of debris. Materials activation will require that the design be changed before significant neutron yields are produced in NIF experiments, but in the time leading up to that point, the solution is inexpensive and effective.

Four subsections describe development of target diagnostics for use with igniting targets. The subsections “X-Ray Crystal Imager” and “Neutron-Imaging Alignment Technique for Use at Omega” deal with two important techniques for imaging the targets near their peak compressions and fuel ignition. The subsections on “Charged-Particle Spectroscopy on OMEGA: A New Window for ICF and the NIF” and “Tests of a Gamma-Ray Detector for Measuring ICF Target Burn History” describe instruments that detect and measure some of the output of igniting targets, and their ability to diagnose the behavior of targets.

All ignition targets must include a fuel capsule contained in a hohlraum, and all current designs require a cryogenic fuel layer in the capsule. The targets therefore need cryogenic support systems and cryogenic hohlraums. Work on two types of capsules is summarized in “Polyimide Capsules” and Beryllium Capsules,” both of which involve coating techniques and require an initial spherical mandrel on which to coat. Development of these coating mandrels is described in “Coating Mandrels for Capsules.” The subsection “Cryogenic Ignition Hohlraum Development” summarizes the problem and approach to providing the necessary cryogenic environment for fuel capsules. The subsections “Cryogenic DT Layers in Spherical Capsules” and “Cryogenic Layers by Infrared Heating” describe our progress toward forming and characterizing the solid fuel layers and ensuring that they are adequate to ignite in an imploding target.

First Wall and Beam Dumps of the NIF Target Chamber

The NIF target chamber interior materials and target designs must be compatible with current plans to retrieve, clean, and recoat the final-optics debris shields weekly and to refinish them after six months. Exposure of the debris shields to metal vapors, dust, and shrapnel from the targets and chamber interior must not exceed a critical threshold during one week. This year, we finalized the conceptual design and testing of the first wall and beam dump panels that meet this threshold, and we refined the specification for acceptable contamination rate of the debris shield and its implications for target mass and chamber cleaning frequency.

Measurements of laser damage were made for single-dose contamination of high-quality, fused-silica optics, both with sputter-deposited thin films of gold, copper, and boron carbide and with a combination of particulates and thin film deposited from targets in the

Nova target chamber. The measurements indicated that debris shield contamination cannot exceed about 1-nm equivalent thickness of total material per shot for the optics to survive subsequent high-energy shots for more than a week. The target mass must thus be limited to 1 g, and the ablated mass from all other sources, including remobilized target debris from the first wall, must not exceed 2 g. The targets themselves must either completely vaporize or send any minor amounts of shrapnel toward the chamber waist to prevent excessive cratering of the debris shields.

Experiments and simple modeling of first-wall materials indicated that a flat first wall would have to be cleaned monthly to limit reablation of target material.[1] Two types of reablation–capture experiments were performed to calibrate the simple model. First, a coupon of boron carbide was placed at 45° relative to a ray from the target to the coupon. A collection plate placed parallel to the coupon collected material ablated from the coupon by x rays produced by the target. After six weeks and 93 shots, about 70% of the target material deposited on the coupon was reablated. We deduced that about 4% of the target debris on the coupon was remobilized during every shot. For flat panels, the debris and amount of remobilized material continue to build up, implying that the first wall would have to be cleaned monthly, which is more than is practical. On the other hand, a louvered first wall could capture most of the reablated material, leading to an asymptotic limit of remobilized contamination of 2 to 3 times the direct contamination from the target. Second, adjacent louvers of boron carbide and stainless steel were placed in the same geometry, and the amount of reablated material captured on the back of an adjacent louver was compared for four weeks. After the first week, the amount of captured reablatant was nearly equal from the steel and boron carbide, indicating that boron carbide louvers have only a slight advantage over steel louvers in the absence of frequent cleaning.

In parallel, we investigated various flat and louvered beam-dump concepts from laboratory to NIF scale, including tests on the Nova 2-beam and 10-beam chambers.[2] Laboratory tests showed that absorbing glass beam dumps had an unacceptably short lifetime for laser fluences greater than 10 J/cm^2 due to catastrophic damage growth. In addition, mitigating x-ray ablation would require a cover plate of silica or borosilicate glass. Analysis indicated that as much or more glass would be ablated from the cover plates as from either B4C or stainless steel. Stainless steel fabricated into louvers with a 90% capture efficiency would evolve half or less of the contamination of any other beam dump design and are the least expensive and most resistant to shrapnel damage. Furthermore, calculations of neutron activation showed that radiation exposure to personnel would be only slightly worse than for other materials, as long as a nickel-free alloy (409 or 410) was used. Finally, having the same design for beam dumps and first wall simplifies the construction and operation of the NIF, for example, by eliminating beam steering constraints other than missing the opposing beam ports.

The first NIF-scale test of the stainless steel beam dump was conducted on the Nova 2-beam chamber. A polymeric film covering the front of the beam dump captured any ablated steel that escaped the louvers. The amount of steel captured was consistent with predictions from small-scale experiments. The second test of the prototype NIF beam dump (Figure 1) was performed on Nova, receiving about 200 NIF-equivalent fluence shots over a period of three months. It showed only the normal expected wear. Witness coupons were analyzed to determine performance. Coupons exposed before and during the beam dump test showed no increase in iron relative to that from targets and diagnostics. Iron collected just outside the beam footprint on the sides of the louvers was about 100 times less than would be ablated from a flat piece of stainless steel. Witness coupons on the collecting side of the louver collected iron in amounts as expected.

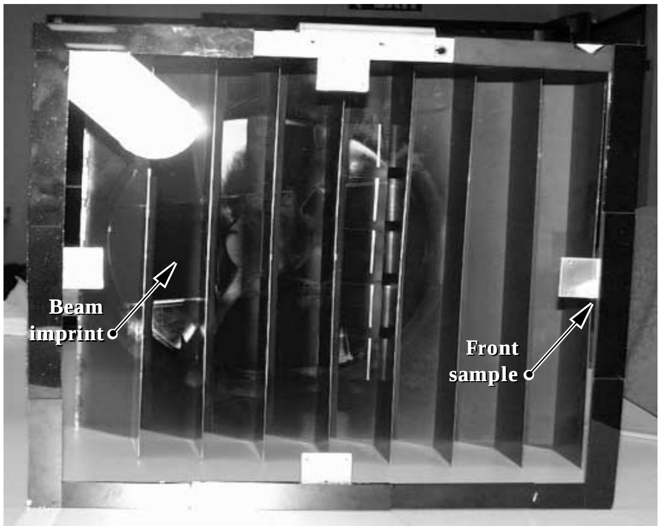

FIGURE 1. Photograph of prototype NIF beam dump with front sample holder attached. The beam imprint is clearly seen after testing. (08-00-0299-0454pb01)

Notes and References

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2. P. K. Whitman et al., *Proc. Third Ann. Internat. Conf. Solid State Lasers for Application to ICF* (Monterey, CA, 1998); Lawrence Livermore National Laboratory, Livermore, CA, UCRL-JC-129706 (1998).

Target Diagnostics Development

X-Ray Crystal Imager

Analytical and numerical studies,[1] coupled with promising experimental results,[2,3] show that near-normal-incidence, two-dimensionally bent, reflective Bragg crystals may be good options for a variety of moderate-to-high-energy, line-emission, x-ray imaging applications at the NIF. Such crystals have relatively high imaging brightness, large working distance, good damage resistance, spectral purity, and potentially high spatial resolution compared with pinholes or grazing-incidence multilayer mirror microscopes. Spherically bent crystals are most easily made and are available from several sources, and the resulting instruments are simpler to align than more complex, toroidally bent imagers.[4] However, several improvements are needed before spherically bent crystals can fulfill their promise as routine imaging diagnostics for a variety of applications. In particular, the number of usable crystal planes must be increased to provide flexibility in operating energies, and the number and quality of sources for bent crystals must be increased. In addition, the crystal working distance must be increased to >200 mm while maintaining acceptable spatial resolution, and higher-energy imaging (>4 keV) must be developed, using higher-order Bragg reflections in some cases. Finally, the instrumentation must be engineered with NIF experiments in mind, particularly with regard to simplicity of alignment.

In the past year, we have pursued several of these issues in collaboration with the Naval Research Laboratory. In particular, we designed and built a prototype crystal imager for use on Nova and, later, on OMEGA. The geometry of the instrument is shown in Figure 2a. It uses a commercial, spherically bent, 360-mm-radius, quartz 203 crystal plane. This crystal plane has not previously been used for x-ray imaging applications.[1] The crystal has a 2d spacing of 2.749 Å; it thus reflects Ti Kα (4.51 keV) at 1.64°, and it reflects Sc Lyα (4.53 keV) at 5.6° relative to normal incidence. In Nova experiments, the crystal and associated motorized manipulators are held at the opposite end of the

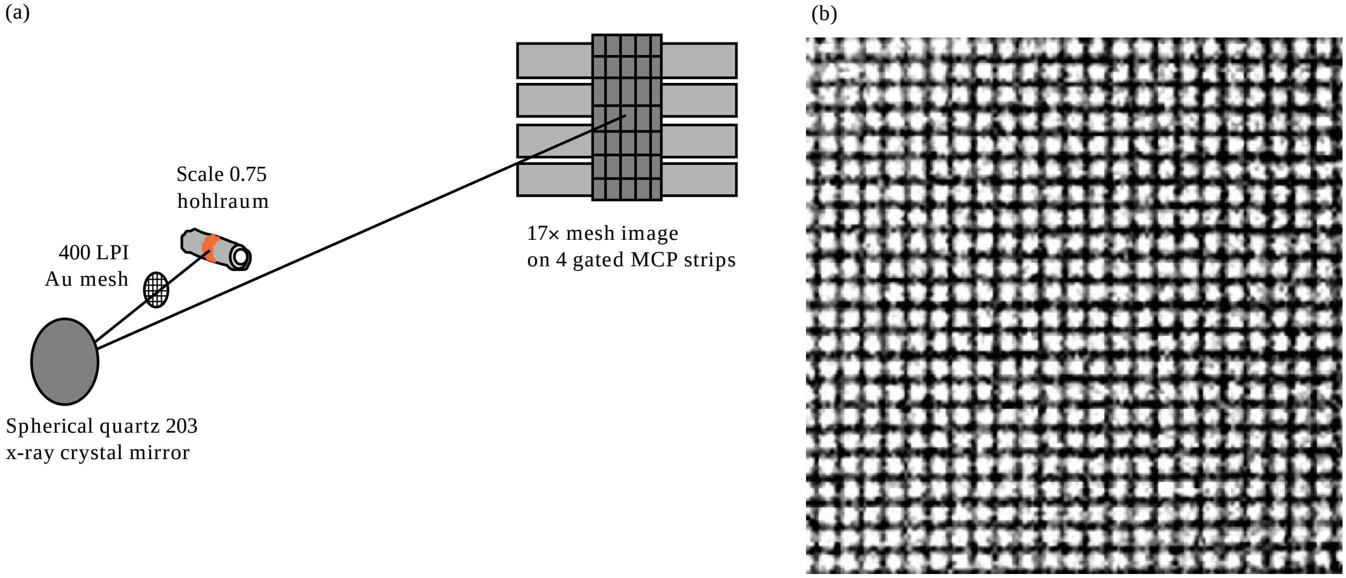

FIGURE 2. (a) Geometry of the x-ray crystal imager as implemented on Nova. In Nova, the crystal is held at the opposite end of the target chamber from the detecyor. (b) Backlit image of a 1000-line/in. Au mesh taken with 4.5-keV, Ti Kα x rays in laboratory bench tests. Spatial resolution is less than 5 μm in some areas of the image. (08-00-0299-0453pb01)

chamber from the detector. Alignment for Nova experiments has proven straightforward and takes less than two hours. The imaging magnification is 17×, and the crystal working distance is 190 mm.

Tests show that the quartz 203 crystal is capable of less than 5-μm spatial resolution (Figure 2b) at the 190-mm Nova working distance. Recently, two preliminary experiments at Nova were performed with a grid target backlit by Ti Kα x rays from a Ti patch on a scale-0.75 hohlraum. The data clearly showed a grid image; however, low signal to noise arising from a high background precluded a fair test of its performance. Further experiments planned for early next year will incorporate modifications to the instrument based on these preliminary experiments. We are also purchasing spherically bent quartz 223 crystals (2d = 2.024 Å) with identical radii to incorporate into the instrument for imaging at 6.15 keV[1]. Work will continue at OMEGA after Nova is shut down.

Notes and References

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2. Y. Aglitskiy et al., *Appl. Opt*. **37,** 5253 (1998).
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Neutron-Imaging Alignment Technique for Use at OMEGA

A high-precision aperture alignment technique is essential for neutron imaging. One requirement of the neutron penumbral aperture microscope (NPAM) alignment system for use at the OMEGA laser is that it must provide 5-axis motion (x, y, z, θ, and ϕ). Another requirement is that it must align the aperture to a straight-line reference (SLR) established from the target center to the neutron detector, to ~75-μm centering and ~1-mrad pointing accuracies. NPAM details are given elsewhere.[1,2]

Figure 3 is a schematic of the alignment technique. In Figure 3a, the output from a laser is coupled to a single-mode optical fiber whose output is expanded, collimated, and passed around a 2.5-cm-diam, rounded-edge disk placed at the target chamber center. The Poisson line of the resulting diffraction pattern is used to establish an SLR between the target and the detector.[3] In Figure 3b, the target disk is replaced with the neutron aperture. The aperture is centered on a similar diffraction disk and has a mirror mounted on one end. The aperture is then positioned and aligned to the established SLR.

One critical aspect of this technique is that the established SLR must remain stable over the ~30 min time required to align the aperture. The components cannot suffer from large vibrations and drift. In addition, the area must be kept free of temperature changes and thermal wind currents. To test the stability of the SLR, a Poisson line was established using a setup similar to that shown in Figure 3a. The Poisson spot at several distances was monitored with a charged-coupled-device camera at 5-s intervals over a 30-min time period. Each image was analyzed to determine the location of the center of the spot. An SLR was established that is stable to within 20-μm centering and 0.5-μrad pointing, indicating that it will be possible to align NPAM on the OMEGA laser using this technique.

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2. D. Ress, et al., *Rev. Sci. Instrum*. **66**(10), 4943 (1995).
3. L. V. Griffith, R. F. Schenz, and G. E. Sommargren, Lawrence Livermore National Laboratory, Livermore, CA, UCID-21591 (1989).

Charged-Particle Spectroscopy on OMEGA: a New Window for ICF and the NIF

In the past year, two charged-particle spectrometers have been installed on the OMEGA facility at the Laboratory for Laser Energetics. This project is a collaboration among researchers at Massachusetts Institute of Technology, the Laboratory for Laser Energetics, and LLNL. The goal of the spectroscopy is to measure key capsule parameters, such as fusion yields, core ion temperature, fuel and shell a real density, and any asymmetries that might exist in the respective a real densities. We measure the energy spectrum of a wide variety of charged particles that escape from the imploding capsule. Some of the nuclear lines observed to date with the spectrometers are:

$$\mathrm{D} + {}^3\mathrm{He} \rightarrow \alpha(3.6\ \mathrm{MeV}) + \mathrm{P}(14.7\ \mathrm{MeV})\ , \tag{1}$$

$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}(1.01\ \mathrm{MeV}) + \mathrm{P}(3.02\ \mathrm{MeV})\ , \tag{2}$$

and

$$\mathrm{D} + \mathrm{T} \rightarrow \alpha(3.5\ \mathrm{MeV}) + \mathrm{n}(14.1\ \mathrm{MeV})\ . \tag{3}$$

Nuclear continua processed observed to date include:

$$\mathrm{n}(14.1\ \mathrm{MeV}) + \mathrm{D} \rightarrow \mathrm{n}' + \mathrm{D}(\leq 12.5\ \mathrm{MeV})\ , \tag{4}$$

and

$$\mathrm{n}(14.1\ \mathrm{MeV}) + \mathrm{T} \rightarrow \mathrm{n}' + \mathrm{T}(\leq 10.6\ \mathrm{MeV})\ . \tag{5}$$

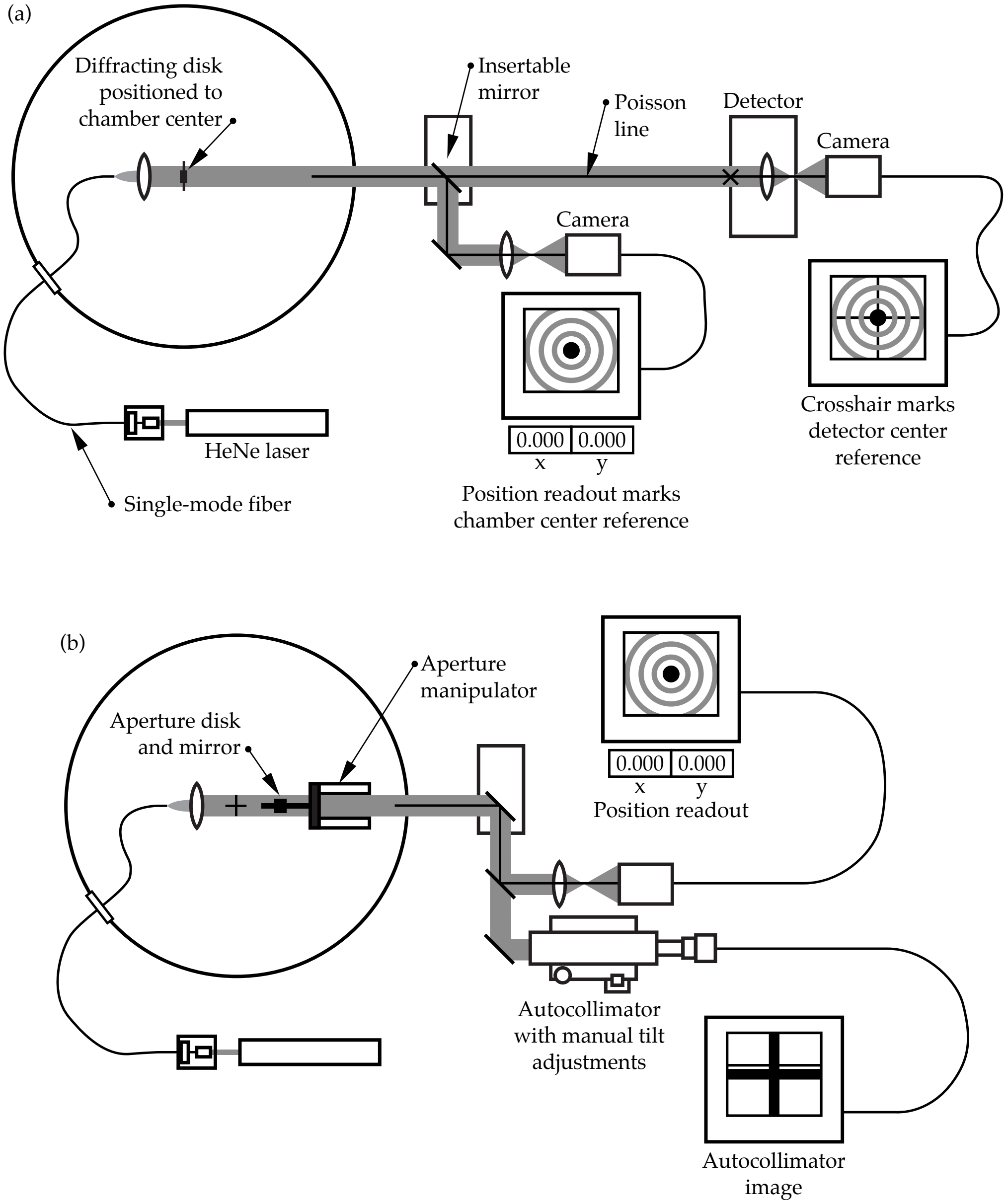

FIGURE 3. Schematic layout of the alignment system planned for the installation of NPAM on the University of Rochester Laboratory for Laser Energetics OMEGA laser.
(08-00-0299-0455pb01)

Data for a wide range of different shots and capsules are currently being obtained. Figure 4, for example, shows the 14.7-MeV proton line (Eq. 1) that is generated from D-^{3}He fusion. For this shot, which was a 1-ns square pulse, 28 kJ of 1/3-μm light directly irradiated an 18.4-μm-thick, 939-μm-diam CH capsule that contained 8 atm of D and ^{3}He of equal atomic concentrations. The 14.7-MeV line is downshifted by 1.9 MeV from its birth energy, largely as a consequence of the energy loss that occurs as protons pass through the shell plasma. From this energy loss and the fact that the shell electron temperature is relatively cool (~1 keV), we infer that the shell ρR is about 60 mg/cm^2. (The full range of the 14.7-MeV proton is 300 mg/cm^2.) In contrast, the 3.6-MeV alpha from this same reaction has a range of only about 20 mg/cm^2, so it is ranged out in the capsule, as evidenced by the fact that it was undetectable for this shot. For other implosions that have thin (≤3-μm) shells, we do detect these alphas. D-D fusion (Eq. 2) also occurs for this implosion, but, as for the alpha, the range of particles is also relatively small (~50 and ~20 mg/cm^2 for proton and triton, respectively), so they too do not escape the capsule.

By taking the ratio of D-^{3}He yield to D-D yield (determined in this instance from neutron activation), a core ion temperature of 3.9 keV is obtained, in

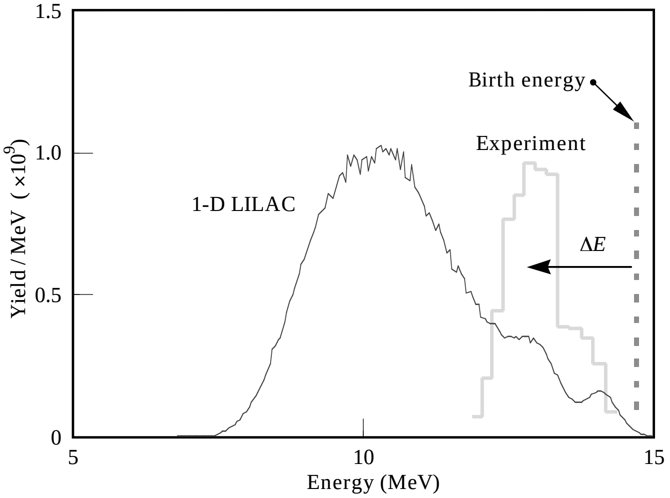

FIGURE 4. Experimental proton spectrum from D-^{3}He fusion reactions for a direct-drive implosion on OMEGA. Protons are downshifted from their birth energy (14.7 MeV) by 1.9 MeV, corresponding to a shell ρR of 60 mg/cm^2. The 1D LILAC-calculated D-^{3}He proton spectrum is also shown. The predicted downshift of 4.6 MeV corresponds to a shell ρR of 120 mg/cm^2, well outside the experimental error. (08-00-0299-0456pb01)

reasonable agreement with the value determined from the neutron Doppler method. However, for this shot, the width of the D-^{3}He profile is much larger than the Doppler width. This result probably reflects the increase of the shell ρR during the burn, which broadens the profile beyond that due to Doppler broadening. For thin-shell implosions, however, the ion temperature deduced from the ratio method agrees well with that deduced from the width of the charged-particle profile.

Figure 4 also shows the theoretical 1D prediction (from LILAC) of the 14.7-MeV proton spectrum. It is much broader, more downshifted (4.6 MeV), and has a yield that is greater by a factor 2.6. From the downshift, the predicted shell ρR is 120 mg/cm^2, substantially larger than the measurement of 60 mg/cm^2 and well outside experimental uncertainty.

For a thinner-shell D-^{3}He implosion than that shown in Figure 4 (i.e., a 14-μm CH shell), with all other laser and capsule parameters the same, the 14.7-MeV proton was measured to be downshifted by 0.9 MeV, indicating a shell ρR of 30 mg/cm^2. However, the LILAC prediction for this shot was 85 mg/cm^2, corresponding to a predicted downshift of 3.0 MeV. These and other shots are now the focus of intense study. We will also use 2D modeling to see if better agreement can be obtained between experiment and theory.

In the future, several other nuclear transitions will be the studied, in particular the 30.8-MeV tertiary proton that has sufficient range to be directly useful for NIF plasmas. In general, the principles and techniques of charged-particle spectroscopy should be readily applicable to the NIF.

Tests of a Gamma-Ray Detector for Measuring ICF Target Burn History

Measurement of the fusion reaction rate, or burn history, is a sensitive probe of the dynamics of an imploding ICF target. The average neutron emission time relative to the incident laser pulse depends on the coupling of laser to target and on the hydrodynamics of an implosion. Details of the burn history, most often characterized as the burn width, are related to plasma conditions during the peak of target compression.

One technique for determining the ICF target burn history relies on measurement of primary fusion neutrons using an instrument such as the neutron temporal diagnostic (NTD), which is based on the fast rise time of a plastic scintillator.[1] Two conditions limit the temporal resolution. First, there is uncertainty in the location within the scintillator where neutron kinetic energy is converted to light. For a 1-mm-thick scintillator, the detector interaction point uncertainty adds 19 ps of temporal dispersion for deuterium–tritium (DT) neutrons. The second condition is the Doppler broadening of neutrons. Primary reaction product neutrons are created within the burning fuel with a temperature-dependent kinetic energy spread.[2] Differences of the neutron velocities in traveling from target to detector result in a temporal smearing of the measured signal. At the NIF, target fusion energy could dictate a target-to-scintillator distance of up to 5 m. For a 1-keV plasma, the temporal spread of neutrons will be 640 ps, which is unacceptable for measuring details of the burn history to a resolution of 25 to 50 ps.

NIF yields will allow for the accurate sampling of other, heretofore inaccessible, reactions, in particular, the T[D,γ(16.7 MeV)]^{5}He branch, which is 5×10^{-5} times weaker than the main T[D,n(14.1 MeV)]^{4}He branch. Gamma rays escape the dense fuel and preserve details of the target burn in a manner similar to neutrons. In addition, gamma rays do not suffer from temporal broadening and detector interaction point uncertainty, allowing a gamma-ray-based burn history instrument to be located at 5 m or more.

For detection, gamma rays are converted to energetic electrons (with velocities βc) in a high-Z material mainly through pair production. The electrons travel through a material with an index of refraction n, and provided that the condition of $n\beta > 1$ is met, Cherenkov photons are emitted, which can be detected. To maintain a system resolution of <25 ps, it is envisioned that the detector will consist of a streak camera coupled to a charged-coupled device (CCD), the same readout scheme as that for the NTD.

An initial successful test of this concept was performed by Lerche et al. using the NTD and Nova laser.[3] Electrons were produced in a Hevimet nose cone and converted to light in a 2.5-cm-thick, silica–aerogel Cherenkov radiator. The index of refraction of the aerogel is 1.06, which sets the electron energy threshold to produce Cherenkov light at ~1 MeV. In a series of four direct-drive implosions, each yielding approximately 10^{13} DT neutrons, the target-to-aerogel distance was varied. Two peaks were observed in the NTD CCD-recorded streak camera trace. The spectra were normalized and temporally aligned to the larger (and slower) peak. The first peak was shifted in time away from the second peak as target-to-aerogel distance increased, indicating that if the second peak was from neutrons, then the source of the first peak was gamma rays. We later determined that the second peak indeed resulted from neutron-induced scintillation of the NTD *f*/2 light collection optic.

Recent installation of the NTD onto the OMEGA laser allowed us to continue this study. We realized at the time of the above experiment that the aerogel has an average transmission of ~18% over the wavelengths of light that NTD can detect. Aerogel was replaced with a DynaSil fused-silica glass, which has ~95% transmission over the NTD-relevant wavelengths. It has an index of refraction of 1.5, which sets the electron kinetic energy threshold to produce Cherenkov radiation at ~0.2 MeV. These factors combine to boost the Cherenkov photon signal from the glass by at least 25× over the signal observed with aerogel.

The OMEGA laser was used to implode four, DT-filled, glass microballoon targets, each yielding ~10^{13} DT neutrons. For each shot, the Cherenkov radiator-to-target distance was varied, and streak camera traces were recorded. Figure 5 shows normalized and temporally aligned signals. Each trace shows two peaks; however, as distance is varied, the relative time between the two peaks does not change, suggesting that they both result from the same source particle. The centroids and widths of the two peaks are consistent with neutron-induced scintillations of the glass radiator and the *f*/2 light-collection optic. It is likely that the Cherenkov light signal is masked by this rather unexpectedly large peak. Note that when operating at the NIF, neutron-induced scintillation of the Cherenkov radiator will not be an issue—at 5 m, the neutrons will be arriving at the radiator ~81 ns after the fusion gamma rays.

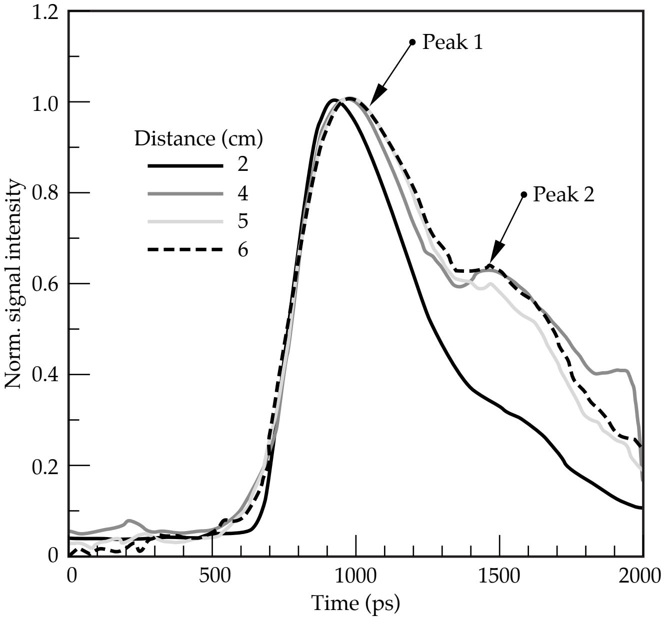

FIGURE 5. Tests of a gamma-ray detector for measuring ICF target burn history. (08-00-0299-0457pb01)

Monte Carlo calculations show that the glass radiator emits more total light than aerogel. However, a significant fraction of photons in each case is emitted in a direction that is outside the acceptance of the NTD *f*/2 optic. The NTD was designed such that only light emitted within a cone of 14° is captured and focused through the relay optics to the streak camera. Hence, a significant portion of emitted light was not recorded. Future development of a gamma-ray, burn-history diagnostic must proceed through the fielding of instruments that can more efficiently couple light from the Cherenkov radiator to the streak camera.

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NIF Cryogenic Support and DT Fill Systems

Cryogenic Ignition Hohlraum Development

Cooling and controlling the uniformity of a frozen layer of deuterium and tritium (DT) on the inner surface of a capsule mounted in a cylindrical hohlraum is required for most NIF target designs. Cooling is required to remove the heat released during tritium decay. Assuring the layer thickness uniformity requires that the heat flow from the layer into the capsule wall be spherically symmetric. Controlling the temperature profile along the hohlraum wall from the ends to the midplane can satisfy this requirement. We have designed a cryogenic hohlraum, shown in Figure 6, to provide the required hohlraum wall-temperature profile.

We completed a temperature-control sensitivity analysis based on a model of the cryogenic hohlraum. Results indicate that sufficient control can be achieved with commercially available, calibrated thermometers. We have also begun an analysis of fluid convection in a gas-filled hohlraum. The hohlraum will be filled with He–H_2 tamping gas mixture at a nominal density of 1.0 mg/cm^3. Rayleigh numbers estimated for the distances and temperature differences involved are in the range of 40 to 400. For these values, correlation of experimental data for horizontal and vertical surfaces[1] indicates that free convection would increase the heat transfer over conduction by less than 5%. However, to ensure the validity of the design, we require that the heat-transfer increase due to convection remain below ~0.5%. We will model the effectiveness of thin-film barriers in decreasing convective heat transfer, and, if necessary, we will lower the fill pressure of the hohlraum during layering and increase the pressure just before the shot.

The cryogenic hohlraum test system is complete. It was used to test thin polyimide window strengths and survivability at 20 K. These data were necessary for design and fielding of laser–plasma interaction experiments with He/H_2 mixtures planned for FY99. We created a prototype data collection and control system for the cryogenic hohlraum experiments. General Atomics (GA) fabricated glass capsules with 1.3- to 1.7-mm diameters that are 3 to 5 μm thick. These capsules are required for cryogenic hohlraum testing and development. DT pressurization testing of the 1.3-mm plastic-coated glass shells at LANL was successful, but the capsules failed after eight weeks in storage. We are now designing a hohlraum assembly system and developing procedures to accommodate capsule failure during hohlraum assembly. GA is investigating ways of fabricating thicker (glass) wall capsules. Capsules holding at least 100 atm, which would have 25-μm-thick layers, are required for evaluation of layer symmetry and control in the cryogenic hohlraum experiments.

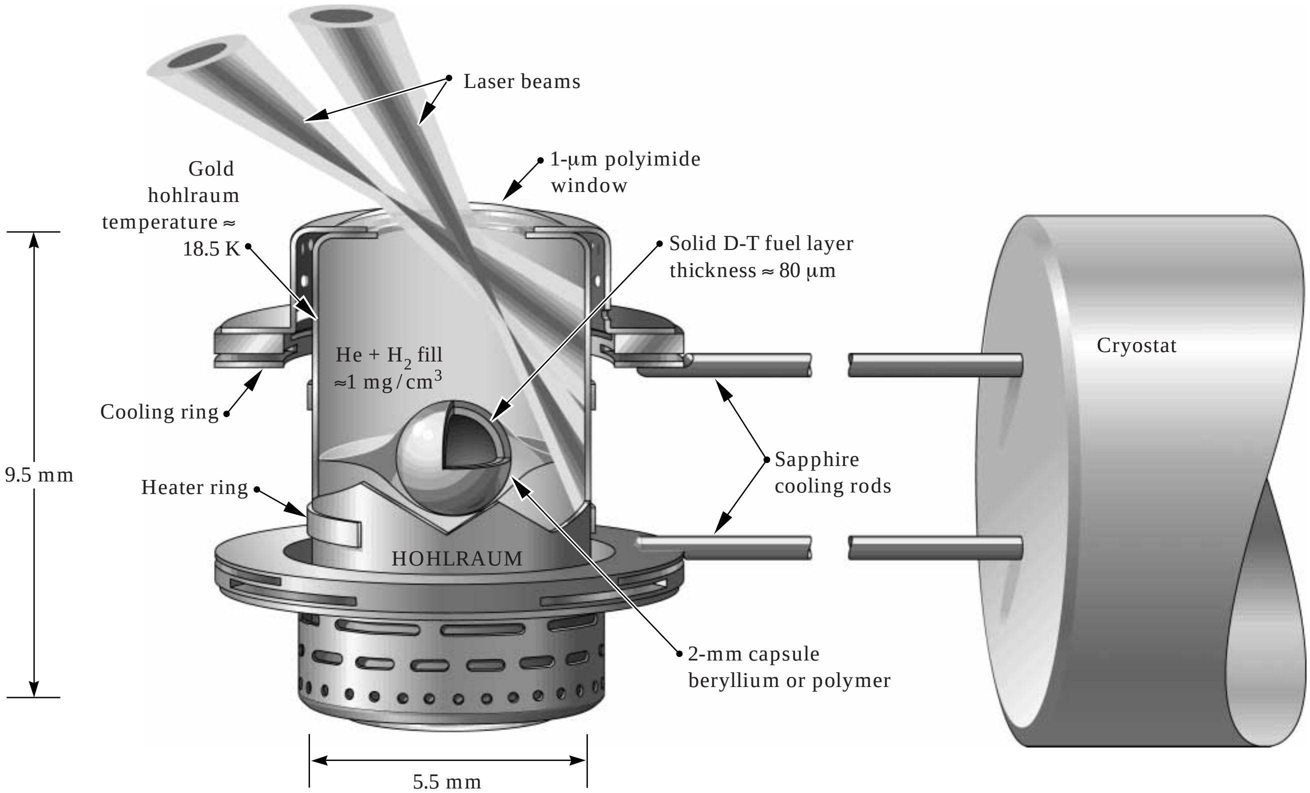

FIGURE 6. Cryogenic hohlraum prototype design for fielding thermally shimmed cryogenic targets. Heat from the capsule, environment, and control heaters flows through the heat-flow symmetrizers to be collected by sapphire rods and transferred to the cryostat. (08-00-0299-0458pb01)

We must measure the axial P1 and P2 defects for feedback to the hohlraum-wall-temperature control system. We must also measure the fuel-layer surface finish. We constructed an optical model of the capsule within the hohlraum, and showed that standard interferometry with the optical axis along the hohlraum axis, viewing the capsule through the laser entrance hole, will not be sufficiently sensitive to determine P1 and P2 defects with required accuracy. For the near term and to determine experimentally whether P2 defects can be controlled without optical feedback, we have designed a hohlraum with centrally located windows that will allow us to use standard techniques to measure P1 and P2 with a view perpendicular to the hohlraum axis.

Next year, we will finish fabrication of the NIF-scale hohlraum target assembly. We plan to demonstrate axial (P1 and P2) layer symmetry control in thermally shimmed, gas-filled hohlraums.

Notes and References

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Ignition Capsule Development

Coating Mandrels for Capsules

All options for NIF capsules, except machined Be, require a mandrel upon which the ablator is deposited. The mandrel sets the baseline sphericity of the final capsule, especially over the low modes. Subsequent coating operations may degrade the capsule surface finish, but they are unlikely to improve it. We are developing methods to produce 2-mm-diam mandrels for NIF capsules.

In 1995, the decomposable mandrel approach to forming plastic mandrels was developed.[1] A spherical mandrel is made from poly(α-methylstyrene), or PαMS, and then overcoated with 5 to 10 μm of plasma polymer. It is heated to 300°C to depolymerize the PαMS mandrel to gaseous products, which diffuse away and leave a spherical plasma polymer shell. With proper processing, the sphericity of the final shell reproduces the sphericity of the PαMS mandrel. The resulting mandrel has extremely uniform wall thickness because of the nature of the omnidirectional plasma-polymer-coating process, and it is thermally stable to temperatures of at least 300°C.

The initial PαMS mandrel can be either a solid PαMS bead or microencapsulated PαMS shell. The key requirement is that the outer surface be extremely spherical. This was our focus in FY98, with emphasis on the Legendre mode-2 out-of-round (OOR), the difference between maximum and minimum mandrel diameters. Our goal was to reduce the OOR to 1 to 2 μm, which meets requirements for a NIF capsule. The objective was achieved for both PαMS beads and shells, as described here. Work in FY99 will focus on reducing the roughness over the important region of mode 10 to 50.

Both beads and shells are made by suspending a fluid sphere in an immiscible phase, then hardening it to its final geometry. Spherical symmetry in the fluid mandrel is driven by the interfacial surface tension γ. Loss of symmetry, particularly at mode 2, can be caused by a gravitational deformation due to density mismatch with the suspending fluid and by hydrodynamic interaction, such as shear of the suspending fluid acting on the deformable fluid mandrel. A simplified model analysis of these effects was performed.[2,3] A density mismatch $\Delta\rho$ between the bath and the mandrel leads to a mode-2 OOR given by:

$$OOR \cong \frac{5gr^3\Delta\rho}{4\gamma} \qquad (1)$$

where g is the acceleration of gravity, and r is the mandrel radius. For a fluid droplet in a linear shear,

$$OOR \cong \frac{8\mu Gr^2}{\gamma} \qquad (2)$$

where μ is the bath viscosity, and G is the linear shear field in the bath. In both Eqs. 1 and 2, the OOR strongly depends on the droplet radius. It is clear from these simple models that good density matching and attention to bath agitation are both critical.

We studied two approaches to spherical bead formation.[4] In the first approach, low-molecular-weight, highly plasticized, commercial PαMS beads with softening temperatures of about 50°C were suspended in a stirred water bath at 95°C containing polyvinyl alcohol as an anticoagulant for 4 to 8 hours; then the bath was cooled. The softened beads were driven spherical by surface tension. We obtained batch-average OORs as low as 3 μm, and individual beads were less than 2 μm OOR. Further improvement could not be obtained, most likely because of the density mismatch and hydrodynamic deformations.

Our second approach attempted to improve this situation. We used a heated density-gradient column formed by layering mixtures of 1,2-propanediol and glycerol of decreasing densities to bracket the density of the PαMS bead. Beads were then suspended in a perfectly quiescent environment. The column could be heated to 150°C, causing the bead to become fully fluid for several hours without loss of the vertical density gradient. This approach perfectly density matches the center of mass of the bead with the surrounding fluid, but it subjects the bead to a density gradient. If the gradient β is linear, then deformation due to the gradient is approximated by:

$$OOR = \frac{g\beta r^4}{4\gamma} \tag{3}$$

A gradient on the order of 0.04 g/cm^3 per cm is necessary to produce a droplet with an OOR of about 1 μm. We experimentally obtained beads with OORs of less than 2 μm. However, the diol and triol solvents necessary for the elevated temperatures needed to liquefy the PαMS bead also provide some solubility to the plasticizers present in the bead. Plasticizers redeposit on the bead surface when cooled and form surface debris. Although there are possible ways to eliminate the problem, our success with the microencapsulation route described below has precluded further work.

In the microencapsulation method,[5] a water droplet (w_1) is encapsulated by an immiscible organic phase (o) containing dissolved polymer, in our case PαMS dissolved in fluorobenzene. The encapsulated droplet is suspended in an aqueous bath (w_2). The organic solvent slowly dissipates into the aqueous bath, leaving a solid polymer shell. The internal water droplet can be removed by air drying. Details of the process have been published elsewhere.[6] Our objective is to optimize the process for NIF-scale shells.

We found that gravity-induced, mode-2 deformation can be suppressed by careful density matching of the composite w_1/o droplet with the bath. This is done by controlling the PαMS concentration in the o, the relative amount of o to w_1 in the droplet, the addition of salts to the bath, and control of temperature. When the composite droplet is density matched to the bath, w_1 and o are mismatched by approximately 0.02 g/cm^3; however, core centering mechanisms[7] associated with agitation eliminate this problem as long as the density difference is not too great.

Figure 7 shows the power spectra of several of our best PαMS shells. For comparison, the current power spectrum being used for ignition capsule modeling is also shown. This design specification is the goal for the outer surface finish of the final capsule with ablator. Thus, the initial PαMS mandrel must be smoother than this specification. All the PαMS mandrel spectra shown have a mode-2 OOR of less than 2 μm. However, improvement is needed in the critical region of mode 10 to 100. Such improvement will be the focus of our FY99 efforts.

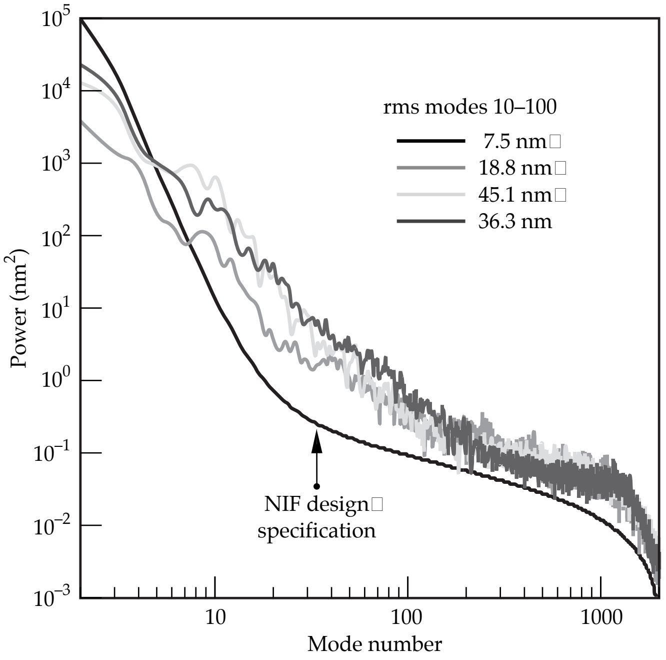

FIGURE 7. Power spectra for three of the best 2-mm-diam PαMS shells produced at LLNL. (08-00-0299-0459pb01)

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Polyimide Capsules

Polyimide capsules could be capable of holding the full deuterium–tritium (DT) fill at room temperature, allowing for easy transport and handling.[1] The required tensile strength at room temperature for a

350-atm fill needed for current designs is about 120 MPa. The strength of polyimides depends on the specific formulation and spans from 100 to more than 400 MPa. Polyimides are optically transparent, so the inner DT ice layer can be characterized, and capsules can be filled by simple diffusion. Recent design calculations[2] also show that polyimide ablators perform nearly as well as beryllium if the DT ice layer has an rms roughness between 1.0 and 1.5 μm, such as is typically obtained by native β layering. In addition, the optical transparency of the material may allow for layer enhancement by infrared (IR) heating techniques (see "Cryogenic DT Layers in Spherical Capsules" and "Cryogenic Layers by Infrared Heating," below).

Polyimide capsules must have the desired thickness, be extremely uniform in both thickness and density, and have a surface finish over all modes that meets the design requirements. In addition, the material must be resistant to radiation damage from the DT fill and have dimensional stability when filled.

To produce polyimide ablators of uniform thickness, we vapor deposit the dianhydride and diamine monomer precursors onto 2-mm-diam plastic mandrels (see the previous subsection, "Coating Mandrels for Capsules") that are agitated in a standard bounce pan. These monomers react to form a poly(amic acid) that, upon thermal treatment, is converted to a polyimide. Figure 8 shows the process schematically. We are exploring whether a vapor-deposition technique can produce thick polymide spheres, and we are measuring the basic physical properties and structures of the materials so produced to determine whether they could be suitable as ICF ablators or for other applications. Whereas very thin (<1-μm) coatings have been made for microelectronic applications[3] by vapor deposition and for thin, high-strength shells for direct-drive ICF experiments,[4] thick (<150-μm) coatings and their properties have not been explored.

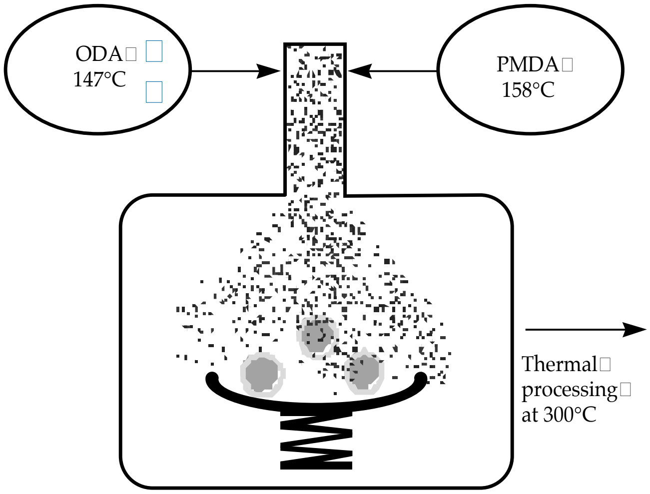

FIGURE 8. Schematic of polyimide vapor-deposition process. (08-00-0299-0460pb01)

The quality of a polyimide coating depends critically on monomer flow rates. We have used a Kapton-like chemistry, using pyromellitic dianhydride (PMDA) and 4,4′-oxydianiline (ODA) as our monomer precursors. We measured the vapor pressures of the two components as a function of temperature so that their deposition rates could be thermally controlled and matched. Typical depositions are done at 147°C for ODA and 158°C for PMDA. When the monomers were deposited in a ratio of 1:1 as flat films, they had strengths as great as 100 MPa, about 40% of the strength of commercial Kapton films. Departures from a 1:1 ratio produce weaker films. We expect to improve the strength of 1:1 films by more careful optimization of the thermal curing profile. However, part of their lower strength is due to the formation of lower-molecular-weight polymers by the vapor-deposition approach, which is essentially a solid-state polymerization, compared to the solution techniques used to prepare commercial Kapton films. Our initial work has been done with a Kapton-like chemistry because of the existence of vapor-deposition literature for this chemistry. However, in FY 1999, we plan to change to the higher-strength Upilex formulation, which can give films with tensile strengths as great as 400 MPa.

We have prepared flat films with thicknesses from 50 to 100 μm. Fracture cross sections examined by scanning electron microscopy show a perfectly uniform and homogeneous coating. This is an important result because, during imidization, water is evolved, and heating that is too rapid can lead to bubbles, voids, and blistering. Surface-finish patch scans by atomic force microscopy on both thin and thick coatings show the intrinsic surface to be extremely smooth, with an rms of about 1 nm over a 20-μm patch. Gravimetrically based density measurements of the deposited films yield 1.4 g/cm^3, consistent with the value for commercial Kapton. We have also measured the creep behavior of commercial Kapton and Upilex films to investigate time-dependent dimensional stability of these materials. At the tensile forces that an ICF ablator will experience with a filled capsule, we find that over several hours at room temperature, the strain for Kapton is about 15%, whereas for Upilex, it is about 2%. Temporary storage at lower temperatures would reduce this value significantly. For Upilex, the strain was almost completely recoverable, whereas for Kapton, about 2% strain remained when the tensile force was removed. Initial strain modulus measurements of our vapor-deposited, Kapton-like materials gave values similar to that of the commercial Kapton film. In FY99, we will investigate creep properties for our vapor-deposited materials as both flat films and on shells.

We began our first Kapton-like coating experiments on 2-mm-diam plasma polymer mandrels prepared by the PαMS decomposable mandrel route (see the previous subsection, “Coating Mandrels for Capsules”). Coatings were applied using standard bounce pan techniques, and coated shells have been imidized at 300°C. Figure 9 shows a 22-μm-thick polyimide coating on a 20-μm-thick plasma polymer mandrel. A 55-μm-thick coating on a 2-mm-diam mandrel has also been completed, and examination of the fracture cross section shows a uniform, homogeneous coating.

In FY99, we will optimize techniques for thick, Kapton-like coatings on shell mandrels, and we will employ facilities for coating with Upilex. Our primary focus will be on developing conditions that produce materials with good surface finish, a task that will depend on control of the monomer ratios as well as optimization of the imidization thermal profile. In collaboration with LANL, we will test the radiation stability of polyimide materials by direct exposure to DT. Burst-strength testing of coated shells will determine whether room-temperature transport is viable for polyimide capsules.

Notes and References

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Beryllium Capsules

Development in FY98 of sputter-deposited Be suitable for ICF capsules has proceeded on three fronts: materials development, strength testing, and permeation studies. Studies of dopant incorporation have yielded interesting results in modifying the morphology of deposited films, although it is not yet clear whether such materials will be usable for making capsules. Tensile tests on plain Be capsules, performed in a separate project in the Chemistry and Materials Science Directorate at LLNL, have shown that application of bias during deposition increases capsule strength from 35 to 200 MPa. The high strength values are consistent with room-temperature storage and transport of filled ignition capsules.

Much of our materials development focused on studying the codeposition of B- and Cu-doped Be to modify the bulk and surface morphology of the resulting films,[1] which were deposited on silicon flats. By varying the B concentration in small increments between 5 and 18 at.%, we found an abrupt transition at approximately 11 at.% B between films, with a decrease in rms surface roughness from ~20 nm (less boron) to ≤ 2 nm. Away from this transition, the roughness and morphology change only gradually with B content. We also studied B-doped films deposited on capsules, with B concentrations from 3 to 25 at.%. At 3 and 5 at.%, the films have uniform, straight columnar grains with well-defined crystal facets at the surface. At 10 at.%, poorly defined columnar grains are accompanied by rounded surface features. At greater B concentrations, no structure is visible in SEM micrographs of fracture cross sections, and the surfaces have rounded nodules varying in size up to ~1 μm. Although 15 at.% B is somewhat above the minimum required for a desirable bulk morphology, this concentration was chosen for further study because films with even higher levels of B are more prone to degrade at elevated temperatures. We found that, unlike undoped Be, this material roughens as the coating becomes thicker, exceeding 400 nm rms for a 15-μm-thick film. Experiments on stress disks and plasma-polymer-coated flats demonstrated that B-doped Be films deposit with high levels of compressive stress and adhere poorly to the mandrel, a combination that may contribute to the dissimilar results on capsules and flats. Efforts are under way to determine whether these problems can be resolved.

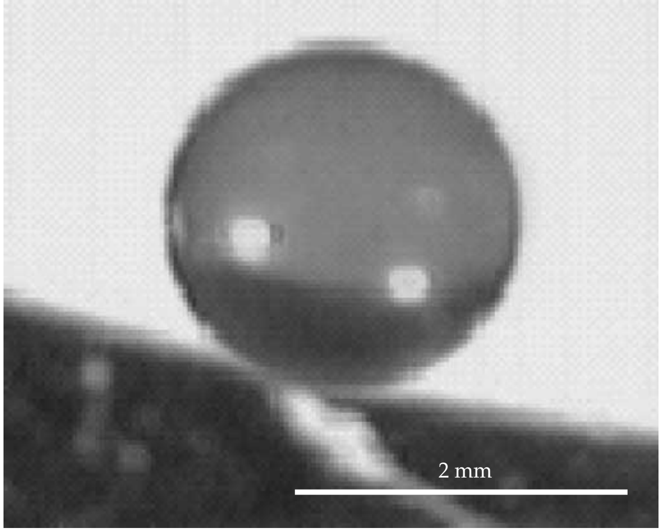

FIGURE 9. Polyimide capsule with 22 μm of Kapton-like polyimide deposited on a 2-mm-diam plasma polymer mandrel.
(08-00-0299-0461pb01)

A method for filling Be capsules is a high priority. Our emphasis during FY98 has been to determine the hydrogen permeation properties of sputter-deposited films. We studied both low-temperature, Pd-enhanced permeation and high-temperature (≥400°C) permeation. The low-temperature option allows the mandrel to remain in the capsule. Moreover, experiments at LANL[2] suggested that thin layers of Pd deposited on either side of a Be membrane could improve its hydrogen permeability dramatically. The Pd presumably acts as a protective layer to prevent formation of BeO, which is highly impermeable, without restricting the passage of hydrogen. Literature values[3] for the permeability of bulk Be do not yield sufficient permeability for a true low-temperature solution, but the large potential benefit and positive preliminary data motivated several attempts to implement this concept. No unambiguous, positive results were obtained, strongly suggesting that sputter-deposited Be does not have greatly enhanced permeability compared to bulk-processed Be. At the same time, efforts have been made at General Atomics to measure permeability of Be coatings on glass spherical mandrels in the 400° to 500°C range. This work has been complicated by the persistent appearance of a substantial oxide layer during the fill process, which prevents permeation. We are now studying how to prevent the phenomenon. Because such high-temperature permeation will require removal of the mandrel, we have begun identifying methods for drilling small, high-aspect-ratio holes in Be. Preliminary tests using a femtosecond laser produced holes with a 5- to 6-μm entrance and a 3-μm exit through 125 μm of sheet Be. Such an approach might also be applicable to a drill-and-plug fill scenario, should that prove necessary. Future effort will be directed toward further reducing the hole diameters.

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Cryogenic DT Layers in Spherical Capsules

Over the past year, beta layering experiments have been conducted on solid deuterium–tritium (DT) in 1-mm-diameter, plasma polymer spherical capsules. The capsules have an attached fill tube, and layering occurs inside a 25-mm inside-diameter (i.d.) layering shroud. The experimental apparatus has been previously described (see Reference 1).

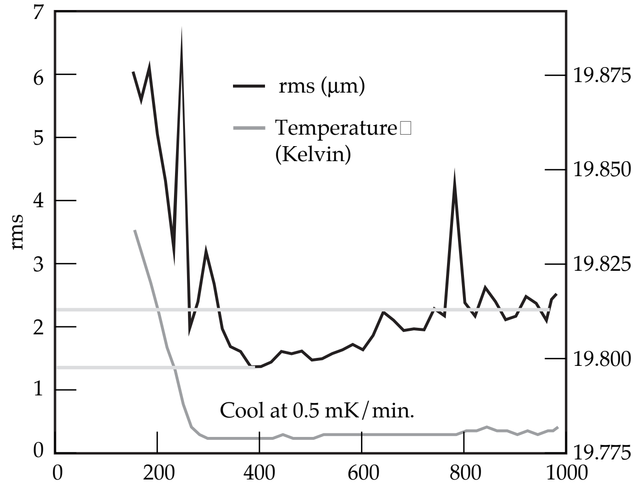

FIGURE 10. Temperature and rms surface roughness on a three-day-old sample of DT. (08-00-0299-0465pb01)

Figure 10 is a plot of temperature and rms surface roughness σ during the course of an experiment carried out on a three-day-old sample of DT. The surface morphology is measured using shadowgraphy, and σ is calculated from modes 2 through 128. We cool slowly through the triple point at a constant rate of 0.5 mK/min to a base temperature of 19.78 K. The temperature is then held constant for a period of time. The DT layer grows during the temperature ramp with a single growth front that begins near the top of the shell. The crystal growth front converges at the bottom of the shell to complete the layer. After formation, $T = 19.78$ K, time is 295 min, and $\sigma = 2.65$ mm. The layer continues to smooth, reaching a minimum σ of 1.15 mm at about 383 min. Afterwards, the layer roughens, but the roughening behavior is not well understood.

Figure 11 shows the power spectra for the layer at 400 and 1000 min. The layer at 400 min is smoother for all modes, except perhaps a single point at mode 7. Most of the difference between the two layers occurs in modes 2 to 4.

Figure 12 shows collected roughness data with cooling rates between 1 and 2 mK/min and layer thickness between 150 and 225 μm. The 4.2-μm point is for a layer formed at the upper end of the cooling rate. The data indicate that σ increases with decreasing layer thickness. A contributing factor is the increase in variation of temperature near the ice–gas interface with thicker layers, i.e., $\delta T_{\mathrm{bump}} \cong Qh\,\delta h_{\mathrm{bump}}/k$. Here, δT is the variation from the average temperature at the ice–gas interface, which is the driving term for beta layering. The variation from the mean ice thickness is δh. It is reasonable that a larger δT for a given δh would produce a smoother layer.

We have also observed that layers formed and then cooled to more than 0.5 K below the triple point

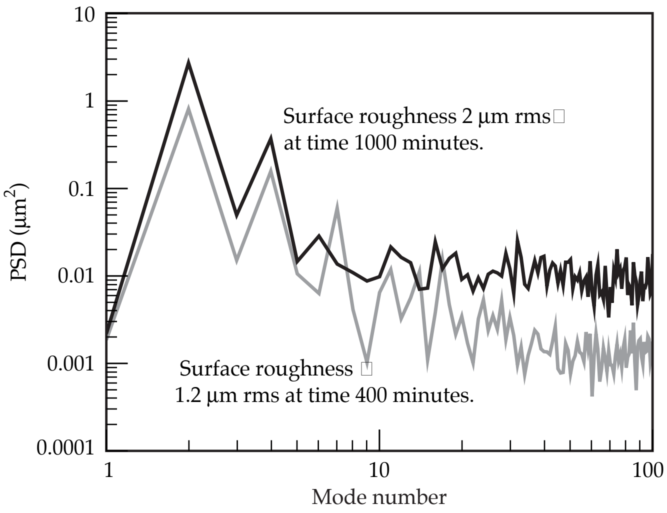

FIGURE 11. Power spectra at 400 and 1000 min. The increase in roughness over time after minima is largely due to effects at modal numbers between 2 and 4; however, the largest relative increase occurs above mode 20. (08-00-0299-0466pb01)

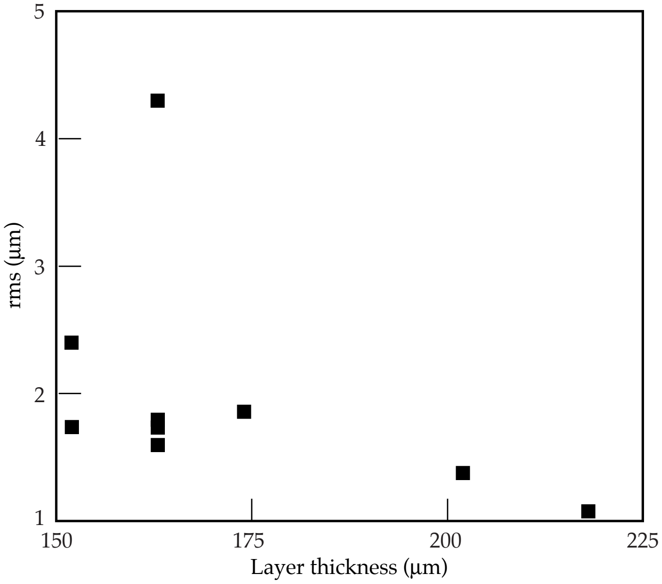

FIGURE 12. Thinner ice layers have a larger σ. (08-00-0299-0467pb01)

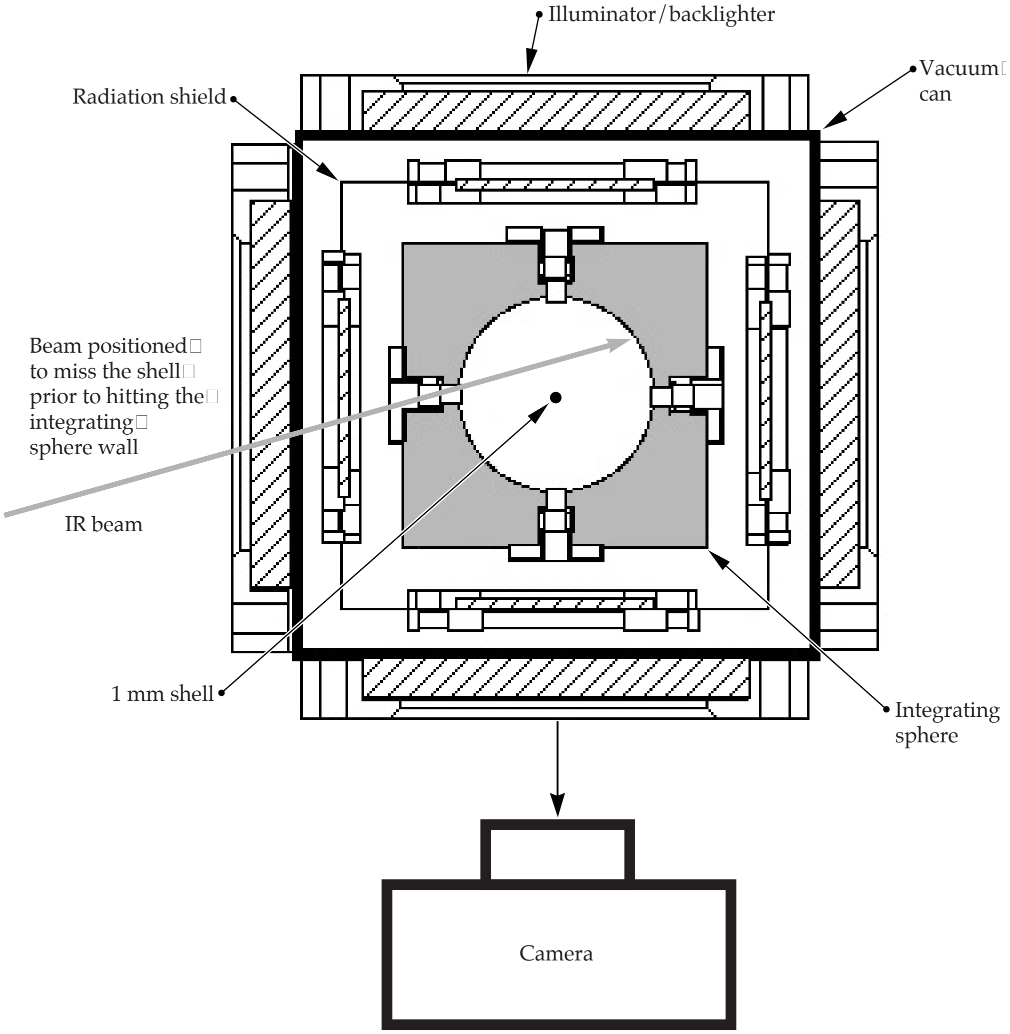

FIGURE 13. Schematic diagram of IR direct-injection technique. (08-00-0299-0462pb01)

become rougher than layers formed and held at temperatures just below the triple point. Currently, NIF ignition target designs contain 80-μm-thick DT layers at 18 K inside a 2-mm outside-diameter capsule. Our best DT layers to date are produced just below the triple point at about 19.7 K. The gas density inside the capsule is ρ_{gas} = 0.7 mg/cm^3, instead of the specified ρ_{gas} = 0.3 mg/cm^3, and thus would change the convergence of the ignition capsule design. We are continuing to develop a method to reduce the temperature to 18 K while maintaining the surface smoothness.

Notes and References

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Cryogenic Layers by Infrared Heating

Previous experiments have shown that solid hydrogen can absorb infrared (IR) radiation, which substitutes for the beta-decay heat from tritium and drives a layer symmetrization similar to beta layering (see the previous subsection and Reference 1). We have performed layering experiments in 1-mm spheres contained in an integrating sphere into which the IR is injected (see Figure 13).

Initial IR layering experiments used a sapphire ball lens mounted on the integrating sphere viewports to disperse the IR light inside the integrating sphere.[2,3] The integrating sphere contained diffusely reflecting walls to reduce spatial coherence effects of IR laser illumination on the shell. By using this method, more IR was incident on the shell's equator on the beam's first pass than on subsequent reflected beam passes. The result was a thinning of the layer near the shell equator. To remove this type of layer defect, we implemented a different IR injection scheme, as shown in Figure 13. The sapphire ball lenses were removed, and the collimated IR laser beam was injected into the integrating sphere at an angle to miss the shell before hitting the integrating sphere wall. Experiments conducted this fiscal year employed this direct-inject technique.

Our initial layering experiments were performed with shells containing HD layers that were typically 150 to 200 μm thick. Layers of interest for ignition targets are approximately 100 μm thick. Therefore, the focus of our activities this fiscal year was studying thinner layers. In addition to working on protocols for generating uniform 100-μm-thick layers, we studied the time evolution of layers to determine if surface roughness, measured from shadowgrams, changed with time, and the effects of temperature change on a layer. Figure 14 shows a 90-μm-thick layer. The layer rms was

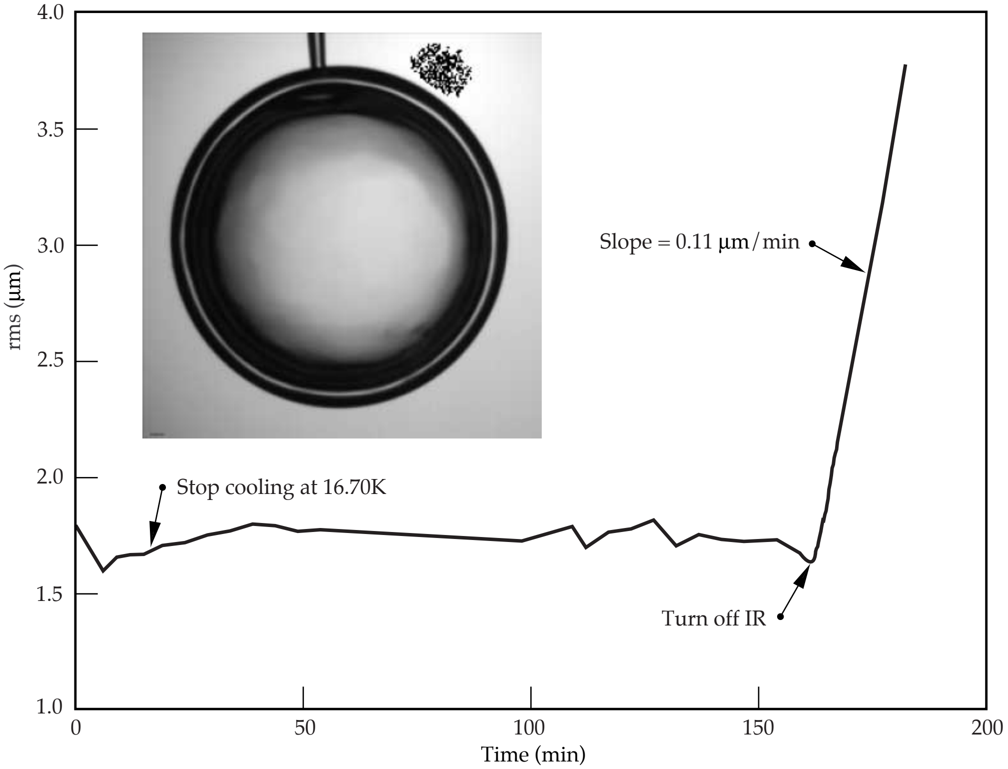

FIGURE 14. Time evolution of a 90-μm-thick HD layer. (08-00-0299-0463pb01)

monitored for approximately 2.5 hours at constant temperature (16.7 K) and laser power (~90 mW/cm^3) without noting significant changes in the rms value. At the end of this time, the IR was turned off, and degradation in layer quality with time was monitored. In this case, the layer rms increased at a rate of ~0.11 μm/min. Typically thinner layers generated at lower illumination intensities degraded less quickly than thicker layers generated at higher illumination intensities.

Experiments conducted at LANL on DT layers formed in a toroidal cell indicate that the rms surface roughness of the layer decreases by abruptly increasing or decreasing the temperature of the cell. From such results, we should expect to improve the surface finish of the layer by warming and cooling the layer in a stepwise fashion. We attempted a set of three temperature-stepping experiments to try to reproduce the LANL results. The experiments were performed at three different layer thicknesses (150, 140, and 100 μm). In each case, the protocol for initial layer generation was the same. First, under IR illumination, the layer was warmed to melt the solid and then immediately cooled at a rate of 5 mK/2 min until a solid HD layer formed. The temperature was held constant for a period of time, and then a temperature step sequence was applied. Figure 15 shows results from the experiment on a 140-μm-thick layer. Here, $t = 0$ indicates the earliest time that rms calculations could be performed from shadowgraphs of the layer. The results are typical of the three experiments. We did not observe an improvement in layer rms; instead, the layer degraded in quality.

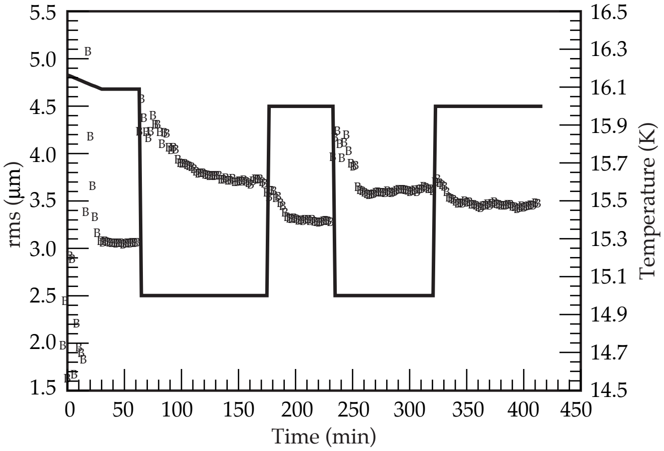

FIGURE 15. Layer rms (data points) and corresponding sphere temperature (solid line) versus time for a temperature-stepping sequence. (08-00-0299-0464pb01)

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5.0 NIF LASER DEVELOPMENT

This past year, the National Ignition Facility (NIF) laser technology effort essentially concluded a four-year campaign to develop the laser components necessary to successfully deploy the 1.8-MJ laser facility. We achieved development milestones in laser systems, beam control, and integrated computer control, as well as important demonstrations of integrated laser performance on Beamlet, the NIF single-beamline prototype.

In the front end, we assembled and operated a prototype integrated system, including master oscillator, preamplifier, and beam transport system, achieving the system performance requirements for NIF. In the main amplifiers, analytical and experimental data verified that residual optical distortions would be reduced to acceptable limits within the requisite seven-hour time frame. Gain, gain uniformity, and prompt pump-induced wavefront distortion were measured on NIF-like amplifiers in the Amplifier Module Prototype Laboratory (AMPLAB) and extrapolated to NIF conditions. Tests of amplifier flashlamps were conducted to qualify vendors for the upcoming large-scale production for NIF. A full NIF-size 4 × 1 plasma electrode Pockels cell was constructed and demonstrated, as was a prototype of the power conditioning module.

In the beam- and computer-control areas, a prototype system was developed to demonstrate the key components of the power balance diagnostic system, which requires measurement of both first- and third-harmonic (1ω and 3ω) powers to stringent accuracy. A common-object request broker architecture was developed for the integrated computer system, which takes advantage of newly developed industry standards applicable to the NIF's large-scale computer control system. In addition, we completed development at Lawrence Livermore National Laboratory (LLNL) of a 40-cm deformable mirror to reduce the effects of optical distortion of the laser-beam spot size on target, and worked with multiple vendors to produce prototypes of such adaptive optic systems for NIF.

During this past year, the integrated laser system in Beamlet concluded operations with a series of important experiments. We demonstrated 1ω output-beam quality equivalent to the NIF baseline ignition requirements and validated various aspects of the 3ω final optics design via use of a test mule to field 37-cm-aperture versions of the conversion crystals, focusing lens, and a diffractive-optics package. Finally, experiments utilizing beam smoothing by spectral dispersion demonstrated only modest sensitivity to performance due to pinhole closure, nonlinear beam breakup, and reduced frequency conversion.

Integrated Performance of the Optical Pulse Generation System

During the past year the focus of the Optical Pulse Generation (OPG) group has been design, fabrication, and testing of NIF front-end prototype components. The OPG system consists of three subsystems:

1. The Master Oscillator Room (MOR), which will contain a fiber laser oscillator, multiple fiber amplifiers, pulse shaping, phase modulation, and fiber distribution systems. The MOR produces 48 1-nJ shaped and timed pulses.
2. The Preamplifier Module (PAM), which amplifies and shapes the MOR-produced pulses to 15 to 20 J employing a diode-pumped regenerative amplifier and a flashlamp-pumped, four-pass rod amplifier.
3. The Pulse and Beam Transport System (PABTS), which divides the PAM output into four pulses and provides pulse timing, beam magnification, and collimation. We are currently in the design phase for this subsystem.

Recently we have begun an integrated system test campaign beginning with prototype components on hand and ultimately concluding with an integrated MOR, PAM, and PABTS demonstration. This first-article test will be completed early in FY 2000 using NIF first-article hardware prior to occupancy of the NIF facility.

MOR System Development

The MOR pulse-generation system has been reconfigured with a new oscillator. The prototype oscillator, shown in Figure 1, is a commercial distributed feedback (DFB) fiber laser producing 8 mW (continuous-wave) in a single longitudinal mode. Integrated system testing of this prototype hardware is an important milestone because it could reveal system problems associated with the design. In addition, the current configuration has much-improved stability over previous systems, which is required for long-term integrated PAM testing.

PAM System Development

We performed four integrated OPG test bed runs in early FY 1998, demonstrating all of the PAM requirements except wavefront and power balance with a high-contrast shaped pulse. The run series met the following goals:

- Demonstration of PAM energetic specifications with flattop and spatially shaped beams.
- 50-shot demonstration of steady-state operation at a fixed set point (24 J output).
- Operation of the PAM at maximum performance levels with 3-Å bandwidth and supercritical spectral dispersion.
- Operation of the preamplifier with all subsystems in place and functioning.

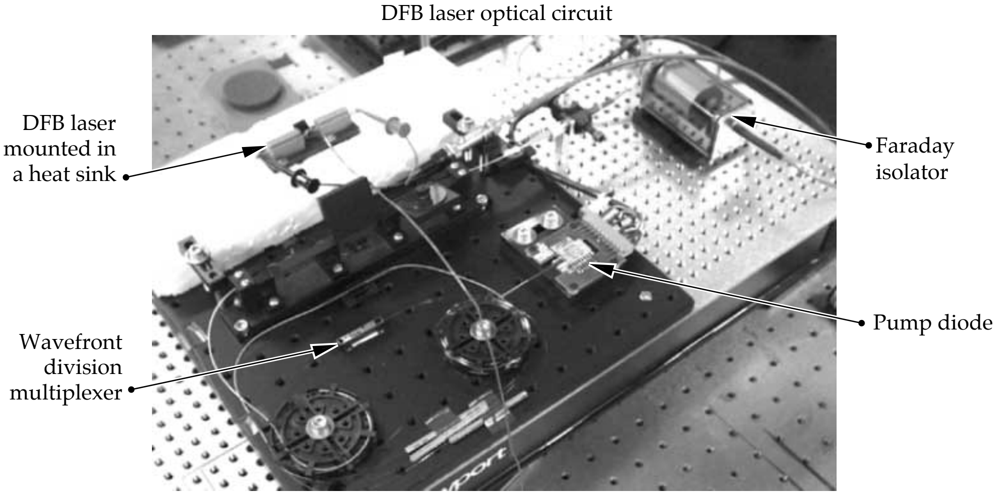
We completed a series of wavefront measurements on the PAM prototype prior to the Title II Review in October and showed both that the measured output wavefront was comparable to the value predicted by optical code modeling, and that it met the performance specifications for the PAM.

Gain, Gain Uniformity, and Wavefront Distortion Measurements on a 4 × 2 Amplifier Module

To verify that the NIF amplifiers will meet their requirements, and to validate our amplifier performance models, we performed detailed optical performance measurements on the NIF prototype amplifier, a four-aperture-high by two-aperture-wide multisegment amplifier with 40-cm-square apertures. This prototype amplifier was nearly identical to the NIF baseline amplifier design, with the same size flashlamps and laser slabs, nearly the same reflector shapes, similar antireflective (AR) coatings on the blast shields to improve pumping efficiency, and flowing gas to cool the flashlamps and to accelerate thermal recovery after shots.

Measurements performed on one-, two-, and three-slab-long amplifiers allowed gain and wavefront distortions of both interior slabs and end slabs to be determined.

FIGURE 1. The NIF prototype distributed-feedback fiber oscillator. (70-00-0299-0298pb01)



3D Ray-Trace Model

Gain distributions measured on the prototype amplifier were in close agreement with 3D ray-trace model predictions for both interior slabs and end slabs.

The 3D code calculates pump rates for neodymium-ion inversion by using a reverse ray-trace technique in which rays are propagated backward from the point of interest on the slab to the flashlamp plasma. The ray-trace model tracks the change in spectral content of each ray as it interacts with various reflecting and transmitting media present in the pump cavity.

The 3D code was found to accurately predict gain changes due to variations in aperture position, laser-glass composition, and electrical energy delivered to the flashlamps. After being successfully validated, the 3D code was used to predict the performance of the NIF amplifiers.

Figure 2 presents the predicted beamline-averaged gain-coefficient distribution for a NIF laser beamline. Propagation-code modeling of the NIF beamline shows that the gain distribution has sufficient magnitude and uniformity for the NIF laser to meet its beam power and energy requirements.

Wavefront Distortion

Wavefront measurements performed on the NIF prototype amplifier showed prompt pump-induced wavefront distortion to be several times greater than the residual slab distortion, within seven hours after a shot. Further, the measured prompt pump-induced wavefront distortion was in close agreement with model predictions for all prototype-amplifier configurations.

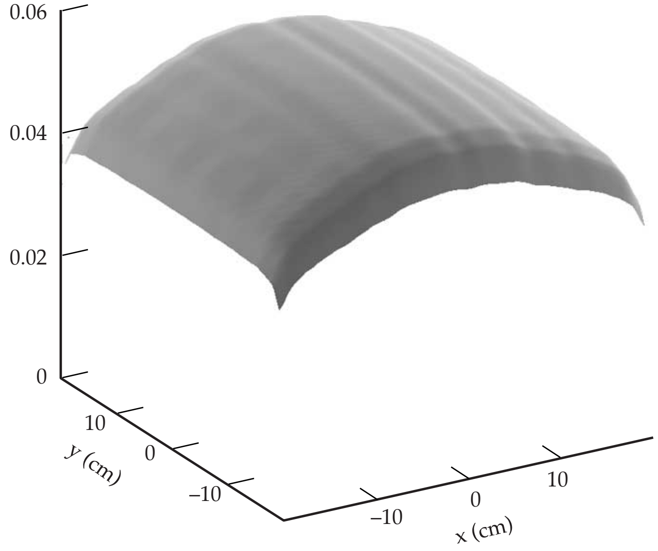


FIGURE 2. NIF beamline-averaged gain-coefficient distribution predicted with the 3D ray-trace code. (70-00-0199-0066pb01)

Thermal-Recovery Experiments on AMPLAB

Historically, we have defined thermal recovery in the context of two requirements: (1) wavefront recovery of the laser slabs and (2) wavefront recovery of the gas columns within or adjacent to the amplifier.[1,2] Because both are driven by temperature imbalances, characterizing temperature recovery has been an important intermediate step.

Numerical model predictions of amplifier thermal performance using several thermal models[3,4,5,6] were compared to data from AMPLAB thermal-recovery temperature experiments. Excellent agreement between model results and the experimental data was achieved, giving us confidence in our ability to predict temperatures in the amplifiers.

Wavefront Recovery of the Laser Slabs

Figure 3 gives model projections of slab optical distortions for the entire cooling cycle. The conservative result employs a correcting factor that was required to correlate model results with the AMPLAB-measured wavefront, while the aggressive result ignores this correction.[7] It is noted that for either assumption, slab wavefront recovery will meet NIF requirements well within the requisite seven-hour recovery time.

Wavefront Recovery of the Gas Columns

Figure 4 projects NIF gas-motion wavefront-distortion recovery for the cases of ambient gas cooling and chilled gas cooling.[3] These results are based on a projection model founded on AMPLAB and Beamlet data, with the conservative results incorporating height-scaling effects.[7] These results indicate that there is a high probability that ambient gas cooling will be sufficient to achieve seven-hour recovery, and that as little as 1°C subcooling will be adequate for an accelerated-shot, three-hour recovery.

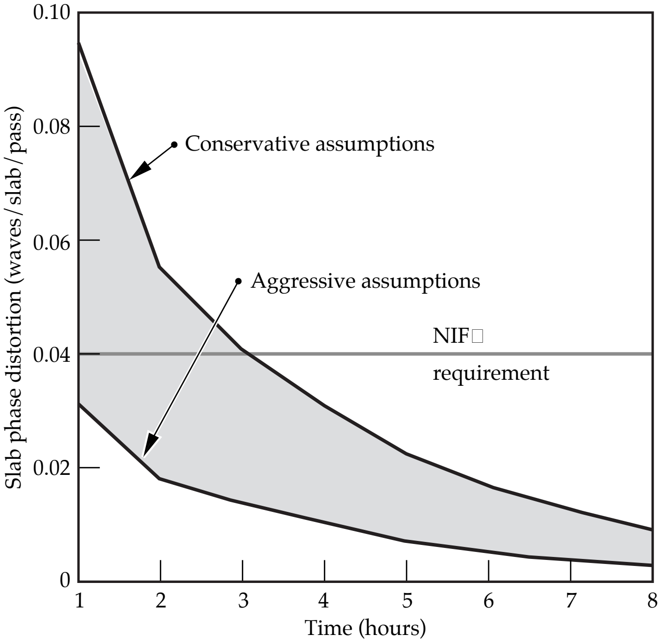


FIGURE 3. Model predictions of the residual slab distortion in the NIF laser slabs during the recovery cycle. The conservative assumption applies a correction factor that is addressed in Reference 7. The aggressive assumption employs uncorrected model results. (70-00-0299-0288pb01)

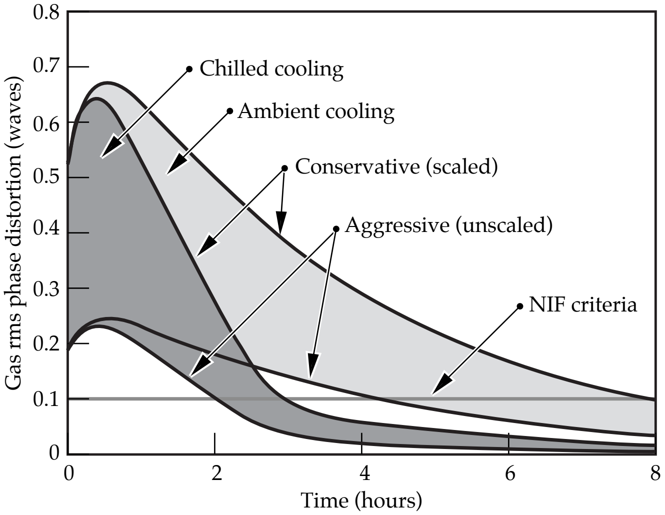


FIGURE 4. Predicted gas motion phase distortions for the NIF system, for both ambient gas cooling and chilled gas cooling. The conservative assumptions incorporate height-scaling effects (see Reference 7), while the aggressive assumptions assume negligible height-scaling differences. (70-00-0299-0289pb01)

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6. The optical propagation code used in this study is under continuing development at LLNL. Principal authors are W. Neumann, M. Rotter, and S. Sutton.
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Qualification Tests from Multiple Flashlamp Vendors

In the NIF amplifiers, large-bore xenon flashlamps will generate intense bursts of radiant energy by passing a pulsed electrical current through the xenon gas contained between electrodes within a cylindrical cerium-doped-quartz envelope. The optical energy between 400 and 1000 nm will be used for generating gain in the 3,072 neodymium-glass laser amplifiers. A total of 7,680 flashlamps are required to power the NIF amplifiers. The NIF flashlamp dimensions of 180-cm electrode-to-electrode spacing and 4.3 cm bore diameter were chosen using LLNL-developed global optimization codes that incorporate the understanding gained from previous generations of fusion lasers, such as the Nova and Beamlet lasers. The design service life is greater than 24,000 shots over a 30-year period, firing at 20% of the explosion energy and with a mean time between failures (MTBF) greater than 100,000 shots.

Vendor qualification is the final phase of a three-year program to develop these flashlamps. During prequalification tests with dozens of lamps, engineering problems associated with large-bore flashlamps were solved and the vendor designs frozen. Qualification test data give us the confidence that these flashlamps can be produced and will perform properly.

Two vendors are competing for the contract to supply flashlamps for NIF. We have received approximately 400 of the 500 flashlamps ordered and expect to receive the balance early in 1999. The testing of large numbers of flashlamps from each potential vendor assures that the NIF flashlamps can be manufactured in quantity to meet NIF quality, cost, and technical objectives.

Qualification Test Criteria

A set of objective criteria is being used to assess each manufacturer's ability to deliver flashlamps for NIF. There are three criteria involving flashlamp failure:

- Flashlamps explode.
- Flashlamps experience an insulation problem.
- Flashlamps fail to trigger.

In addition, there are two types of "soft" failures—electrode sputtering and quartz solarization—that diminish the optical output of the flashlamp as the number of shots increases.

Flashlamp Testing

The critical performance specifications affecting NIF reliability are tested in a flashlamp tester built for this purpose. In this tester, 40 flashlamps are fired simultaneously around the clock every 3 minutes. At the end of qualification testing (mid-1999), as many as 200 flashlamps from each manufacturer will have been fired at 110% of the required energy, with 80% fired to 10,000 shots and the remainder to 20,000 shots. A number of flashlamps will be taken past 20,000 shots towards the end of testing. At the end of each test, the failure rates will be compiled and then compared with those statistically predicted using hypothetical failure rates. The "soft" failures are also tested by taking transmission measurements of a few envelopes after 10,000 or 20,000 shots. The inspection of new flashlamps with respect to quartz flaws, mechanical tolerances, and electrical insulation properties is an important quality assurance activity taking place for developing risk-reduction criteria in the acceptance of the flashlamps that will be manufactured for NIF.

Present Status

Both vendors are at different stages in the qualification testing. Vendor 1 is approaching the end of testing, having delivered 230 flashlamps, 180 of which have received (on average) 12,000 shots; only two of Vendor 1's flashlamps have failed. Vendor 2 has delivered 116 flashlamps with 59 receiving 14,000 shots on average; six of Vendor 2's flashlamps have failed. The failure rates will be analyzed against statistically derived criteria at the end of testing. We are pleased with the results thus far and are confident that the large-bore flashlamp will perform well its intended role within the NIF amplifier.

Validation of NIF Requirements for a 4 × 1 NIF Prototype Plasma Electrode Pockels Cell

The NIF laser architecture is based on a power amplifier that allows the beam to travel through it multiple times, boosting its power on each pass in order to reduce cost and maximize performance. A key component of this laser design is an optical switch that, through polarization control of the beam, "closes" to trap the optical pulse after it has entered the amplifier cavity. It remains closed for four passes, in which the pulse gains energy, and then opens to divert the optical pulse out of the amplifier cavity. This switch is composed of a plasma-electrode Pockels cell (PEPC), which provides fast voltage control of the laser beam polarization, and a reflecting-transmitting polarizer.

PEPC Design for NIF

As with many other NIF components, the NIF PEPC is designed as a line replaceable unit (LRU). This is the smallest subarray of apertures that will be installed or removed from the NIF beamline. The PEPC LRU is a 4 × 1 module (four apertures high by one wide). A PEPC LRU is composed of an operational core mounted in an L-shaped support frame. A total of 48 PEPC LRUs will be required to provide optical switching for the 192 beamlines in NIF.

Each LRU is driven by a set of pulse generators: four plasma pulse generators (PPGs) and two switch pulse generators. Each PPG delivers a 1.2-kA pulse of current through the plasma channel. Plasma discharges form on each side of four 40-cm × 40-cm KDP crystals. These plasma discharges act as transparent, yet highly conductive, electrodes that allow application of a 17-kV voltage pulse directly across the crystals. This voltage pulse controls the PEPC switching action (i.e., opening, closing, and reopening the cell) by inducing 90° of polarization rotation as the laser pulse traverses the cell.

Testing Extinction-Ratio Uniformity

An operational prototype is designed to allow testing of the actual electro-optic switching operation of the 4 × 1 PEPC. In this prototype, we forgo the external frame to be used with the NIF LRU and orient the assembled PEPC horizontally.

Our experimental setup uses a pulsed laser with the same wavelength as the NIF laser. We split the beam from this laser into four beams that we expand to NIF size (40 cm) and NIF shape (square). Each of these beams passes through one of the four PEPC apertures and is then measured with charge-coupled-device (CCD) cameras and photodetectors.

With this experimental setup, we can measure the top-level requirements of the NIF PEPC: extinction-ratio (ER) uniformity and switching speed. The purpose of the PEPC is to rotate the polarization of the incoming beam exactly 90°. Ideally, 100% of the light is rotated perfectly, but in real devices there are always at least small sources of error. ER is the ratio of perfectly rotated light to unrotated light, so higher ER represents better operation. The NIF requirements are that the average ER for each aperture must be greater than 100, while the worst spot can have an ER no lower than 50. In our measurements, the photodetectors tell us the average ER while the CCD cameras display a picture of the ER everywhere on the aperture. From this we can determine the worst-spot ER. In our tests, we found that the minimum ER for each aperture is about 200 while the average for each aperture is well over 500, thus easily meeting the NIF requirements.

Switching Speed

Switching speed is the other top-level requirement. We have determined that it takes about 100 ns to turn the optical switch on or off. It is important for NIF that the ER requirements are met for each of the four times per shot that the NIF laser pulse traverses the PEPC. On the first pass, the PEPC is off and has been off for a long time. Because the PEPC is off, it does not rotate the polarization. It takes 277 ns for the pulse to return to the PEPC for the second pass. By this time, the PEPC must be fully on. The PEPC must still be on for the third pass, which is only 40 ns after pass two. After the third pass, the PEPC starts to turn off. Again, the optical pulse returns in 277 ns. By this time, the PEPC must be fully off again. We have used our laboratory setup to verify proper operation at each of these key times, thus validating the PEPC's ability to meet NIF switching-speed requirements.

NIF Main Amplifier Power Conditioning System Requirements and Design

Design of NIF's power conditioning system (PCS), which must simultaneously deliver over 260 MJ of electrical energy to nearly 7,700 flashlamps, is nearing completion. Computer modeling predicts that PCS design will meet all of NIF's performance requirements.

The prototype (or first article) system, which is being designed and built by Sandia National Laboratories (SNL) in collaboration with LLNL and industrial partners, is of a different architecture than any laser power conditioning system previously built at LLNL. System design is driven by the performance requirements and cost. Performance requirements are defined by subsystem design requirements derived from the overall performance and operational goals of the laser system. These requirements also define the lifetime, reliability, and maintainability that must be achieved by the PCS.

Module Design

The design of the NIF power conditioning module represents an evolution of developments and improvements that have occurred over many years and several generations of lasers. Modules are being designed that can handle larger amounts of energy with fewer components. Design has evolved from small, independent modules that store less than 100 kJ to the NIF power conditioning system, which must store nearly 2 MJ in a single module. This evolution has been driven primarily by the need to continually reduce the incremental cost of supplying energy to drive lasers as the size of the laser systems increases.

In the NIF design, power conditioning equipment is located in capacitor bays adjacent to each laser cluster. Each capacitor bay houses 48 independent power conditioning modules. Each module is charged in approximately 60 seconds with its own capacitor-charging power supply. The 60-second charge time was chosen because it was an acceptable compromise between capacitor lifetime, switch prefire probability, and power supply / prime power cost. Each module stores, shapes, and delivers pulses of energy to 40 flashlamps. Modules are designed to deliver a minimum of 34 kJ per flashlamp with the capability of expanding to approximately 40 kJ per flashlamp.

The potential for faults to cause significant damage increases as the amount of energy in a single module increases. Significant investments have been made to develop components that are either robust against all known failure modes or that fail in a well controlled fashion and can be easily replaced.

Module Performance

One of the important measures of the NIF laser amplifier performance is the gain coefficient of the amplifier. Gain coefficient is a measure of the change in light intensity versus the path length of the light through the laser glass. Gain coefficient is dependent not only on the laser glass, but also on the temporal characteristics of the light pulses generated by the flashlamps. The desired temporal characteristics of the flashlamp light translate directly into requirements on the shape, amplitude, and timing of the drive pulses supplied by the power conditioning system. A computer model, GainCalc v1.0, has been developed to calculate the gain coefficient of the NIF amplifier for a given electrical drive input. This code is used to verify that the output waveforms of the amplifier PCS meet the gain coefficient requirement of >5.0%/cm.

A first-article power conditioning module, built at SNL-Albuquerque, is being tested to verify design performance and system lifetime. The final design of the module to be built to drive NIF will be based on the information and understanding gained from operation and testing of the first-article module.

Evaluation of a Prototype NIF Power Balance Diagnostic

Experiments at the NIF will require precise beam-to-beam power balance. The power balance measurement accuracy, averaged over a 2-ns interval, is required to be no greater than 4% throughout a 20-ns-wide pulse having peak-to-foot contrast ratios of 50:1. The temporal power measurement system that we developed, the Power Sensor, has been allocated 2.8% of this 4% measurement-error budget. Development of this diagnostic requires an understanding of both the performance characteristics of each component in the system and how each component affects the error in the measurement. During FY 1998, we demonstrated that even with error contributions from speckle noise, the digitizer, and time alignment, the Power Sensor can measure power balance to an accuracy of 1.5%.

We examined the temporal response and demonstrated recording of time-multiplexed, 1.05-μm laser pulses on a prototype NIF Power Sensor channel. A procedure was developed to characterize and then normalize the transient recorder channels. "Stitching" together and time-aligning the corrected waveforms from the four transient recorder channels yielded the final waveforms used to calculate power balance.

The power for a laser beam may be written as

$$P(t) = Ef(t - \Delta t) \; , \qquad (1)$$

where E is the total beam energy, $f(t)$ is the normalized temporal shape of the beam, and Δt is the beam synchronization error. Power balance between all NIF beams depends upon the accuracy with which beam energy, temporal shape, and beam synchronization are determined.[1] A useful figure of merit for describing the power balance is the standard deviation (rms deviation) in the power divided by the average beam power, which expresses the power balance as a percent. Figure 5 shows the percent power balance and temporal beam shape calculated using a 2-ns-wide boxcar-averaging window for the 40:1 contrast pulse data. For our measurements, a time-alignment error showing up in the power balance result tells us how well the Power Sensor can time-align data; in this plot, the Power Sensor contributes a time-alignment error less than 10 ps, and we see a measured power balance error ≤1.5%.

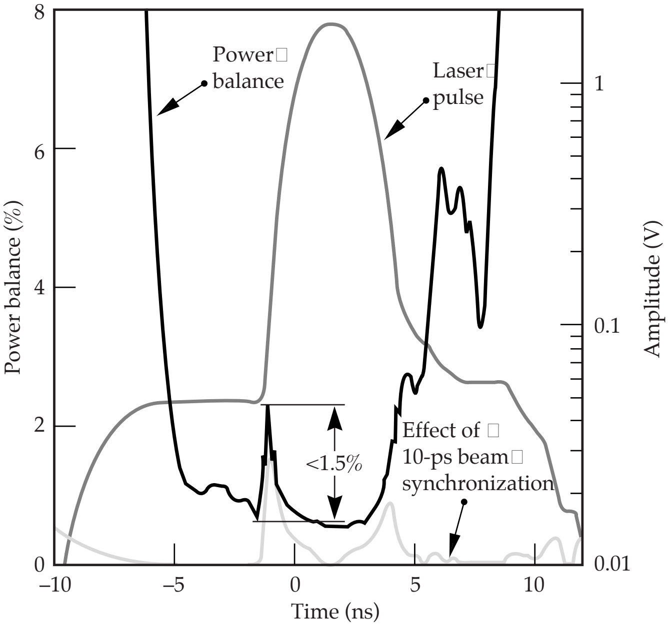

FIGURE 5. The prototype NIF Power Sensor measured a power balance error of ≤1.5%, except during the fast-rising edge of the pulse, for 40:1-contrast laser pulses, well within the 2.8% requirement. (70-00-0199-0129pb01)

Notes and References

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Adaptive Optics Development

The NIF missions in weapons physics and ICF research make stringent demands on the focusability of the delivered energy. To meet these requirements, the NIF will employ an adaptive optic system in each of its 192 beams to correct wavefront aberrations that would otherwise enlarge and distort the target focal spot. This year, prototypes of the major components of the adaptive optic system were fabricated and tested

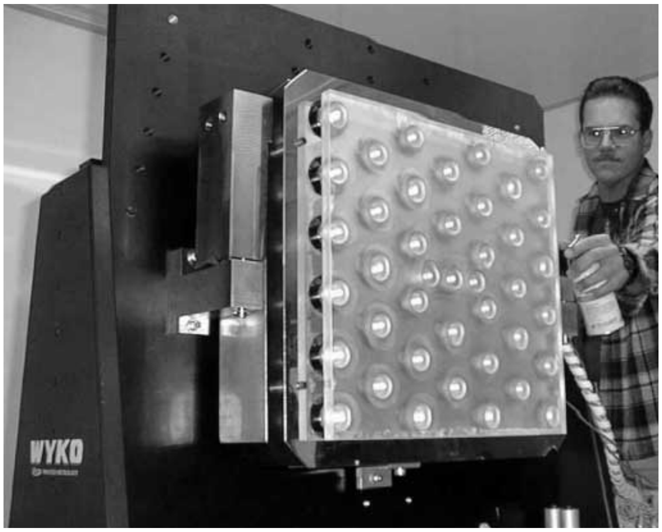


FIGURE 6. Second-generation LLNL-designed deformable mirror. (70-00-0299-0308pb01)

individually and as an integrated system. These included the deformable mirror (DM), the wavefront sensor, and the computer control system. A large-aperture interferometer facility was developed for the integrated tests. Computer models predicted NIF focusability using the test data.

The most expensive and difficult-to-produce adaptive-optic component is the 40-cm-aperture DM. A second-generation LLNL design, shown in Figure 6, has met NIF requirements. This DM employs 39 lead-magnesium-niobate actuators in a hexagonal configuration to deform the mirror surface by pushing against a rigid metal block. The DM must attain a very low residual error (difference between the DM surface and a reference surface that the DM controller tries to match) and must operate in the harsh environment produced by nearby laser flashlamps.

The second-generation LLNL design employs the same proven actuator-to-faceplate attachment method as the first-generation DM, an epoxy shear joint in a metal cup that holds each aluminized mirror post. Formerly, the cups were directly attached to actuator flexures attached, in turn, to the metal block. In the improved design, the flexures were removed and a butt joint was added. This modification reduces residual error by preventing small lateral misalignments (between the mirror posts and the actuator assemblies) from creating moments on the posts and corresponding ripples on the mirror surface. The DM achieved a measured rms residual error of 0.031 waves—a factor of 2.5 improvement over the original design.

A beam propagation model was constructed to assess the performance of the wavefront control system in the NIF. The code models all significant optics and includes measured or modeled representations of significant wavefront aberrations, including the measured DM residual error. The 39 measured influence functions (actuator responses) and a model of the operation of the wavefront sensor were used to generate the model correction. In the results presented here, aberrations were limited to those having spatial frequencies that a 39-actuator DM can correct: laser-slab thermal distortions, low-order Seidel aberrations in the optics, mirror distortions from coating stress, and distortions from mounting and gravity sag. Figure 7a

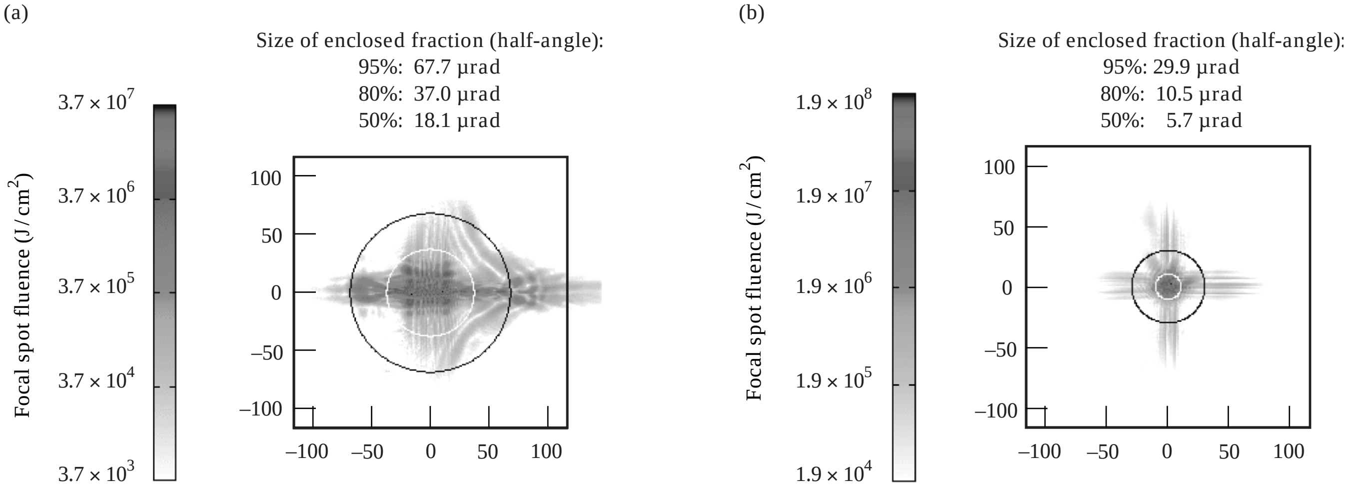


FIGURE 7. (a) Propagation-model prediction of the NIF target spot with only long-wavelength aberrations and no wavefront control system. (b) Propagation-model prediction of the NIF target spot with the same aberration set and a wavefront control system activated. (70-00-0299-0309pb01)

shows the predicted target spot when wavefront control is omitted. Most of the energy falls outside of the 250-μm-diam target-spot goal (a 16-μrad radius). Figure 7b shows the predicted target spot when wavefront control is included in the simulation. Here, 80% of the energy resides within a 162-μm-diam (a 10.5-μrad radius) spot, meeting the goal. Higher spatial-frequency aberrations not included in this calculation, such as those induced by gas turbulence or by optic figure errors, will have to be kept in check for the NIF to meet its spot-size goal.

CORBA-Based Simulator

For the last several years, LLNL has been developing an abstract software framework, the Integrated Computer Control System (ICCS), for building distributed, event-driven control systems for large, mission-critical facilities such as the NIF. The ICCS integrates data acquisition and control hardware with a supervisory system and reduces the amount of coding necessary by providing prebuilt components that can be reused and extended to accommodate specific additional requirements. It is interoperable among computers of different kinds and provides plug-in software connections by leveraging a common object request brokering architecture (CORBA) to transparently distribute software objects across the network of computers.

CORBA communications performance data between 300-MHz UltraSparc computers is shown in Figure 8 (percent utilization data is only shown for 100-Mb/s Ethernet traffic). Most control system transactions average 100-byte messages. In this operating regime, CORBA transacts over 2000 messages per second, while using up to 80% of a powerful processor. For small messages, the processor is the limiting resource, as network bandwidth is not heavily used. As messages become larger (e.g., during data retrieval), the network eventually becomes the limiting factor, but this does not impact time-critical operations preceding the NIF shot. These results led designers to partition the NIF control system such that the design point for each of seven subsystems will average about 500 control transactions per second. This approach reserves substantial capacity for traffic peaks and other computational tasks.

To complement the CORBA measurements, key operating scenarios were modeled to study performance under resource constraints using a general-purpose simulation tool. Scenarios modeled included computer system restart, equipment status monitoring, and automatic alignment of the 192 NIF laser beams. Simulation results revealed software and hardware fixes that led to acceptable performance.

The local area network, which delivers timely and reliable communication between control applications, is another critical component of the ICCS. For the NIF, more than 600 computer systems will be distributed throughout the facility over a hybrid network design using both Ethernet 10- and 100-Mbit/s and Asynchronous Transfer Mode 155-Mbit/s technologies (the latter for time-sensitive video data). Key portions of the NIF network were analyzed by simulating network operation and assessing its performance under worst-case conditions. Actual performance data collected from the ICCS test bed verified simulation parameters.

Analysis of results indicates that the network will be capable of meeting the throughput and latency requirements of the NIF laser alignment process, which presents the highest traffic to network switches. Expected traffic involves the simultaneous transfer of motion video to operator stations at 75 Mbit/s and sensor image transfers at 60 Mbit/s, as well as control messages—all between 100 computers comprised of image processors, supervisory workstations, video

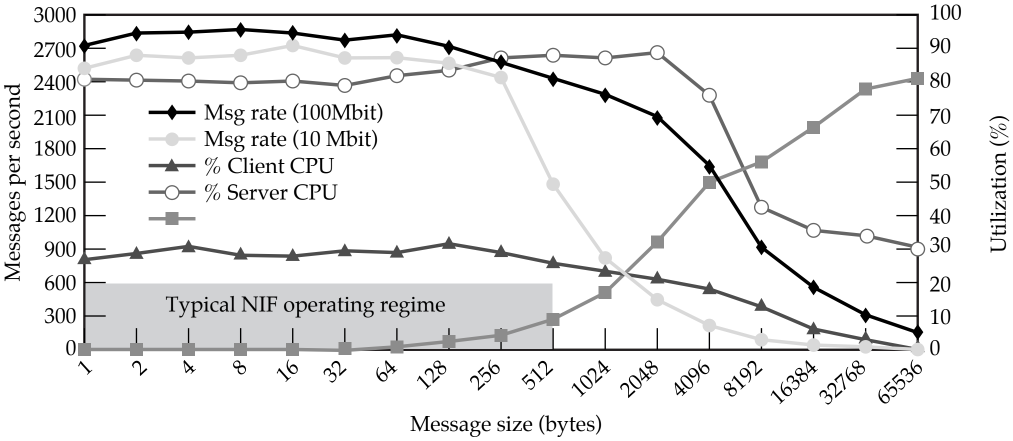


FIGURE 8. CORBA performance tests show adequate headroom for typical control scenarios in a partitioned system. (70-00-0299-0300pb01)

digitizers, and motion control systems. The overall requirement is to provide a steady stream of video images to operators while automatic closed-loop processing choreographs the precise adjustment of over 9000 motorized optics within a 30-minute period.

Beamlet 1ω Laser-Performance Demonstration

Laser performance is characterized by output beam quality and is usually quantified by its near-field beam contrast parameter and by its beam divergence. The first parameter is important for validating damage risk to optical components, while beam divergence determines the size of the third-harmonic (3ω) spot size after frequency conversion (i.e., from 1ω). For short pulses, performance is limited by nonlinear steepening of small-scale beam modulation, while for longer-pulse and higher-energy operation, the damage threshold of optical coatings presents a limit. Beam divergence is determined by gradient performance of the optical components, pump-induced aberrations in the main amplifiers, and the performance of the deformable-mirror–based wavefront correction system. In FY 1998, we demonstrated 1ω performance on Beamlet, including beam divergence, beam contrast, and ignition pulse.

Beam Divergence

Beamlet's beam divergence was extensively characterized using high-resolution far-field imaging and radial shear interferometry. Test results show that prompt pump-induced aberration can entirely be corrected by the 39-actuator deformable mirror located in the injection beam path. The static wavefront errors are only partially correctable, resulting in a residual error of ~1 wave peak-to-valley, 0.2 waves rms. The corresponding 1ω output focal spot is nearly 2.5 times the diffraction limit, with only a small increase in the 80% power diameter observed at output power levels up to 5.1 TW. The corresponding 0.35-μm focal spot meets the NIF requirements of 500 TW inside a 250-μm-diam circle.

Beam Contrast and Spatial Filtering

Spatial filters perform an essential function stripping high-angle scatter from the beam before it has a chance to grow nonlinearly through interaction with the main beam in optical elements with nonzero intensity-dependent refractive index. Most previous Beamlet shots were fired using ±200-μrad pinholes. Safe NIF operation requires spatial filtering with smaller cut-off angle, down to about ±150 μrad. Too small pinholes, however, can cause the focal spot to hit the edges of the pinhole at sufficient intensity to cause plasma blowoff into the filter aperture and thus allow destructive back reflection into the amplifier chain. Pinhole closure results in large near-field modulation, with the risk of damage and filamentation at the peaks in the near field.

During FY 1998, a pinhole interferometer was installed to diagnose plasma density within the pinhole throughout the duration of the propagating laser pulse, while systems diagnostics measured both modulation in the forward-propagating beam as well as back-reflected beam properties. These evaluations resulted in a suggested baseline that consists of a newly designed stainless steel conical pinhole with a ±150-μrad cutoff angle, providing sufficient margin to propagate the NIF ignition pulse shape with baseline smoothing by spectral dispersion (SSD) and alignment tolerances having no detectable back reflections.

Ignition Pulse Demonstration at 1ω

Using the abovementioned pinholes, we successfully demonstrated the propagation of 15.5 kJ in a 20-ns shaped pulse with 10:1 temporal contrast (5.4-ns-equivalent pulse duration) and ±7.5 μrad added divergence for SSD. These conditions correspond to nearly 19 kJ when scaled to the NIF beam size. Figure 9 shows pinhole interferometric data for this shot comparing the plasma-induced phase shift in the transport spatial filter against closure conditions.

Beamlet Demonstration of Feasibility of NIF Final Optics

Beamlet 3ω Laser Performance Demonstration

A significant fraction of Beamlet experiments in FY 1998 were devoted to testing prototypes of the NIF final optics design. The NIF final optics perform these critical functions:

1. Frequency converting the 1.053-μm fundamental wavelength of the laser amplifier (1ω) to a wavelength of 0.351 μm (3ω) with high efficiency.
2. Focusing the 3ω energy onto the target.
3. Diverting the unconverted energy away from the target.
4. Providing a full-aperture sample of the 3ω beam for diagnostics.
5. Randomizing the spatial coherence of the laser energy at the target.

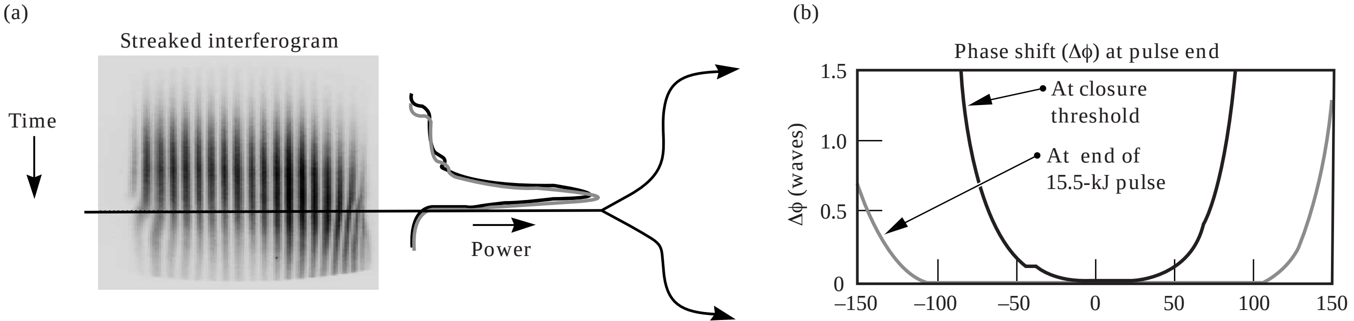


FIGURE 9. (a) Beamlet data from a 15.5-kJ pulse demonstrating the 1ω NIF ignition pulse requirements; (b) the optical distortion (Δϕ) is far below the value at which it would cause pinhole closure on the NIF. Power is scaled to NIF beam size. (70-00-0299-0301pb01)

6. Shielding upstream optics from debris and high-energy x rays and neutrons emitted from the target.

To test and validate various aspects of the final optics design on Beamlet, we constructed a test mule at the output of the main laser amplifier that allowed us to field 37-cm-aperture versions of the optical components in a NIF-like configuration without the cost and complexity of activating a complete final optics assembly. A NIF-like 1ω window at the input to the test mule isolated the vacuum environment of the final optics from the main amplifier, allowing safe operation at full 3ω fluence. The frequency-conversion crystals and final focus lens were supported in a compact final optics cell utilizing full-perimeter clamping, as per the NIF design.

3ω Conversion Efficiency

Experiments conducted with the test mule played a critical role in testing the design of the NIF frequency converter and validating the physics model on which a detailed error analysis of its performance is based. These experiments measured (1) the 2ω conversion efficiency of a type I potassium dihydrogen phosphate (KDP) doubler from the first conventionally grown NIF boule, (2) the 2ω conversion efficiency of the first 37-cm rapidly grown doubler, (3) the 3ω conversion efficiency of a converter consisting of the conventionally grown doubler and a conventionally grown type II deuterated potassium dihydrogen phosphate (DKDP) tripler, and (4) the 3ω conversion efficiency of a converter consisting of the rapid-growth doubler and the first 37-cm rapid-growth tripler (see Figure 10). The Beamlet work was able to validate the model to within the few-percent uncertainty of the component transmissions and verified that peak-power 3ω conversion efficiencies of 80% or greater should be achievable at NIF ICF drive irradiances, provided that high-quality antireflection coatings are maintained on the optics.

3ω Focal Spot

The quality of the 3ω focus was measured to gauge compliance with the NIF goal to deliver 500 TW of peak 3ω power inside a 250-μm-diam spot for special high-brightness weapons physics applications. Tests at power levels up to 3.1 TW and *B*-integrals up to 2.6 radians produced a NIF-equivalent power of 540 TW inside a half-angle of 15 to 16 μrad when scaled for beam size and expected transmissions. These results confirmed that the NIF focusing goal can be achieved if the quality and associated static errors of the NIF optics are held to Beamlet levels.

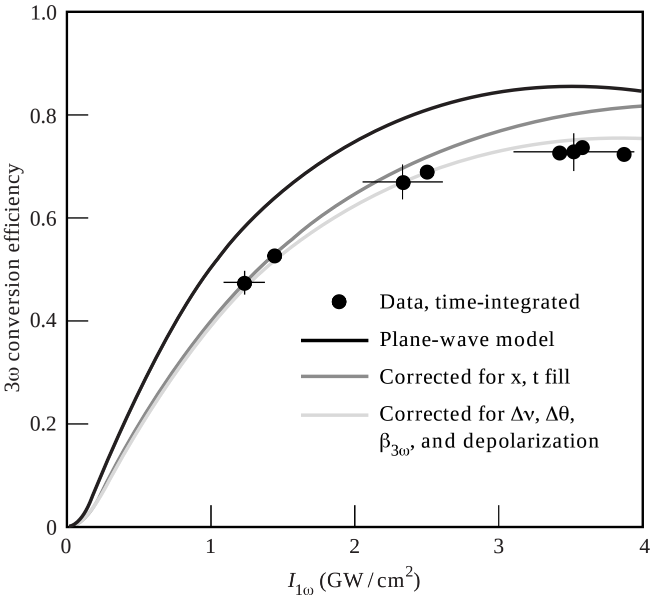


FIGURE 10. Measured and calculated 3ω energy conversion efficiency for rapid-growth frequency doubler and tripler, plotted vs 1ω irradiance of the incident laser pulse. (70-00-0299-0302pb01)

3ω High-Energy Operation

High-energy operation of the final optics was investigated as high-damage-threshold fused-silica components became available. 3ω fluences of up to 8 $\mathrm{J/cm^2}$ and NIF-equivalent energies of up to 9.6 kJ in 3-ns square pulses were achieved in a series of three campaigns that produced valuable data on component performance and lifetime for the NIF. Results of the high-fluence tests revealed problems with beam modulation and damage associated with the sol-gel coating on the color separation grating (CSG) being nonconformal with the surface—an effect previously identified as being responsible for reducing CSG diffraction efficiency. Improved CSG designs under development are expected to eliminate this problem.

Performance of Smoothing by Spectral Dispersion on Beamlet and the NIF

Optimal performance of an inertial confinement fusion target requires that the driver laser beam be spatially conditioned such that the illumination on target is sufficiently uniform. For the indirect-drive target configuration, the enhancement of laser–plasma instabilities by illumination nonuniformity underlies the requirement to smooth the target illumination. For the direct-drive configuration, a much smoother beam is required because the illumination nonuniformity is directly imprinted onto the target surface and is subsequently amplified by hydrodynamic instabilities. The smoothing by spectral dispersion (SSD) method is particularly well suited to ICF with glass lasers because the pure phase modulation used preserves the near-field beam quality and thereby allows for efficient extraction of energy from the amplifiers. For a modest uniformity requirement (indirect-drive, near-field contrast of 15 to 30%), it is thought that the 1D SSD method is sufficient, and for a more uniform beam (direct-drive, contrast less than 10%), 2D SSD is required.

A schematic of the 1D SSD configuration used on Beamlet is shown in Figure 11. In the usual implementation, sinusoidal phase modulation (FM) is imposed on the low-power beam in the laser front end. A diffraction grating then induces angular divergence on the beam. Each FM sideband is shifted off axis in proportion to its frequency shift, and thus 1D SSD produces a series of shifted speckle patterns in the far field. To obtain optimal smoothing, each of these speckle patterns must be shifted by at least the angular width of a speckle; this requirement is referred to as "critical dispersion." The increased divergence of SSD provides an essential limitation, e.g., increased clipping from the spatial-filter pinholes, which can lead to more rapid closure of the pinholes, increased near-field modulation, and therefore reduced amplifier extraction. To minimize the divergence at critical dispersion for a given bandwidth, one must minimize the number of sidebands and hence maximize the frequency of modulation. For this reason, a new high-frequency modulator was developed that can provide up to 5 Å of bandwidth at infrared wavelengths and operates at 17-GHz modulation frequency.

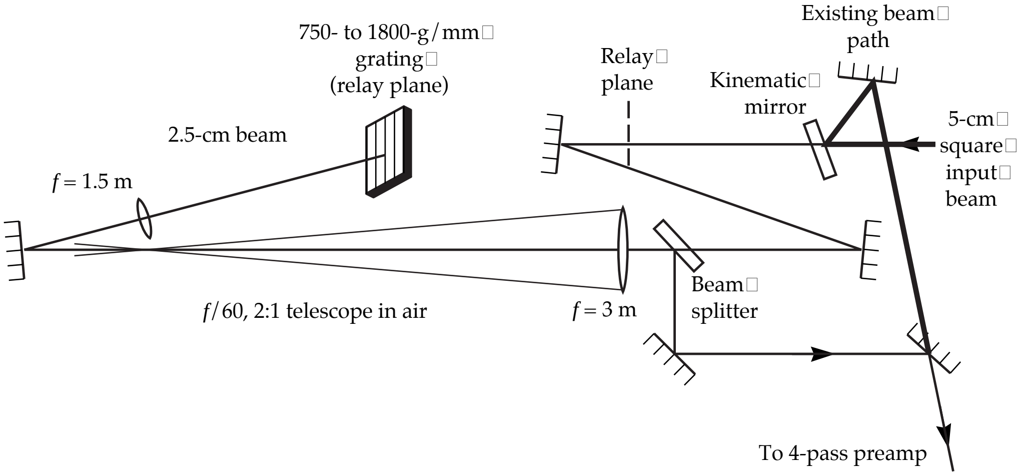


FIGURE 11. Schematic of modifications made to Beamlet to accommodate 1D SSD. Removing the kinematic mirror allows the beam to traverse the SSD section before going to the four-pass preamplifier. (70-00-0299-0303pb01)

Results

Measurements of the performance of Beamlet demonstrate a modest sensitivity to the implementation of 1D SSD. At the baseline level of SSD for indirect-drive (±7.5 μrad), neither a significant effect on pinhole closure nor nonlinear (*B*-integral–induced) beam breakup was observed. At the ±25-μrad level required for direct drive, there is a ~10% reduction (2.2 → 2.0) in the Δ*B* integral required to initiate beam breakup (see Figure 12). Pinhole closure was also observed to be accelerated with ±25-μrad SSD, indicating that a small (~±10-μrad) increase in pinhole size (relative to indirect drive) might be required. Finally, it was found that frequency conversion with SSD bandwidth was somewhat better than when calculated with a simple linearly scaled plane wave model. The measured relative reduction in efficiency compared to the configuration of 1-Å bandwidth without SSD was 6% (i.e., efficiency reduced from 73.3% → 68.9%) for 3 Å critically dispersed, 20% (73.3 → 58.6%) for 5 Å critically dispersed, and improved to 14% (73.3 → 62.9%) for three times critical dispersion. The scaled plane-wave model predicts 11, 28, and 26% reduction for these measurements, respectively.

One possible explanation of these results is that the local variation of pointing of the optic axis throughout the volume of the tripler may be partially responsible for both the reduction in conversion at low bandwidth and the relative improvement at larger bandwidth. That is, this variation, in effect, would both broaden and reduce the peak of the phase-matching curve in the tripler.

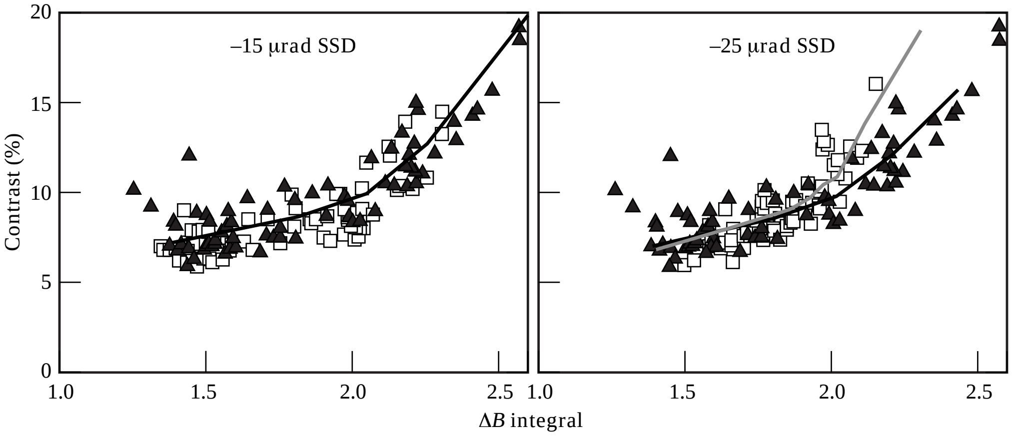


FIGURE 12. Measured contrast in 5- × 5-cm patches of the Beamlet 1ω output near-field beam, with the indicated amount of SSD divergence (squares, gray line) and without SSD (triangles, black curve). No significant degradation is found for ±15-μrad SSD, but there is some effect at ±25 μrad. The curves are guides for the eye. Δ*B* is calculated for propagation from the last ±167-μrad cavity pinhole to the 1ω output. (70-00-0299-0304pb01)

6.0 OPTICS TECHNOLOGY DEVELOPMENT

This past year, the four-year optics technology development effort was essentially completed to demonstrate the feasibility of the new technologies, equipment, and manufacturing processes to meet the National Ignition Facility (NIF) cost, performance, and schedule requirements.

In amplifier slab development, there were successful laser glass melting campaigns at Schott Glass Technologies (full size) and Hoya Corporation USA (half size) using the continuous melting technologies planned for NIF. These campaigns produced laser glass meeting most of the NIF technical specifications, including platinum inclusions, absorption at 400 nm and 1053 nm, refractive index stability, bubbles, and striae. Schott and Hoya used these results to confirm most of the design details of the full-size melters to be used in 1999 for the pilot production, as well as to make minor changes in some of the process parameters.

NIF-size amplifier slabs were finished to NIF specifications at Zygo Corporation using the NIF process and NIF equipment designed and installed under the facilitization contract awarded in 1997. The pilot production contract was awarded to Zygo to begin hiring and training critical staff in preparation for the main pilot in FY99.

In the rapid-crystal-growth development effort, NIF-quality potassium dihydrogen phosphate (KDP) and deuterated KDP (DKDP) boules were grown with constant filtration to NIF-size. Crystals were fabricated and tested on the Beamlet laser facility, a prototype NIF beamline at Lawrence Livermore National Laboratory (LLNL), and shown to meet the NIF optical and frequency conversion specifications. The rapid-growth pilot was started in April 1998 based on these successful development results. The pilot production campaign produced a NIF-size tripler boule that should yield about 15 plates (remarkably about 8% of NIF from one boule), and KDP boules to yield about 20 Pockels cell plates (about 10% of NIF).

Following work in 1997 that identified the importance of polishing compound composition and minimizing subsurface damage to achieve high damage thresholds at a wavelength of 351 nm, we fabricated full-size, high-damage-threshold focus lenses at Eastman Kodak and Tinsley Laboratories, Inc. The damage thresholds were demonstrated by raster-scanning in the Large Area Testing facility. The pilot production contract for fused silica was awarded to Corning on schedule and budget.

All three diffractive optic components for NIF were fabricated and tested at full size: the color separation grating (CSG), the beam sampling grating (BSG), and the kinoform phase plate (KPP). These optics met all performance specifications in the absence of sol-gel coatings. The CSG and BSG both produced unacceptably high wavefront modulation following application of the sol-gel antireflection (AR) coating. This modulation was traced to nonuniformities in the coating thickness, and has led to reevaluation of the baseline design. It is now expected that an uncoated BSG and subaperture CSG will be used on NIF.

NIF-size polarizers were coated at the Laboratory for Laser Energetics (LLE) at the University of Rochester and Spectra-Physics. These polarizers were laser conditioned to meet the NIF damage threshold using an advanced single-step process. Improvements in the coating process also produced coatings that met the stress/reflected-wavefront specification for a low-humidity environment, as well as the challenging spectral requirements.

The reconfiguration of the Building 391W facility at LLNL was completed to create the glass processing capability in the Optics Processing Development Laboratory. Virtually all of the full-scale cleaning and sol-gel coating equipment was also ordered for the facility. The crystal spin coater was received; initial coating experiments on glass substrates exceeded the design specification of ±5% uniformity.

NIF-Size Laser Glass Continuous Melt

Schott Glass Technologies was successful in melting and forming phosphate-doped LG-770 laser glass at full NIF-size in the first attempt ever to melt laser glass continuously at this size. This glass, shown in Figure 1, met many of the NIF specifications, including platinum inclusions, bubbles, and absorption losses both at 400 nm and 1053 nm. The refractive-index stability of the glass was also very good, which is needed to achieve high yields with good optical wavefront quality. This run showed that most of the laser-glass melter units should not require any modification for the pilot production work in 1999. Some design issues were discovered during the course of the run, and additional experiments at Schott and LLNL were done to guide appropriate responses. The interpretation of this work was aided by a chemical engineering process model developed this past year at LLNL to relate key glass properties to manufacturing conditions. Modifications to the melter design and process conditions based on these experiments were implemented in late 1998 in preparation for the pilot production.

FIGURE 1. NIF-size laser glass slab from Schott's 1998 development campaign. (70-00-0198-0098pb01)

Laser-Glass Formation at Approximately Half NIF-Size

Hoya completed its final subscale development campaign, successfully producing phosphate laser glass at half-NIF linear aperture size; the glass met all NIF specifications except for size. Homogeneity tests on sixty fine-annealed pieces of the Hoya glass demonstrated that the Hoya melter is capable of meeting the NIF specifications, thus indicating the potential of this continuous melting process to achieve high yields. The process model discussed above was also used to analyze the results of the Hoya run, and identified modified conditions that should further improve the glass quality. The results of this campaign were used to finalize the design of Hoya's full-size melter (designed and built as part of NIF optics facilitization). The facilitization effort was completed in 1998 in preparation for Hoya's pilot production in 1999. Figure 2 shows the first full-size, continuous-melted laser glass from Hoya's initial pilot production.

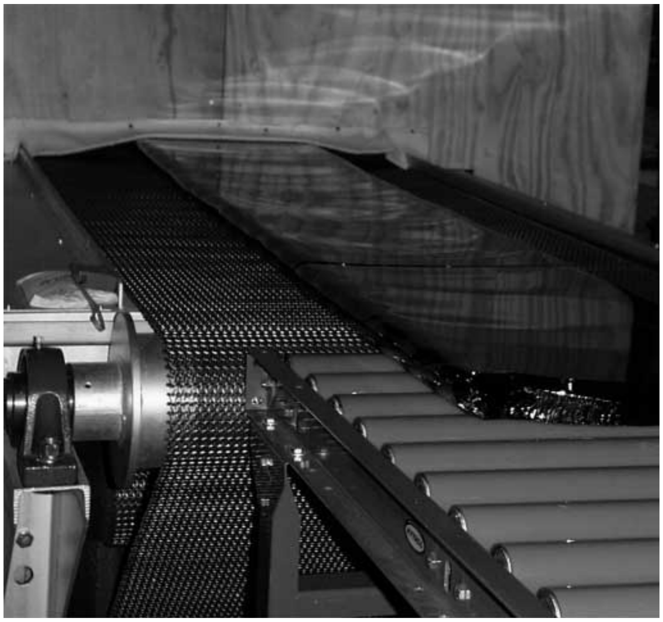


FIGURE 2. The first full-size, continuous-melted NIF laser glass from Hoya's initial pilot production. (40-00-0299-0474pb01)

KDP Rapid Growth, Including Fabrication and Beamlet Testing

The rapid-growth technology was demonstrated early in the year by growing two KDP boules to NIF size and one DKDP boule very close to NIF size (see Figure 10 on p. 68). Pockels cell, doubler, and tripler crystals of NIF or Beamlet size were fabricated from these boules. These crystals demonstrated that the rapid-growth material can meet the NIF specifications for optical absorbance, birefringence, wavefront distortion, phase-matching homogeneity, and 1ω damage threshold.

Rapid-growth doublers and triplers, both together and with conventionally grown counterparts, were used on Beamlet to test the NIF frequency-conversion model. The rapid-growth doubler performed equally to the conventional-growth doubler, and the rapid-growth tripler performed nearly as well as the conventional-growth tripler (80.7% versus 82.5% total conversion efficiency).

The primary remaining concern for rapid growth material is the 3ω damage threshold. The damage threshold is specified to keep the obscuration from bulk pinpoint damage less than 0.1% over a two-year period of NIF operation. Measurements on the Optical Sciences Laser at LLNL determined the relationship between fluence and pinpoint density (i.e., the obscuration) for a few samples. Convolution of this dependence with the NIF beam fluence predicted the obscuration for NIF conditions.

Comparison to the commonly measured damage-fluence distributions indicated that material having a 10% damage probability at 15 J/cm^2 for a ramped sequence of 7.6-ns pulses represents the border of acceptable NIF material. The best rapid-growth DKDP grown in small laboratory crystallizers, samples 367 and 586 shown in Figure 3a, meet the NIF 3ω damage theshold. The only large DKDP boule measured so far, RG8A, had a damage threshold significantly below that required for the peak NIF fluence. By comparison, most of the NIF-scale DKDP grown conventionally, shown in Figure 3b, meet the 3ω damage specification. A focus of our work in 1999 will be to determine the impurity levels and conditions consistent with high 3ω damage resistance.

Demonstration of All Critical Steps in Fabrication of Full-Size NIF Amplifier Slabs

The major process steps involved in the fabrication of an amplifier slab are shaping, grinding, cladding, polishing, final figuring, metrology, and cleaning. Figure 4 shows pictures of full size equipment to be used for this process. The shaping operation is required to bring the optic to near final dimensions. The optic is then ground with a fixed-abrasive diamond wheel in a controlled manner to eliminate microcracks from the previous operation. Edge-cladding glass is then epoxied to the chemically treated laser slab with a special fixture in a two-step process. After the optic is ground to the final dimension, the optic is prepolished to remove any grinding-induced damage below the optic surface. The optic is then moved to a specially designed ring polisher to deterministically final-figure the optic for minimal transmitted wavefront distortion of the NIF laser beam. After the optic meets the NIF specifications, it is characterized in final metrology and before shipment to LLNL.

In May 1997, Zygo began construction of a 25,000-ft^2 facility to finish NIF amplifier slabs. This facility was

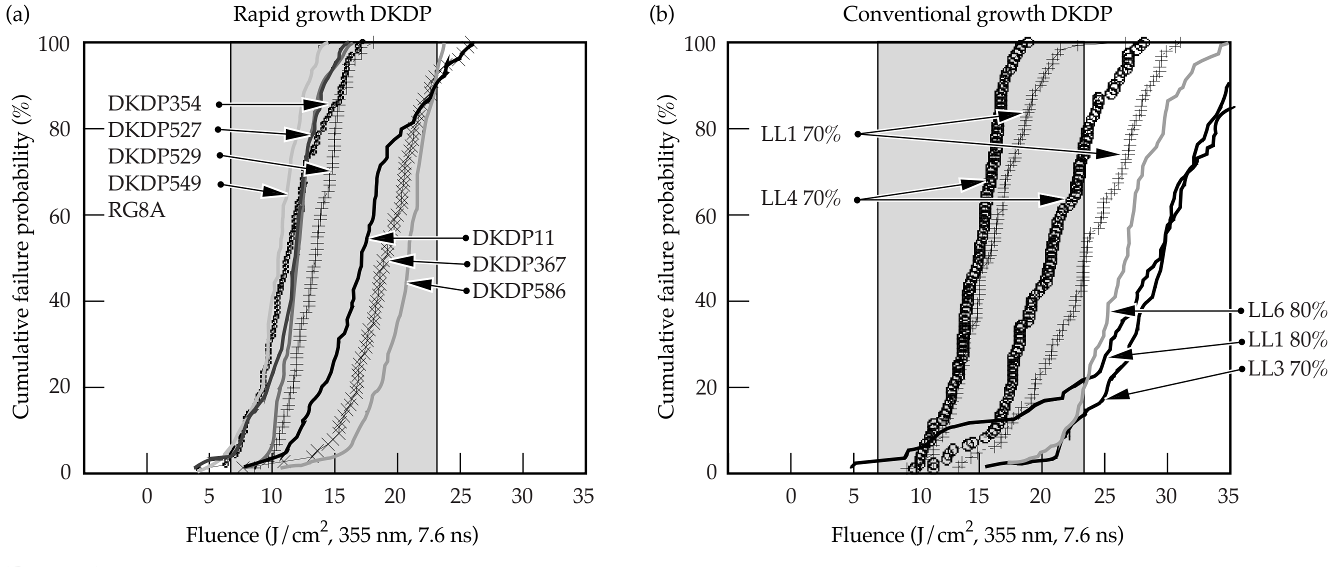
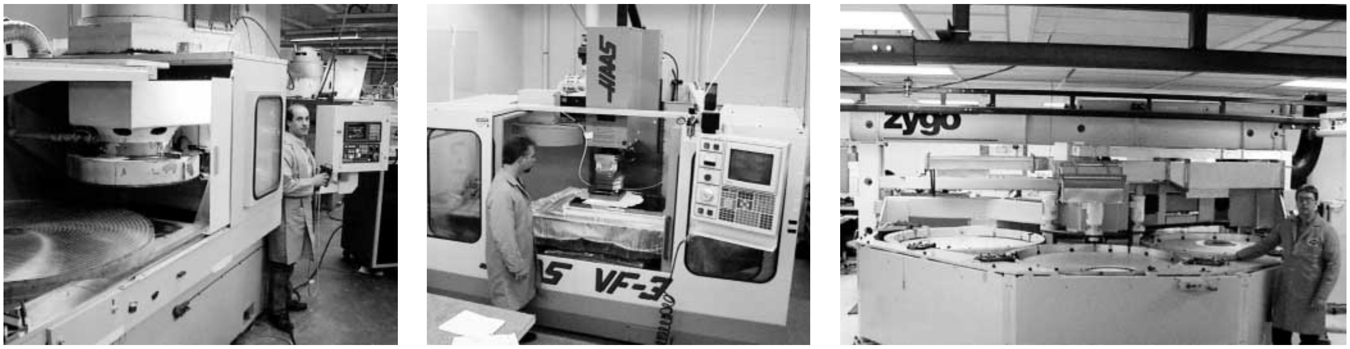
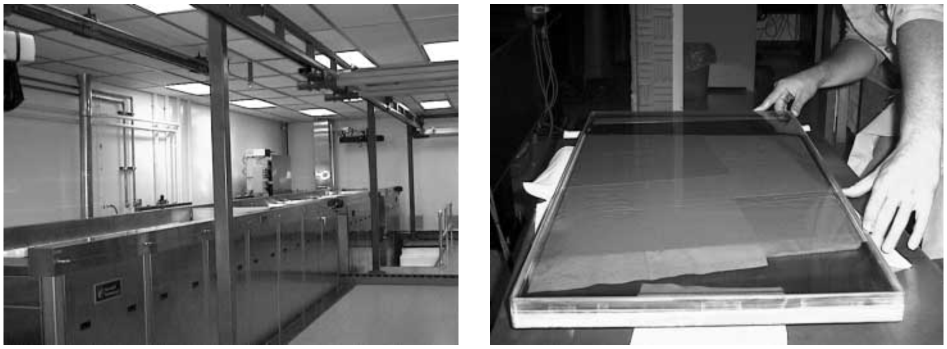


FIGURE 3. Bulk damage fluence distributions of various DKDP samples, both (a) rapidly and (b) conventionally grown. The best two rapid-growth DKDP samples meet the NIF specification, while most of the conventional-growth material meet the specification. (40-00-0299-0451pb01)



1. Grinding 2. Polishing 3. Final figuring



4. Cleaning 5. Cladding

FIGURE 4. The major process steps involved in the fabrication of an amplifier slab: shaping and grinding, polishing, final figuring, cleaning, and cladding. (40-00-0299-0475pb01)

designed around the manufacturing process that was demonstrated on subscale optics during their development program. In August 1998, the facility was sufficiently complete for a full-scale demonstration of the NIF finishing process on a laser slab. In each processing area, the equipment that would eventually be utilized in production of the approximately 3000 slabs was used to validate performance.

This effort was very successful. The optic was completed in a timely manner, and process areas requiring further refinements were identified with sufficient time for corrective action before beginning fabrication of pilot optics. This was also the first opportunity to start collecting machine and labor hours to begin validation of anticipated unit costs and factory capacity projections.

Fabrication of NIF-Size 3ω Focus Lens

Finishing development efforts, both at LLNL and at several vendors, have demonstrated there are several paths to obtaining fused silica optics with finished surfaces that meet the NIF 3ω average fluence requirement of 8 J/cm^2. For high-quality fused silica substrates, the damage performance of polished surfaces is largely controlled by subsurface damage in the optical material resulting from the grinding and polishing steps, and from contamination in the nominally 100-nm-thick polishing redeposition layer. Meeting the NIF laser-damage specifications requires a combination of careful attention to the classical techniques of grinding and polishing to control subsurface damage with an understanding of the role played by contaminants in the polish redeposition layer. Through collaboration with the vendors, several rules have been developed that help produce high-performance surfaces. The rules can be summarized in two main groups:

1. **Subsurface damage**. High-performance parts are created through multiple finishing steps, each using successively smaller grinding particles. The depth of material removed in each step should be about three times the maximum size of the polishing particles in the previous step. A wet chemical etch can be used to expose any remaining subsurface damage.
2. **Polishing contamination**. Polishing with cerium oxide, the most common polishing material for

precision surfaces, has been associated with a laser-induced pitting of the surface. The cerium-oxide–related damage can be prevented by either removing the contamination layer with a wet (or possibly an ion) etch or by careful polishing using a zirconium oxide slurry.

To quantify the laser-damage performance of the optics, new testing procedures have been developed at LLNL. A Large-Area 3ω Testing (LAT) facility measures the density of damage sites on the optic as a function of fluence. The measurements involve rastering a 1-mm-diameter Gaussian laser beam across greater than 100 cm^2 of the optic surface. Figure 5 shows the damage concentration as a function of fluence for lenses produced by two different vendors using different finishing processes. Both lenses meet the current NIF goal of 0.3 defects/cm^2 at 8 J/cm^2. Similar measurements on flat surfaces have also led to the qualification of several finishing vendors for debris-shield and diffractive-optic plate production.

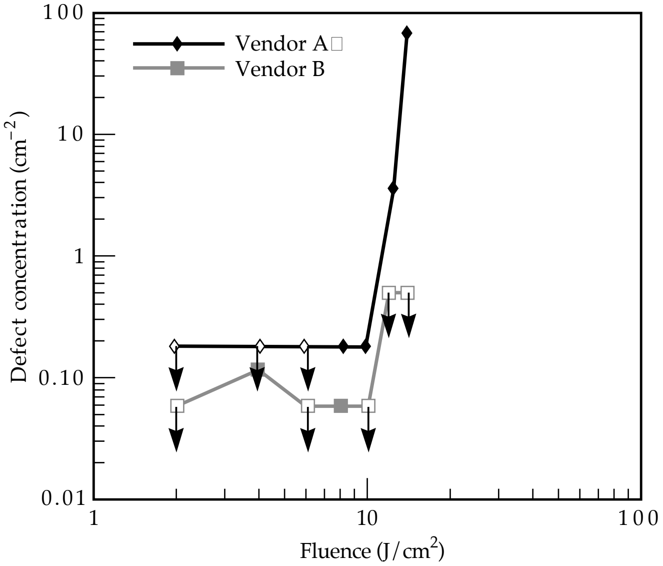


FIGURE 5. Damage concentration as a function of fluence for lenses produced by two different vendors using different finishing processes. Arrows indicate that the defect concentration was below the detection limit marked by the open symbols. (40-00-0299-0476pb01)

NIF-Size Beam Sampling Gratings, Color-Separation Gratings, and Kinoform Phase Plates

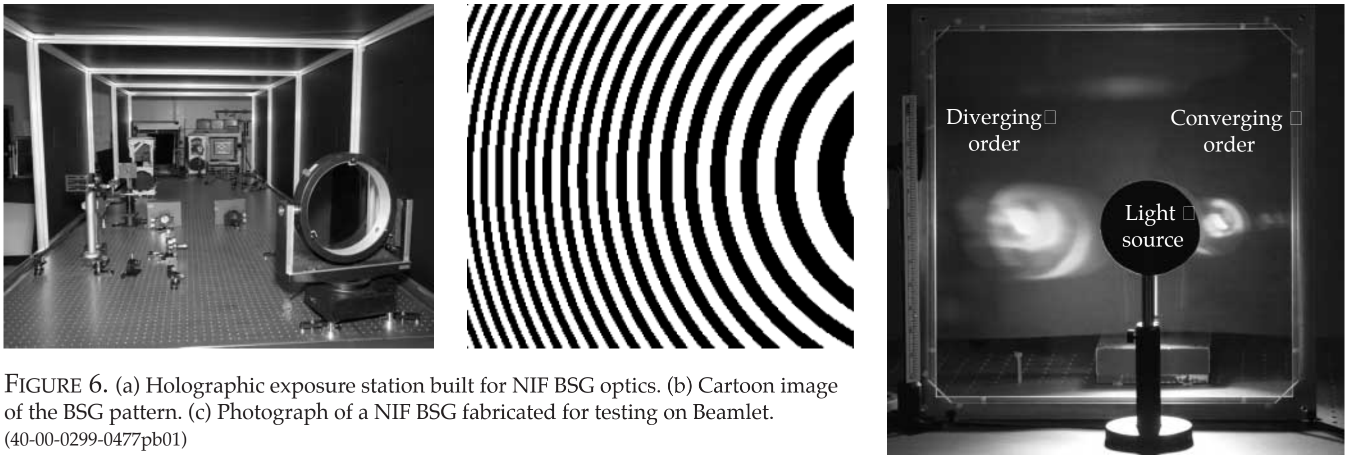
The NIF baseline laser design incorporates three diffractive structures in the third-harmonic (351-nm, or 3ω) final optics assembly:

1. A beam-sampling grating (BSG) with focusing power that sends a known small fraction (0.2 to 0.4%) of the transmitted light into a calorimeter for energy diagnostics.
2. A color-separation grating (CSG) that transmits with high efficiency the 3ω light to the target while redirecting the unconverted 1ω and 2ω light away from the target.
3. A kinoform phase plate (KPP) that smoothes the beam within a super-Gaussian envelope with a tailored spot size at the target plane.

These optics are nominally 40-cm-square at aperture, and to withstand the design fluence, the patterns comprising the diffractive structure must be etched into the bulk fused silica substrate. Wet chemical etching by a buffered hydrofluoric acid (HF) solution has been chosen as the pattern transfer method for several reasons: the low aspect ratio of these structures is conducive to this process; it is inherently spatially uniform due to the kinetic control of the dissolution; and it is inexpensive to implement.

The BSG is a lamellar grating with a nominal period varying from 1 to 3 μm and a modulation depth of approximately 20 nm. It is made holographically by projecting two interfering coherent spherical waves onto a photoresist-coated substrate in the appropriate geometry. One beam simulates the main beam going to target focus and the other the sampled beam focusing to a calorimeter. The latent image is developed to give a grating mask in resist. This pattern is transferred to the substrate surface by etching the exposed areas between the resist grating lines with HF solution. Figure 6 shows (a) the holographic exposure station built for NIF optics, (b) a cartoon image of the BSG pattern, and (c) a photograph of a NIF BSG fabricated for testing on Beamlet. Several NIF-size BSGs were fabricated in 1998 to allow metrology and full-aperture integrated damage testing on Beamlet.

The CSG is a stairstep grating design made by proximity-printing one line of the period through a chrome-on-quartz master mask onto a photoresist layer on the target substrate, developing this pattern and transfer etching with HF solution to a precise depth equal to one wave of optical phase difference in transmission at the use angle and wavelength. This process is repeated with the second line of the period by use of a mask offset laterally relative to the first line etched. The precision of this fabrication process is demonstrated in the white-light interferometer profile shown in Figure 7. To meet the NIF color-separation targets of less than 1% transmittance at 1ω and 2ω,

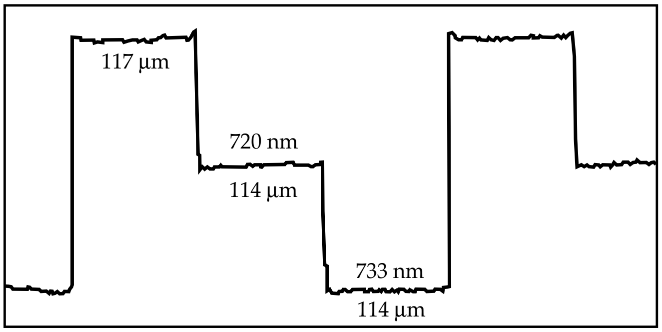


(a) Holographic exposure station

(b) BSG variable-focusing grating 1–3 µm period

(c) BSG with white light

FIGURE 6. (a) Holographic exposure station built for NIF BSG optics. (b) Cartoon image of the BSG pattern. (c) Photograph of a NIF BSG fabricated for testing on Beamlet. (40-00-0299-0477pb01)



Measured profile of CSG stairstep grating

FIGURE 7. 3ω CSG transmittance and 1ω and 2ω rejection are controlled by the etch-depth precision of the two steps. This white-light interferometer profile shows the precision of this fabrication process. (40-00-0299-0478pb01)

etch-depth precision and uniformity must be no worse than ±10 nm. Several full-aperture CSGs were fabricated with 3ω transmittance (uncoated) of 90%. The zeroth-order transmittance at 1ω and 2ω was generally less than 1%, enabling a tightening of the NIF CSG transmittance specification at these wavelengths by a factor of two.

The KPP is fabricated using a four-mask process similar to that used for the CSG. Transfer wet etching is used to produce 16 step levels approximating continuous, irregular topography on a several-millimeter-length scale, with maximum optical path difference of one wave. The KPP has been fabricated and reported on in the past for Nova and other laser systems. A NIF design was fabricated on a square, high-damage-threshold NIF diffractive optics plate in 1998 to allow integrated testing along with the BSG and CSG on Beamlet.

In late 1997, we identified a detrimental interaction between the stairstep CSG grating and the colloidal sol AR coating that has historically been used on fused-silica transmissive optics for high-fluence laser applications. When a dip-coated AR coating is applied to the CSG, the zeroth-order 3ω transmittance is reduced by about 1% rather than increased by 8% as would normally be expected. The loss is caused by nonconformal coating effects due to partial planarization of the etched structures by surface tension effects during postapplication drying of the coating. This nonconformal effect is readily apparent in scanning electron micrographs of bare and coated CSGs, shown in Figure 8.

A combination of experiment and modeling in FY 1998 showed that these surface-tension effects cannot be overcome for colloidal sol coatings by variations on dip coating, meniscus coating, or spin coating. The coating defects are detrimental not only because of decreased 3ω transmittance to the target but also because of increased modulation, which can damage downstream optical surfaces.

Because of the difficulty in fabricating an acceptable AR coating, the NIF CSG will likely have no AR coating over the actual grating surface. A new subaperture design has been proposed to minimize the impact of leaving the CSG uncoated by reducing the area that must be left uncoated. This design, which also improves management of unconverted stray light in the target chamber, requires the CSG grating only on the central 15% of the diffractive optics plate. This new grating is being fabricated in FY 1999 for evaluation as the new NIF baseline design.

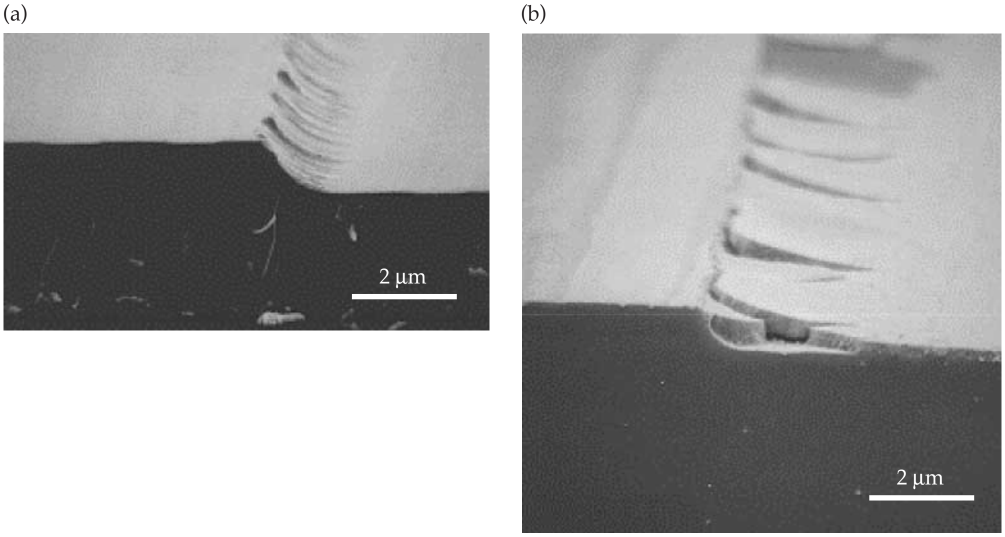


FIGURE 8. Scanning electron micrographs of (a) bare and (b) dip-coated CSG; the dip-coating process introduces a nonconformal effect during drying. (40-00-0299-0479pb01)

Coating the NIF-Size Polarizer Prototype

The coating development program has focused on three main specifications for polarizers: coating stress, spectral performance, and damage threshold. Development has concentrated on subscale witness plates until sufficient progress has been made for a full-aperture demonstration. In 1997, the emphasis was on improving the damage threshold by the elimination of the delamination of the outermost layer. This was realized by a redesign of the coating, which yielded a 2× improvement in the damage threshold. In 1998, the emphasis was on reducing coating stress in the operating environment.

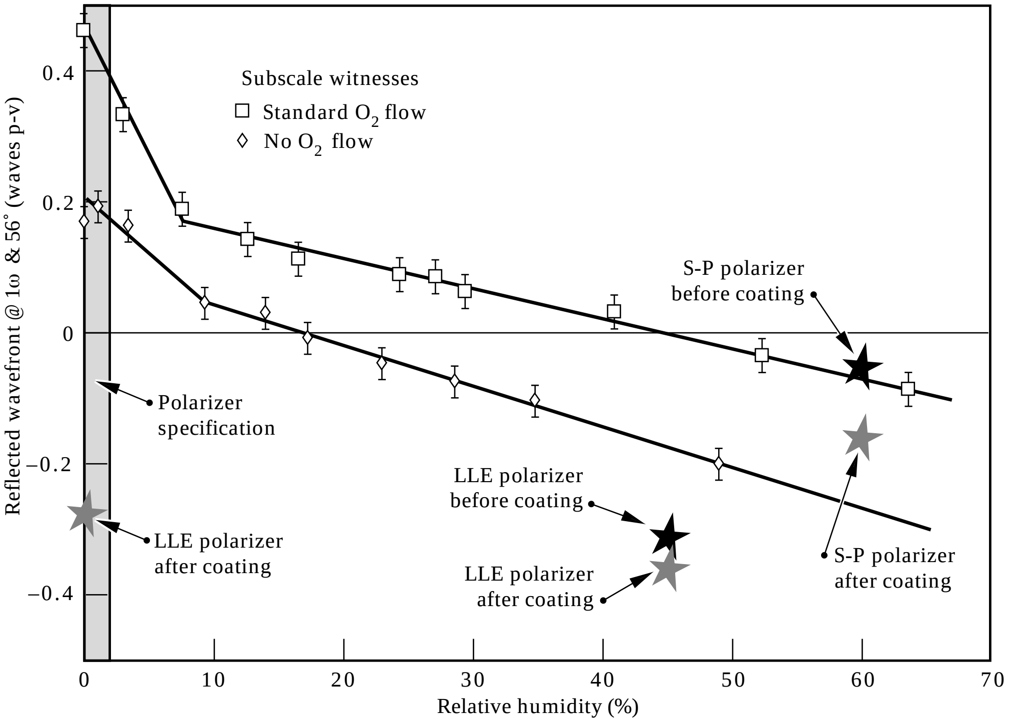
Previous coating-stress optimization was done for ambient humidity conditions (40 to 60% relative humidity). Under low-humidity conditions, coatings become tensile, which can result in crazing of the coating or noncompliance with the NIF specification. For NIF, the polarizer is located in a dry environment (i.e., less than 2% relative humidity). In an effort to make the coatings more compressive, the relationship between reflected wavefront (as influenced by coating stress) and oxygen partial pressure during silica deposition was determined (see Figure 9). As the oxygen partial pressure is reduced, the compressive stress is increased. The partial pressure of oxygen is limited by the evaporation of the material, and, in the case of subscale Spectra-Physics polarizers, yields coatings that meet the NIF specification but are still tensile.

Upon completion of this work, large-aperture polarizers were coated at LLE and Spectra-Physics. In each case, the coating was compressive in ambient condition. However, based on previous subscale measurements, the Spectra-Physics polarizer is expected to exhibit tensile stress in the operating environment, but the stress is well within the NIF specification for reflected wavefront distortion. Further work with subscale witness plates at the end of 1998 have demonstrated compressive coatings, even in 0% relative humidity, by additional process modification.

Of equal importance are the damage threshold and spectral performance. The damage threshold of subscale damage test witness plates was two times higher than the specification. The full-scale optic was raster-scanned on the Plato facility over the full aperture and met the NIF peak fluence requirement. Both vendors met the 97% “P” transmission and 99% “S” reflection goals, which are just below the NIF specification of 98% “P” transmission.

Finally, during this development phase, LLE had to replace its planetary in its 72-inch coating machine to accommodate NIF-size optics. A significant effort in masking development proceeded to meet the challenging specification of less than 1% thickness variation over the area of the coating. By developing software to simulate the depositional process and final manual mask trims, the specification was successfully met.

FIGURE 9. Coating stress can be tuned to meet reflected wavefront specifications in the operating environment. (40-00-0299-0480pb01)



Defining and Testing Full-Scale, Automated Optics Cleaning Procedures: the ICF Optics Processing Development Laboratory

The Optics Processing Development Laboratory (OPDL) was completed on November 19, 1998. The OPDL will be a world-class optics processing area that will clean optics to a precision-level, sol-gel coat optics, complete subassemblies of various optical components, measure the optical transmission and reflectance of various optics, and process amplifier blast shields. The construction activities included the demolition of approximately 8000 square feet of the former Nova Two-Beam area, construction of a 5,500-ft^2 Class 100 clean-room processing area, remodeling of approximately 2000 square feet of Class 10,000 clean-room transfer area, construction of two Class 100 gowning areas, and the installation of processing systems such as high-purity deionized water, exhaust, nitrogen, and vacuum. Reconfiguration of the space began in February, and beneficial occupancy of the facility occurred on November 19. Dome Construction was the contractor awarded this project. This project was completed on the proposed time schedule and within the estimated budget. Cleaning, coating, and measurement systems will be installed with process development starting in 1999. Phase II of the OPDL, remodeling of 3000 square feet of existing Class 100 clean-room space to create the KDP Processing Area, will begin in early 1999, with beneficial occupancy expected in June 1999.

The NIF large optics will require four different cleaning and coating process sequences. The amplifiers, dielectric coated mirrors and polarizers will require precision cleaning. The fused silica windows and lenses and the KDP/DKDP crystals will require precision cleaning prior to application of colloidal sol AR coating. With the exception of the KDP/DKDP crystals, all of these optics can be cleaned using environmentally friendly aqueous processes. Two automated aqueous cleaning systems each consisting of a 40/70/104-KHz ultrasonic process bath, two cleaning solution reservoirs, a manual preclean station, and an automated two-axis transport system were designed and fabricated at JST Manufacturing, Inc., in Boise, Idaho. Under normal circumstances, one system will be dedicated to cleaning fused silica and dielectric coated mirrors and polarizers using elevated temperature processes, and the other system will be dedicated to cleaning amplifier slabs at room temperature. The systems are equipped with point-of-use deionized water heaters to supply the elevated temperature for the mirrors, polarizers, and fused silica processes and with chilled water to maintain the 20 to 30°C process temperature required to avoid thermally shocking the amplifier slabs. Because the systems are mechanically identical, either can substitute or supplement the other should the need arise.

The fused silica optics will be AR-coated using a custom dip coater designed by Chemat Technology, Inc., of Northridge, California. Design improvements for the NIF dip coater include a totally enclosed coating environment for improved ES&H and a precision low-velocity gradient ball-screw drive for improved precision, repeatability, and smooth motion. Completion of the fabrication and commissioning of this system is expected in the first half of FY 1999.

The KDP/DKDP crystals are the optics most sensitive to environment and contamination. If not properly cleaned and stored, their surfaces will develop surface roughness, which results in unacceptable scatter. They must be cleaned in nonreactive solvents such as toluene, xylene, and secondary butanol. Two identical automated, nonaqueous cleaning systems were designed for precision cleaning: one system will be placed at the finishing vendor, the other at LLNL. The nonaqueous cleaning systems are being fabricated at Forward Technologies, Inc., in Minneapolis, Minnesota. The nonaqueous cleaning systems each consist of two 70/104-KHz ultrasonic cleaning baths with overhead spray rinses in a tightly controlled, saturated environment to maintain minimum fluctuations in crystal surface temperature during submersion in the baths, rinsing with clean solvent spray, and sheeting/drying.

The KDP/DKDP crystals will be AR coated using a commercial "covered chuck" spin coater designed and built by Karl Suss America, Inc., in Waterbury Center, Vermont. The spin coater have been installed at LLNL, and coating uniformity and repeatability exceeding the design specification of ±5% have been demonstrated on 41-cm glass substrates. The first KDP crystal was coated in September and met NIF surface reflection specifications.

Preparation of Full-Size NIF Prototype Laser-Glass Melter for Main Pilot Production

As discussed in "NIF-Size Laser Glass Continuous Melt" earlier in this section, the Schott development campaign was largely successful in producing NIF-size laser glass using continuous-melting technology. Analysis of these results showed that only minor modifications were needed to improve the performance of some of the melter units to meet NIF requirements. In addition to improving the performance of the melter, these modifications should also increase the melter lifetime, thereby further improving the overall process yield.

Pilot Production of Rapid-Growth KDP at LLNL

The middle of year marked the transition from development to pilot production. Eight 1000-liter crystallizers with constant filtration were brought into operation, six at LLNL and one each at two potential vendors: Cleveland Crystals, Inc., and Inrad. The vendor systems were first built at LLNL in cooperation with vendor personnel. In addition, a 1000-liter crystallizer system was built and operated by personnel from the Commissariat a l'Energie Atomique (CEA) and its vendor.

Substantial progress was made in the early stages of pilot production to understand the conditions needed to minimize inclusion formation during growth, and thereby improve the yield of usable plates. One factor was the introduction of hydrodynamic, anodized-aluminum platforms, which enabled faster rotation rates to improve mass transfer. In addition, the faster growth rates reduce the contribution of impurities from dissolution of the glass tank in which the boule is grown. A simple leaching and incorporation model was constructed to help estimate impurity concentrations during a run, with the objective of helping to make process control decisions.

Near the end of 1998, two pilot boules reached NIF-size: one was a boule of DKDP about 52 cm square by 49 cm high that will yield about 15 tripler blanks, and the other was a 43-cm-square by 48-cm-high boule of KDP suitable for about 25 Pockels cells. The tripler boule is shown in Figure 10.

Pilot-Production Contract of NIF Amplifier Slab Finishing Awarded

A pilot production contract was awarded in May to Zygo to manufacture NIF amplifier slabs and transport mirrors. The award of this contract was contingent on the completion of the facility and delivery of the majority of the optics fabrication equipment. The critical positions were filled in 1998, as planned.

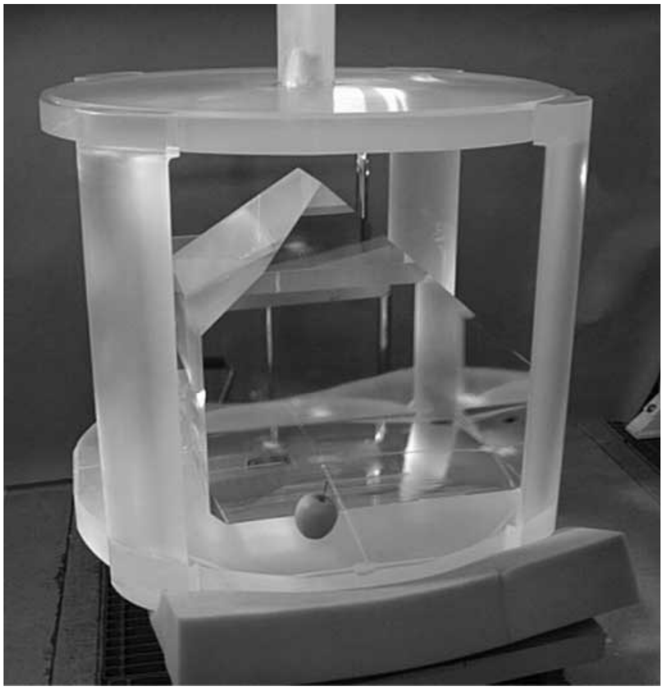


FIGURE 10. The first DKDP boule from pilot production. It measured approximately 52 cm square by 49 cm high. Because of a favorable asymmetry with respect to the angle at which the triplers are cut from the boule, about 15 tripler blanks can be obtained. (40-00-0299-0450pb01)

Pilot-Production Contract of NIF Fused Silica Awarded

Corning completed a development program in FY 1998 aimed at reducing the cost of lens and windows blanks by about two times. The effort combined significant improvements in efficiencies of Corning's proprietary forming process with less complex modifications to blank fabrication, specification, and metrology. Improved interferometry precision was obtained at full NIF aperture by replacing oil-on-flat measurements done in the past with PHOM (polished homogeneity) interferometry on the boule. LLNL provided equipment to allow grinding and polishing of full-sized boules, which is being used in combination with a new 24-inch-aperture Zygo interferometer provided by Corning (see Figure 11). After demonstrating that long-spatial-period index irregularity in the blank is easily corrected by small tool figuring at lens-finishing vendors,[1] the NIF lens-blank specification for inhomogeneity was modified to further reduce total optics cost. The new specification focuses on index gradients while relaxing the amount of long spatial period irregularity acceptable for lens blanks. A change was made from near-net-size ground blanks to rougher sawcut blanks to take advantage of high-speed shaping technologies being implemented at NIF finishing vendors.

Excellent results from the development program enabled an acceleration of the NIF pilot that takes advantage of the current slump in world-wide demand for high-quality, synthetic fused silica. Installation of all new NIF equipment was completed and pilot production begun in late 1998. The new NIF process cell has been debugged; training of dedicated NIF personnel is complete; and fabrication of NIF fused-silica blanks is now in steady production.

Notes and References

1. Parham et al., "Developing Optics Finishing Technologies for the National Ignition Facility," *ICF Quarterly Report*, **9**(2), in press, Lawrence Livermore National Laboratory, Livermore, CA (1999).

Boule ground and polished for PHOM interferometry

Final metrology on a 24″ Zygo interferometer (provided by Corning)

Boule sawed into blocks, then into blanks

Blanks ground to final size on Blanchard (from Oak Ridge)

FIGURE 11. Corning has provided glass forming and interferometry to support the NIF. LLNL supplied most of the sawing, grinding, and polishing equipment. (40-00-0299-0481pb01)

7.0 ADVANCED DRIVER DEVELOPMENT

The inertial confinement fusion (ICF) technology being developed at LLNL has strong spin-off value to an inertial fusion energy (IFE) program. Such a program must develop (1) high gain for both indirect and direct drive as addressed by the National Ignition Facility (NIF), (2) suitable long-level efficient drivers, and (3) economically and environmentally attractive target chambers. In other words, fusion power must be real (it must work), clean, and cheap.

During FY98, the ICF Program addressed two candidate IFE drivers—diode-pumped, solid-state lasers and heavy ions under LDRD and Office of Fusion Energy Sciences support, respectively. These two driver candidates are targeted at direct drive and indirect drive, respectively. Multiyear development programs have been prepared in both cases, as well as a target chamber development program. These plans were developed for presentation to the Office of Fusion Energy Sciences, which may establish a strengthened IFE Program in future years, depending in part on the results from NIF.

100-J "Mercury" Diode-Pumped, Solid-State Laser System

We have continued our campaign to develop the technical basis for the next generation of fusion lasers, having higher efficiency and repetition rate than flashlamp-pumped Nd:glass laser technology, which is currently serving to demonstrate fusion ignition and gain in the NIF. The Mercury laser, which is the first of this new generation of drivers, is designed to provide 100 J of energy in nanosecond pulses at 10 Hz with 10% efficiency. The critical technologies of Mercury are efficient diode-array pumps (instead of flashlamps), Yb:S-FAP crystals (replacing Nd:glass), and rep-rated laser amplifier heads cooled by turbulent He gas flow. This type of diode-pumped, solid-state laser is thought to be scalable to megajoule energy levels and megawatt average powers, and is believed suitable as a driver in laser fusion power plants.

Figure 1 contains a sketch of the design of the Mercury laser, as well as pictures of the laser diode-array backplane (with four mounted laser-diode "tiles") and the gas-cooled amplifier head.

During 1998, we have made significant progress in the design and deployment of the Mercury laser in the areas of modeling, facility, controls, the gas-cooled amplifier head, laser-diode arrays, and crystal growth. Areas of progress are summarized in the Table 1 on the next page.

It is anticipated that the Mercury laser will operate in FY00. In subsequent years, we envision it could be used as a rep-rated target shooter with applications to both Defense Programs and IFE.

Systems Analysis on Advanced Driver Candidates for High-Yield Facility

Integrated LASNEX Calculations of a Heavy-Ion Driven, High-Yield Target with Realistic Beam Geometry

Ion accelerators are well suited to energy production because they have the long lifetimes (~30 years), high repetition rates (~10 Hz), and high efficiencies (~25 to 35%) needed for a reactor. In addition, focusing is done by magnetic fields, so there is no final optic in the beam path. Because accelerators are efficient, target gains as low as 30 to 40 are acceptable, and thus indirect-drive targets can produce more than adequate gain for IFE; a heavy-ion driver could also serve as a high-yield facility for DOE Defense Programs applications following NIF. We now have several variations on

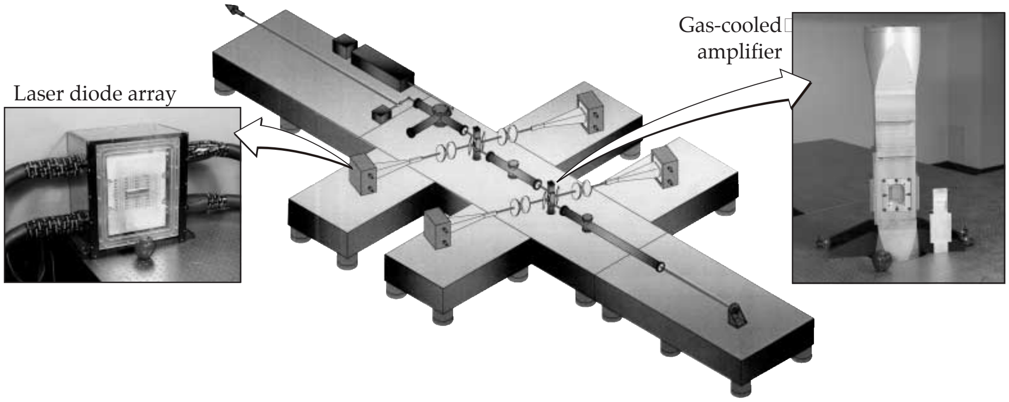


FIGURE 1. Photograph of laser-diode array backplane with four mounted "tiles," the gas-cooled head, and a schematic design of the laser system.
(70-00--0497-0721Jpb01)

TABLE 1. Summary of progress in the Mercury Laser Project.

Technology area	Progress
Modeling	1D propagation calculated with measured wavefront input Optical ghosts analyzed Thermal induced optical distortions modeled Pump delivery optics designed and ordered
Facility	Laser room with clean hoods and temperature control completed Gas blower, diode chiller, optical tables, and interlocks installed
Controls	Power supplies and diode pulsers purchased and tested Software written and testing begun
Gas-cooled amplifier	Head and flow vanes designed, fabricated, and installed Flow tests begun and found to be positive
Laser diode arrays	Backplane cooler completed Diode vendor qualified and 2000 bars ordered 20 BeO heatsinks completed out of a total of 160
Crystal growth	Second crystal-growth furnace activated Automatic SrF_2 feeder installed to eliminate crystal "smoke" and testing begun 4-cm-diam crack-free crystals produced with minimal defects Small samples without grain boundaries grown Diffusion bonding of crystals demonstrated to produce optical elements of larger size

the distributed-radiator, heavy-ion target that produce enough gain for both of these uses. In addition to expanding the parameter space for this type of target, these LASNEX[1] calculations show the flexibility of the target.

In the distributed radiator target,[2–4] most of the cylindrical hohlraum is filled with low-density converter material. The ions stop in these converters and generate x rays, which implode the capsule. The targets described here use beams with a Gaussian distribution. In addition, the number of beams and the angles that the beams make with the axis are consistent with an accelerator designed by a systems code.[5] To minimize the amount of wasted energy, each Gaussian beam was focused to an ellipse, and the ellipses were then overlaid to form an annulus on the end of the hohlraum. The target was driven by a total of 5.9 MJ of beam energy and produced 390 MJ of yield in an integrated calculation (beam deposition to fusion burn in the same calculation) for a gain of 66.

Because accelerators are efficient, target gains as low as 30 may be acceptable for a heavy-ion fusion power plant. Getting higher gain by decreasing the beam energy required may be desirable, however, because the cost of the driver increases with the beam energy. We have therefore designed a close-coupled version of the distributed radiator target that uses a smaller hohlraum while driving the same capsule. This target has produced gain of 132 from 3.3 MJ of beam energy in 2D, integrated LASNEX calculations. The impact of the close-coupled target on the integrated system of accelerator, final focus, and chamber transport will be evaluated in the future.

One of the goals of the IFE Program is to construct an Engineering Test Facility (ETF) that demonstrates all the physics and technology needed for an IFE power plant. A scaled version of the close-coupled target using 1.5 to 2 MJ of beam energy might be the basis for an attractive ETF. 2D, integrated LASNEX calculations predict a gain of 94 from 1.75 MJ of beam energy.

Notes and References

1. G. B. Zimmerman and W. L. Kruer, *Comments on Plasma Physics and Controlled Fusion* **2**, 51 (1975).
2. M. Tabak, D. Callahan–Miller, D. D.-M. Ho, and G. B. Zimmerman *Nuc. Fusion* **38,** 509 (1998).
3. M. Tabak and D. Callahan–Miller, *Phys. Plasmas* **5**, 1896 (1998).
4. M. Tabak and D. Callahan–Miller, submitted to *Nuc. Fusion*, 1998.
5. W. R. Meier, R. O. Bangerter, and A. Faltens, *Nuc. Instruments and Methods in Phys. Research A* **415**, 249 (1998).

Comparison of Linac and Recirculator Induction-Accelerator Concepts for Use in Heavy-Ion-Driven, High-Yield, Post-NIF Capsules

A recent 2D, integrated target design for a heavy-ion driver has again raised the issue of the cost of a recirculator compared to a conventional linac design. We have completed a preliminary comparison of the cost of two heavy-ion-driver architectures. We compared a standard multibeam linac against a driver that replaces the high-energy portion of the system with a ring/recirculator that gives the same final ion energy, and found that the recirculator option provides significant cost savings, but not as great as previous comparisons.

We compared the two driver architectures illustrated in Figure 2. The standard linac has a multibeam injector feeding an array of electrostatic quads at the low energy. When they reach a certain energy, the beams are merged four-to-one and are thereafter transported by magnetic focusing. A final transport section redirects the beams for two-sided illumination and provides the length needed for pulse compression. The final focus design consists of four quads per beam, which first expand the beam and then focus it on target. Linac-design parameters and costs were determined using the source-to-target systems model that Meier has developed in conjunction with Lawrence Berkeley National Laboratory (LBNL).[1]

The linac/ring combination architecture simply replaces a portion of the linac with a recirculator ring. In this way, the front end, final transport, and final focusing designs and costs are the same as for the linac case. The recirculator-ring design and costs are

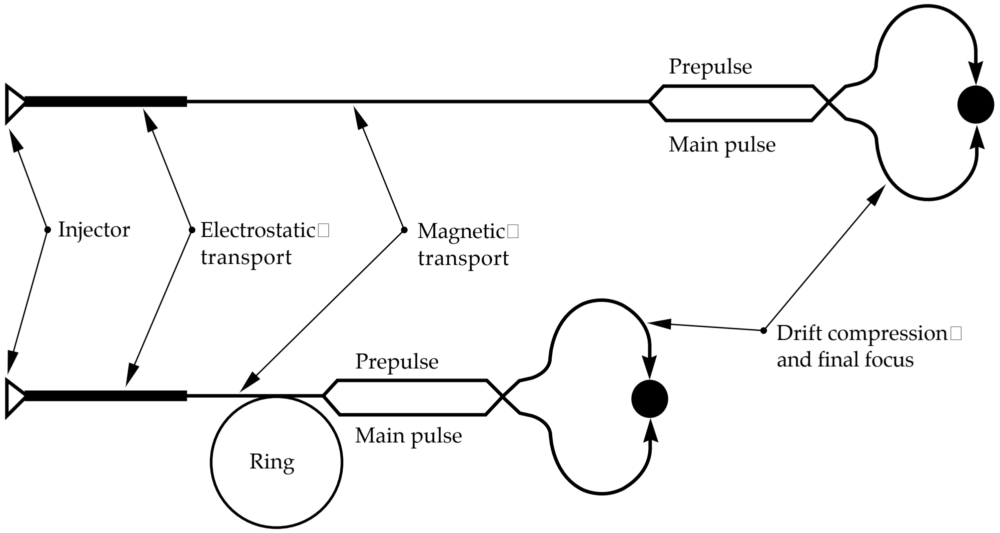


FIGURE 2. Schematic (not to scale) of two driver architectures: a standard linac and a linac/recirculator combination in which a portion of the linac is replaced by a single ring. (70-00-0299-0290pb02)

from a model developed by Barnard based largely on algorithms from the "black-book" study,[2] with costing algorithms developed in this study. We also modified the black-book recirculator design to reduce technical risk.

The need for many beams (to produce a ring of spots on the ends of the target) is harder to accommodate with a ring because the quads cannot be packed as tightly as in the linac. Also, although it appears feasible to design a ring with a large number of beams sharing common cores, the details of interweaving beams to assure equal path lengths and to allow beam insertion and extraction have not been worked out. And finally, although the low-energy transport section of the linac design could be replaced by a low- and medium-energy ring, as in the black-book study, our initial impression is that this option will not provide large cost savings.

The results of our comparisons are summarized in Tables 2 and 3. In the first comparison, the drivers were designed to meet the requirements of the Tabak/Callahan–Miller integrated heavy-ion fusion (HIF) target design.[3–5] For the driver section from 0.3 to 3.0 GeV, the recirculator option results in a 36% cost reduction; for the entire driver, the savings is 17%.

The requirements of this target are significantly different from and more challenging than previous designs. The target requires a total of ~5.9 MJ delivered with ions of two different energies (3.0 and 4.0 GeV). The reference-case design (Figure 3) uses two-sided illumination, with the beams illuminating a washer-shaped ring on each side of a cylindrical hohlraum.

TABLE 2. Cost comparison for drivers for distributed radiator target. Linac/recirculator combination has single, multibeam ring from 0.3 to 3 GeV. E = 5.9 MJ (1.6 MJ prepulse at 3 GeV, 4.3 MJ main pulse at 4 GeV), A = 200 amu ions.

	Standard linac ($B)	**Linac/recirculator combination ($B)**	**Cost ratio = (combo/linac)**
High-energy section (0.3–3.0 GeV)	0.42	0.27	0.64
Hardware subtotal[a]	0.89	0.74	0.83
Total direct cost[b]	1.30	1.08	0.83

[a] Includes front end (injector plus electrostatic transport from 2 to 100 MeV), magnetic transport from 100 to 300 MeV, high-energy section, final-transport/pulse-compression section, and final-focus magnets.
[b] Equals 1.46 times Hardware Subtotal to account for Instrumentation and Controls (12.3% of subtotal) plus Installation and Assembly (23% of subtotal plus I&C).

TABLE 3. Cost comparison for drivers for a hypothetical 10-GeV target. Linac/recirculator combo has single multibeam ring from 1 to 10 GeV. E = 5.9 MJ, A = 200 amu ions.

	Standard linac ($M)	**Linac/recirculator combination ($M)**	**Cost ratio = (combo/linac)**
High-energy section (1.0–10.0 GeV)	0.62	0.30	0.48
Hardware subtotal[a]	0.99	0.67	0.67
Total direct cost[b]	1.44	0.97	0.67

[a] Includes front end (injector plus electrostatic transport from 2 to 400 MeV), magnetic transport from 400 to 1000 MeV, high-energy section, final-transport/pulse-compression section, and final-focus magnets.
[b] Equals 1.46 times Hardware Subtotal to account for Instrumentation and Controls (12.3% of subtotal) plus Installation and Assembly (23% of subtotal plus I&C).

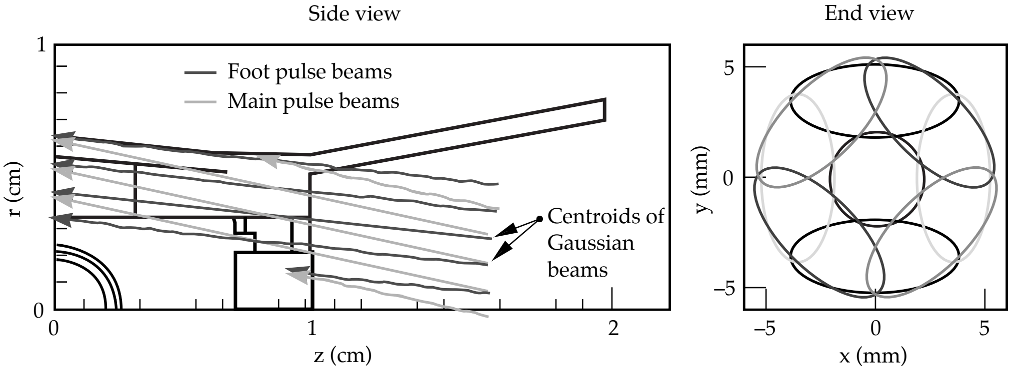


FIGURE 3. Distributed radiator target. (a) Side view shows incident prepulse and main pulse beams. (b) End view shows how beam spots illuminate a washer-shaped ring (only six of 24 beams are shown for clarity). (70-00-0299-0291pb02)

A second comparison was made for drivers that delivered 5.9 MJ with a single ion energy of 10 GeV. This hypothetical case (we do not currently have a 10-GeV target design) illustrates the impact of target requirements on driver design and the resulting costs. For the high-energy section (1.0 to 10 GeV in this case), the recirculator cost is 52% lower, and for the entire driver the recirculator saves 33%—much higher savings than for the Tabak/Callahan–Miller target design.

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2. J. J. Barnard et al., *Study of Recirculating Induction Accelerators as Drivers for Heavy Ion Fusion,* Lawrence Livermore National Laboratory, Livermore, CA, UCRL-LR-108095 (1991).
3. M. Tabak, D. A. Callahan–Miller, D. D.-M. Ho, and G. B. Zimmerman, *Nuc. Fusion* **38,** 509 (1998).
4. M. Tabak and D. A. Callahan–Miller, *Phys. Plasmas* **5**, 1896 (1998).
5. M. Tabak and D. A. Callahan–Miller, *Nuc. Instrum. Methods Phys. Res., Section A* **415**, 75 (1998).

8.0 SCIENCE USE OF NOVA

The Science Use of Nova Program is intended to make unique LLNL Nova facilities available to the larger scientific community for high-energy-density science investigations; 1998 was the third year that this program has been in place. As in the previous years, a call for proposals for Nova use was sent to experts in the field of laser–matter interaction and high-energy-density physics, primarily to faculty at U.S. universities and to the membership of the Division of Plasma Physics of the American Physical Society. We received 20 proposals covering a diverse range of topics in high-energy-density science, including astrophysics, hydrodynamics, material science, and atomic physics. The proposals were reviewed and ranked by an external advisory committee made up of senior scientists from outside laboratories and universities. During FY 1998, approximately 10% of all Nova shots supported these experiments. This section discusses some highlights of this Program. Table 1 lists the 1998 proposals.

TABLE 1. Proposals for the CY 1998 Science Use of Nova Program.

Proposal title	University/Institution
Supernova Hydrodynamics on Nova	Univ. of Arizona, LLNL
Laboratory Simulation of Strong Shock Hydrodynamics in Supernova Remnants	Univ. of Colorado, Univ. of Michigan, N. Carolina State Univ., Rice Univ., LLNL
Nonlinear Richtmyer–Meshkov Experiments in a Divergent Geometry on Nova	SUNY-Stony Brook, Princeton Univ., LANL, LLNL
Study of the Saturation of Stimulated Raman Scattering by Secondary Decays in Large-Scale Plasmas	UCLA, LLNL
In-Situ X-Ray Diffraction from Hohlraum-Driven Shock Waves in Solids	UCSD, Cal Tech, Univ. of Oxford, LLNL, LANL, Physics International
Transforming the Insulating Molecular Phase of Hydrogen into an Atomic Metal with Nova	Cornell Univ., Univ. of British Columbia, LLNL
Effect of Non-Maxwellian Electron Velocity Distribution on Parametric Instabilities and Electron Heat Transport	UC Davis, LLNL
Radiative Jet Experiment for Nova	Univ. of Maryland, Univ., of Illinois, Univ. of Alabama, LLNL
Absorption Spectroscopy of Strongly Coupled Plasmas*	Univ. of Nevada/Univ. of British Columbia, LLNL

*A proposal approved in 1997 but delayed till 1998 due to target fabrication difficulties

LLNL and University of Arizona scientists continued experiments using the Nova laser at LLNL to answer specific questions about hydrodynamic instabilities, in particular the Rayleigh–Taylor (RT) instability, relevant to the evolution of core-collapse supernovae (SN). In particular, the high velocities of core elements nickel, cobalt, and iron in SN1987A are still unexplained (3000 km/s observed, versus predictions of about half that) and may have a bearing on the observed light curve. The group is conducting experiments on the Nova laser to test the hydrodynamics of the supernova code PROMETHEUS. Initial 2D experiments have been successfully completed. The scaling is described in a theoretical paper addressing the validity and limitations of laser-based laboratory experiments for supernovae.[1] The result of the scale transformation is that accelerations of 10^{10} g_o from the laser experiment correlate to 10 g_o for the SN, lengths of 100 μm correspond to 10^{12} cm, and times of 10 ns scale to 10^3 s. The group is now turning to the crucial question of how the instability evolution in 3D differs from that predicted in 2D. The 3D star calculations are still beyond current computational capabilities, but this dimensionality could hold the key to unlocking answers to some of the remaining questions surrounding SN1987A. If the velocities of RT spikes in 3D are significantly larger than 2D predictions, they could enhance mixing in the exploding star and help explain the observed light curve from SN1987A. Furthermore, any progress in advancing our understanding of the time-dependent mixing could shed light on the mechanism by which supernovae explode. Initial experiments are under way to compare RT-induced mixing in 3D versus 2D in a similar hydrodynamic setting.

In a collaboration with the University of Colorado and the University of Michigan, experiments are being conducted on the Nova laser to benchmark astrophysical codes used to model the radiation hydrodynamics of supernova remnant (SNR) evolution. Of particular interest is the supernova remnant now developing around SN1987A. The ejecta from this supernova are expected to collide with its circumstellar ring nebula within five years. The astrophysics codes being used to predict the outcome of this extragalactic collision are being tested using experiments on the Nova laser. Initial experiments were conducted in 1D to observe ejecta plasma flowing into a low-density ambient plasma, forming a classic forward shock–reverse shock system similar to that in the astrophysical SNR. Predicted shock-induced 2D effects are described in a recent paper.[2] The group is now planning 2D experiments to study the predicted shock-induced effects and the RT instability expected to occur at the contact discontinuity between the forward and reverse shocks. Such RT-induced clumping could change the nature of the much-awaited collision from a smooth, 1D, sweeping-up of the ring to something like “hydrodynamic bullets” striking it in radiative bursts or “sparkles.”

Another proposal is focused on astrophysical jets. Although Herbig–Haro (HH) jets, such as the well known HH47, have emerged as galactic laboratories for the study of radiation hydrodynamics, it is desirable to produce similar radiative jets in the laboratory, where the underlying physics can be diagnosed in more detail. University of Maryland researchers are collaborating with LLNL to develop experiments to test the radiation hydrodynamics code ZEUS. In the first of these experiments, five of Nova’s beams will directly drive the interior of an iron cone. The ablated iron will then coalesce to form a jet. From initial numerical simulations, the effects of radiation on the hydrodynamics of the jet are significant. The jet temperature is initially very hot (electron temperature ~1900 eV) but quickly cools through radiative losses, which results in further collapse of the jet on axis. Without radiation effects included in the simulations, the jet erroneously appears to remain hot much longer, and its shape appears to be more diffuse, than in a fully radiative simulation. The Nova-produced radiative jet will be diagnosed with 2D, time-resolved imaging of the jet’s self-emission as well as backlit images of the jet. Thomson scattering will also be used to determine the densities and temperature of the jet. This data will be valuable for benchmarking radiation hydrodynamics codes.

In FY 1998, researchers from LLNL, the University of California at San Diego, the University of Oxford, and Los Alamos National Laboratory investigated the shock response of crystals under extreme conditions. In this work, single crystals of silicon are shock-compressed at pressures of up to 500 kbar using a hohlraum x-ray drive on the Nova laser. A time-resolved x-ray diffraction signal is used to characterize the lattice structure as the shock propagates through the material. These experiments are designed to study the transition of a material from elastic to fully plastic compression at these high pressures.[3] The results of these experiments may be compared with detailed molecular-dynamics codes that are used to predict the lattice response to shocks. To make this comparison, the collaboration has started to focus on face-centered cubic materials that can be more easily modeled.

Another Science Use of Nova campaign, led by researchers from the University of California at Los Angeles, investigated secondary decay mechanisms that may limit the laser reflectivity produced by stimulated Raman scattering (SRS). The Langmuir wave produced by SRS may decay and have its amplitude limited by the production of secondary waves, through at least two possible mechanisms.[4] These processes create an ion acoustic wave as one decay product and have either an electromagnetic wave or secondary Langmuir wave as the other decay product. The matching condition of the wave number (**k**) for the resonant decay insures that the ion wave produced by Langmuir decay instability has nearly double the magnitude of **k** produced by electromagnetic decay instability. The Nova experiments measure the amplitudes of ion waves with various **k** vectors, using Thomson scattering from an ultraviolet (fourth-harmonic) probe beam and a detector at a resonant angle. This process will allow researchers to determine the relative importance of the two different SRS saturation mechanisms from the abundance of their respective ion waves. Experiments to date have demonstrated our ability to detect ion waves by detecting the scattered spectrum from waves produced by stimulated Brillouin scattering (SBS) from a drive beam. These ion waves show the expected red shift for the SBS process and are observed only in the presence of a drive beam at the appropriate angle to **k**-match the scattered probe energy. This work is the first observation of SBS ion waves in Nova's ignition-like plasmas, and it is leading to a separate series of experiments to investigate the location at which SBS occurs. Future experiments will investigate the SRS decay products in these plasmas.

Notes and References

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3. D. H. Kalantar et al., *Rev. Sci. Instrum.* **70**, 629 (1999).
4. R. K. Kirkwood, C. Joshi, et al., *Phys. Rev. Lett.*, to be published.

APPENDIX A

1998 AWARDS, PATENTS, AND REFEREED PUBLICATIONS

1998 ICF/NIF Program Awards

American Physical Society Fellows

Luiz Da Silva (1998)

Guy Dimonte (1998)

Gail Glendinning (1998)

Institute of Electrical and Electronic Engineers Fellows

James Candy (1998)

Robert Deri (1998)

Fusion Power Associates Excellence in Fusion Engineering Award

Stephen Payne (1998)

APS Award for Excellence in Plasma Physics Research

Gilbert Collins (1998)

Luiz Da Silva (1998)

Peter Celliers (1998)

Robert Cauble (1998)

DOE Weapons Program Award of Excellence

Christina Back, Joe Bauer, Kim Budil, Bob Cauble, Anthony Demiris, David Farley, Dennis Johnson, Jeffrey Koch, Larry Logory, Heley Louis, Mike McClure, Paul Miller, Juan Moreno, Stephen Murray, Joseph Nilsen, Ted Perry, Tom Peyser, Phil Ramsey, Jack Reynolds, Don Smith, Peter Stry, Alan Wan, Richard Ward (1998)

Kim Budil, Bob Cauble, Peter Celliers, Gilbert Collins, Luiz Da Silva, Mark Ford, David Gold, Steve Weber, Marvin Ross (1998)

Federal Laboratory Consortium Award for "Excellence In Technology Transfer"

Luiz Da Silva, Dennis Matthews, Peter Celliers, Duncan Maitland, Richard London, Abraham Lee, Peter Krulevitch, William Bennett, and Patrick Fitch (1998)

Stephen Vernon (1998)

1998 R&D 100 Awards

Lasershot Peening System—Lloyd Hackel, C. Brent Dane, Steven Telford, Jasmes Wintemute, William Manning, Balbir Bhachu and James Daly, James Harrison (Metal Improvement Co. Inc.)

Optical Ultra-High Resolution Dental Imaging System—Bill Colston Jr., Matthew Everett, Luiz Da Silva, Jim Cox, Ken Haney and Linda Otis (University of Connecticut Health Center)

Two-Color Fiberoptic Infrared Temperature Sensor—Ward Small IV, Peter Celliers, Duncan Maitland, James Cox, Ken Haney, Luiz Da Silva

High-Performance Electromagnetic Roadway Mapping and Evaluation System (HERMES)—Jeff Mast, Steve Azevedo, Scott Nelson, Tom Rosenberry, Holger Jones, John Warhus, Robert Stever, Tom Story, George Governo, Richard Gilliam, Greg Dallum, Pat Welsh, Mark Vigars, Ming Liu, Jose E. Hernandez and Steve Chase (Federal Highway Administration)

OptiPro Acoustic Emissions Detector (AED)—Mark Piscotty, John S. Taylor and Mike Bechtold (OptiPro Systems Inc.)

1998 Society for Technical Communications Art and Publications Competitions

Art Awards

Sandy Lynn

Bryan Quintard

Publications Awards

ICF Quarterly Report, Vol. 7 No. 2—Jason Carpenter, Pam Davis, Al Miguel, Cindy Cassady, Don Correll, Clayton Dahlen, Roy Johnson, Robert Kirvel, William Kruer, Sandy Lynn, Mark McDaniel, and Dabbie Schleich

ICF Quarterly Report, Vol. 7 No. 3—Jason Carpenter, Pam Davis, Al Miguel, Ken Ball, Cindy Cassady, Don Correll, Clayton Dahlen, Roy Johnson, Sandy Lynn, Mark McDaniel, John Murray, and Ann Parker

1997 ICF Annual Report—Jason Carpenter, Pam Davis, Al Miguel, Ken Ball, Cindy Cassady, Don Correll, Clayton Dahlen, James Hammer, Galen Hazelhofer, Roy Johnson, Robert Kirvel, William Kruer, Karen Lew, Sandy Lynn, Mark McDaniel, John Murray, Janet Orloff, Ann Parker, Joy Perez, Dabbie Schleich, and Charles Vann

NIF Laser Systems Performance Ratings—Cindy Cassady, John Hunt, and Jo Dee Beck

1998 ICF Patents

9231 Merritt Filed
5705902 1/6/98
Halbach Array DC Motor/Generator
Driefuerst, Post

9775 Neev Filed 1/11/96
5720894 2/24/98
Ultrashort Pulse High Repetition Rate Laser System for Biological Tissue Processing
Da Silva, Matthews, Glinsky, Stuart, Perry, Feit, Rubenchik

9501 Sampayan Filed 4/14/95
5729374 3/3/98
Pulsed Hybrid Diamond, Carbide, and Semiconductor Field Emitter

10066 Fitch Filed 3/6/97
5722989 3/3/98
Microminiaturized Minimally Invasive Intravascular Micromechanical Systems Powered and Controlled Via Fiber-Optic Cable
Hagans, Clough, Matthews, Lee, Krulevitch, Benett, Da Silva, Celliers

9472 Tiszauer Filed 7/3/95
5729374 3/17/98
Speckle Averaging System for Laser Raster-Scan Image Projection
Hackel

9341 Vann Filed 8/29/96
5732172 3/24/98
Laser Pulse Sampler

9621-C Cohen Filed 4/1/96
5737137 4/7/98
Critical Illumination Condenser for X-Ray Lithography
Seppala

9901 Barbee, Johnson Filed 11/25/96
5742471 4/21/98
Nanostructure Multilayer Dielectric Materials for Capacitors and Insulators

9540 Chang Filed 9/5/95
5744780 4/28/98
Apparatus for Precision Micromachining with Lasers
Dragon, Warner

9715B McLean Filed 2/11/96
5747120 5/5/98
Laser Ablated Hard Coatings for Microtools
Balooch, Siekhaus

9992 McEwan Filed 7/19/96
5754144 5/19/98
Ultra-Wideband Horn Antenna with an Abrupt Radiator

9567C McEwan Filed 12/17/96
5757320 5/26/98
Short Range, Ultra-Wideband Radar with High Resolution Swept Range Gate

9340B McEwan Filed 11/12/96
5766208 6/16/98
Body Monitoring and Imaging Apparatus and Method

9649 McEwan Filed 6/6/95
5767953 6/16/98
Sub-Millimeter Resolution Laser Tape Measure

9567B McEwan Filed 5/26/95
5744091 6/30/98
Short Range, Micro-Power Impulse Radar with high Resolution Swept Range Gate with Damped Transmit and Receive Cavities

9681A Lee Filed 9/25/95
5771902 6/30/98
Micromachined Actuators/Sensors for Intratubular Position/Steering
Krulevitch, Northrup, Trevino

9937 Druce Filed 6/24/96
5774348 6/30/98
Light-Weight DC to Very High Voltage DC Converter
Kirbie, Newton

9729B Benett Filed 11/27/96
5783130 7/21/98
Fabrication Method for Miniature Plastic Gripper

10046 Post,Vann Filed 10/18/96
5777775 7/7/98
Mechanical Beam Isolator for Laser Driver Applications

8964B McEwan Filed 3/96
5804921 9/8/98
Soliton-Quenching NLTL Impulse Circuit with a Pulse Forming Network at the Output
Dallum

9842 McEwan IPC 11/96 Filed 6/27/97
5805110 9/8/98
Impulse Radar with Swept Range Gate

9681B Lee Filed 7/22/97
5819749 10/13/98
Microvalve
Krulevitch, Northrup, Trevino

9202 Freitas Filed 4/97
5828683 10/27/98
High Density, Optically Corrected, Micro-Channel Cooled, V-Groove Monolithic Laser Diode Array

9920B Glinsky Filed 2/97
5827265 10/27/98
Intraluminal Tissue Welding for Anastomosis
London, Zimmerman, Jacques

9180 Moran Filed 8/5/97
5821543 10/13/98
Transverse-Structure Electrostatic Charged Particle Beam Lens

10016 Neuman Filed 12/20/96
5828491 10/27/98
Phase Plate Technology for Laser Marking of Magnetic Discs
Honig, Hackel, Dane, Dixit

9613 McEwan Filed 1/27/95
5832772 11/10/98
Micropower RF Material Proximity Sensor

9933 Velsko Filed 1/31/97
5841570 11/24/98
Frequency Agile Optical Parametric Oscillator

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"Experimental Studies of Concrete Activation at the National Ignition Facility Using the Rotating Target Neutron Source"
Fusion Tech. **34**(3) Pt. 2, 1028–1032 (1998)

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"On the Dominant and Subdominant Behavior of Stimulated Raman and Brillouin Scattering Driven by Nonuniform Laser Beams"
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"High Average Power 1 μm Performance and Frequency Conversion of a Diode-End-Pumped Yb:YAG Laser"
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Phys. Plasmas **5**(5), SI:1901–1918 (1998)

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"The Safety and Environmental Process for the Design and Construction of the National Ignition Facility"
Fusion Tech. **34**(3) Pt. 2, 760–766 (1998)

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"Multiscale, Multifunction Diffractive Structures Wet-Etched into Fused Silica for High-Laser Damage Threshold Applications"
Appl. Optics **37**(30), 7049–7054 (1998)

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Phys. Plasmas **5**(9), 3402–3407 (1998)

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APPENDIX D

NOVA/BEAMLET/NIF UPDATES OCTOBER–DECEMBER 1997

R. Ehrlich/S. Burkhart/S. Kumpan

Nova Operations

Nova Operations performed 180 full system shots resulting in 197 experiments during this quarter. These experiments supported efforts in ICF, Defense Sciences, university collaborations, Laser Science, and Nova facility maintenance. At the beginning of the quarter the operation of Nova was reduced to 1.5 shifts. Toward the end of the quarter, Bechtel Nevada agreed to provide support for the operation of the target bay. This increase in staffing will allow Nova to again operate for two shifts per day later in the year, increasing the original goal of 700 experiments in FY98 to 900 experiments.

The final shots were fired into the two-beam target chamber this quarter. The two-beam facility was turned over to the NIF project as scheduled. (This process began in mid-November and was completed by the middle of January.)

The Petawatt system underwent a major reconfiguration to add a deformable mirror to the front end of the beamline. In preparation for focal-spot control test shots early in the next quarter, the deformable mirror was installed in conjunction with Hartmann sensors in the Petawatt master oscillator room (MOR), the beamline 6 output sensor, and the compressed beam diagnostic station. Many new diagnostics were installed on the Petawatt target chamber in preparation for the fast ignitor and radiography experiments that will be performed with focal-spot control.

Beamlet Operations

Beamlet completed a total of 40 shots in 16 shot days this quarter. Pinhole closure experiments were performed in October to evaluate the performance of a conical and pyramidal pinhole design of several sizes. Later in the month we prepared for a beamline reconfiguration of the National Ignition Facility (NIF) baseline centered lens, because Beamlet had been originally laid out for a wedged lens which diverted the beam by 2.2°. This required us to offset and repoint the beam in a 4-mirror “mirror tower,” which carried the risk of beam rotation and depolarization. Thus the month of November was consumed measuring these beam properties prior to and following the mirror tower installation. In December, we ramped up the 1ω fluence on the mirrors to near their planned operating point, performed an additional week of pinhole closure tests, and assembled, installed and aligned the NIF prototype integrated optics module (IOM) and final optics cell (FOC). The operational and experimental highlights are as follows:

- The pinhole closure campaign was concluded in October, following tests with conical 100-μrad pinholes, conical 150-μrad pinholes, and the new truncated pyramid (square conical) 100-μrad pinhole. The pulse shape at the transport spatial filter was that calculated for the NIF cavity spatial filter in a nominal NIF red line pulse. It required a 20-ns pulse with a contrast of 90:1 at the MOR. The round 100-μrad pinhole showed initial signs of pinhole closure (contrast ratio increases) above 8 kJ, while the pyramidal pinhole closed hard at 7.0 kJ, and even closed for a 2.2-kJ “foot only” pulse. Fortunately these conical pinholes have virtually no backscatter. The conical 150-μrad pinhole remained open with no signs of closure to 12.9 kJ.
- One week was dedicated to measuring the depolarization of Beamlet at the focal plane prior to mirror tower installation. An extensive setup was assembled at the focal plane, and we

measured the continuous wave (CW), rod-shot, and system-shot depolarization. We measured 0.18% CW, and only slightly greater for rod and system shots. Following mirror tower installation, the depolarization loss went up to 1%, which is insignificant for Beamlet. In any case, we attributed the increased loss to alignment issues in the cavity and not the mirrors alone.

- Beamlet was reconfigured for the centered 3ω lens tests in the month of November. All previous 3ω experiments into the focal plane diagnostics (FPD) vessel used the old NIF baseline, the wedged lens, which required the FPD canted by 2.176° counterclockwise from the 1ω output beamline. Rather than move the FPD, which would have been expensive and time consuming, we shifted the 1ω beam using the Beamlet mirror tower. This required an 18.5-cm beam offset to the south, and involved mixed "s" and "p" reflections
- The last of the thin (35-mm) lenses (L2) and one of the tilted 41-mm-thick lenses (L4) were replaced with 46-mm-thick normal-incidence fused-silica lenses. This was in preparation for the high fluences planned with the centered final focus lens tests commencing in January. Slight damage was found on the vacuum surface of L4, leading to the discovery of FOC back-reflection damage within the transport spatial filter, which has since been corrected.
- We executed 10 shots for the mirror testing, ramping up the fluence on the mirror tower transport mirrors to 8 J/cm^2 in a 3-ns pulse. The ultimate goal to be achieved on a later shot series is 12 J/cm^2. We are testing mirrors with 45°, "s" polarization from four different vendors.
- Problems associated with FOC assembly caused us to insert a pinhole closure series in the third week of December. The goal for this short series was to confirm the Optical Science Laser (OSL) result that Ta leaf pinholes close slower than an equivalent configuration of stainless steel pinholes. This experiment had to be performed on Beamlet because of the higher axial intensity at focus compared to OSL. As expected, the ±100-μrad Ta pinholes closed about half as fast as the stainless steel.
- FOC assembly problems were resolved by the end of the third week in December, and we were able to successfully assemble the cell. Several procedures were revised to accomplish this goal, including the main FOC assembly procedure. The cell and IOM were installed with initial alignment during the week before Christmas, and high-fluence 3ω experiments are planned for January. The rest of December was spent on focal-plane-diagnostics alignment and on activation of the Schlieren On-Line Imaging of Damage (SOLID) system, which uses dark field imaging of damage sites. It is our primary damage detection system for the final optics damage tests.

National Ignition Facility

Overall progress on the NIF Project remains satisfactory for the first quarter of FY98. Despite some delays resulting from unanticipated site conditions, the discovery of mammoth bones, and the rains in November, the overall Conventional Facilities construction schedule slippage was minimized through the use of overtime work. Work-around plans are now being developed to determine what future work to accelerate over the duration of the construction, through the use of accelerated performance contracts and change orders, to recover the original schedule. In Special Equipment, the Title II reviews are proceeding on schedule, and in Optics, the progress on facilitization contracts and development activities remains satisfactory.

There were no Level 0, 1, 2, 3 milestones due during the first quarter. There were 12 Department of Energy/Oakland Office (DOE/OAK) Performance Measurement Milestones due, and all but one (Conventional Facilities, Complete Target Bay Foundation Walls & Pilasters) were completed. One milestone in the Optics area—awarding the polarizer substrate contract—was completed four months ahead of schedule.

Key Assurance activities during the first quarter to support litigation activities and the recovery of mammoth bones included: providing support to the DOE for the settlement of 60(b) (Agreement to prepare a Programmatic Environmental Impact Study supplement analyses and to conduct specific evaluations and surveillance of potential buried hazardous materials), initiating the NIF Construction Safety Program, interfacing with institutional surveillance for buried hazardous/toxic and/or radioactive materials, initiating the *Final Safety Analysis Report*, conducting assurance audits, interfacing with the Safety Management Evaluation team on construction safety, and supporting environmental permits. All activities are on schedule.

Site and Conventional Facilities

The Title II design effort on the NIF Conventional Facilities continued to wind down during the first quarter, with all Construction Subcontract Packages (CSPs) at either Title II 100% design complete or already Bid and Awarded. CSP-9 (Laser Building Buildout and Central Plant) was awarded in December to Hensel–Phelps of San Jose, California, for $65.5 million. CSP-6 and CSP-10

(Target Building Shell and Target Building Finish) will be bid as one contract CSP-6/10 (Target Area Building) in February 1998. Parsons Title II engineering design effort will also be complete in February 1998.

Construction of the retaining wall footing at the west end of the Laser Bay was adversely impacted by unanticipated site conditions, design delays in final configuration of the Environmental Protection System, Walsh Pacific performance problems, and periods of heavy rain during November (see Figure 1). The Target Building portion of the retaining wall footing was remediated and concrete placed in December. Sverdrup (Construction Manager contractor) initially projected a slippage of 10 to 12 weeks in the Conventional Facilities construction schedule, if no activities were accelerated. The current assessment of Project status is that there will be no change to the fourth quarter 01 Level 2 milestone for the end of conventional construction, nor to the fourth quarter 03 Project completion date. However, it is anticipated that there could be a 3 to 6 week impact to the fourth quarter 01 Level 4 milestone for the start-up of the first bundle. There may also be a 6 to 8 week impact to other internal milestones for construction. These impacts are currently being assessed by the construction team and the integrated project scheduling group. Sverdrup is developing a recovery schedule that will require accelerated performance in contracts now being issued and will require change orders to contracts already issued.

Significant work was performed on site to recover and seal rain damaged subgrades, to protect the site by diversion and storage of water during high rainfalls, and to provide all-weather construction access to the jobsite. This site work was performed based upon recommendations from Earth Tech, specialists in wet weather construction from the Seattle area. Sverdrup directed the site remediation activities, and Teichert, a construction subcontractor, performed the work.

FIGURE 1. Target Bay footing construction. (40-60-1297-2604pb01)

Bids were received for CSP-9 (Laser Building Buildout and Central Plant), and the contract was issued to Hensel–Phelps. Competitive bids were received from three bidders with an approximately 2% difference in bids between the two lowest bidders.

Mammoth Bones. Mammoth bones were discovered in the NIF excavation (Switchyard 1 near the Target Area). The bones were recovered by a multidisciplinary team under the direction of a paleontologist who was recommended by the University of California Museum of Paleontology. A permit for the dig was issued by the Department of the Interior, and in accordance with the National Environmental Policy Act, a Supplemental Analysis was issued by the DOE. The bones were preserved in place, encased in fiberglass reinforced plaster, and carefully removed to safe and secure storage at the LLNL site. The work was accomplished in a manner that minimized delays to construction.

Special Equipment

This quarter the Special Equipment FY98 planning was completed, and the Integrated Project Schedule (IPS) has been updated to include the detail Title II plans. Title II guidance for design deliverables has been issued, and Title II design reviews continue to be held on schedule. Procurement reviews were also held. The reliability, availability, and maintainability (RAM) group is helping to produce prototype test plans and procedures.

Laser Systems. During the first quarter there was substantial progress in design and prototyping efforts in Laser Systems. A key accomplishment was resolving the lack of margin in the gain of the amplifier in the baseline design. This was noted at the Title I review and at the NIF Council review in August 1997. An Engineering Change Request (ECR) to allow 23% explosion fraction operation of the NIF amplifier, resulting in provision for increased capacitance in the pulsed power system, was submitted and approved by the NIF Level 4 Change Control Board (CCB) and by the Level 3 Baseline Change Control Board. This change provides for the addition of capacitors at a later date to provide additional gain in the main amplifier if needed. The change provides important contingency in the event of degradation or failure to meet requirements of the amplifier, flashlamps, pulsed power system, and/or main cavity optics.

Optical Pulse Generation. The 17-GHz phase modulator system required for smoothing by spectral dispersion was assembled and tested this quarter. The primary issues are operation of the modulator system and the appearance of amplitude modulation on the laser pulse due to FM to AM conversion of the modulation frequency. The significant modulation observed when the modulation frequency is applied to the fiber-optic system is substantially reduced when the modulation is applied directly to the preamplifier. In addition, assembly of the low-power side of the PAM prototype is under way, and the PAM optical support structure is in procurement with delivery expected in February.

Amplifier. Several meetings were held this quarter to freeze key elements of the amplifier design that must be detailed in the next six months. The major action items generated at the Title I Review and the NIF Council Amplifier Status Review have been resolved and documented. Gain and wavefront measurements on AMPLAB during the last quarter have so far validated the Amplifier design. An ECR was drafted and submitted to reflect a proposal to adopt slab sizes negotiated with the French Atomic Energy Commission (CEA). This will assure that the laser glass vendors will produce interchangeable slabs for both projects (NIF and Ligne d'Integration Laser [LIL], France's 8-beam prototype of their Laser Megajoule). Subscale tests validated the proposed blast shield seal design, and a decision was made to incorporate removable blast shields in the NIF amplifiers. A full-scale prototype design has been completed and parts ordered for testing on AMPLAB. Preferred blast shield glass and coating methods were chosen based on analysis and tests during the past quarter. The 40-flashlamp lifetime test fixture has been activated and successfully fired under manual control with a full complement of 40 flashlamps.

Pockels Cell. Assembly of the 4 × 1 operational prototype plasma electrode Pockels cell (PEPC) was completed during the past quarter, and testing of the device has begun. Two apertures (one-half of the device) have demonstrated switching performance that exceeds the NIF specification. Components for the 4 × 1 PEPC mechanical prototype have arrived, and assembly is in progress. Mounting, vibration, and other mechanical tests will be performed using this prototype over the next several months. A successful Mid-Title II (65%) design review was held for the PEPC in December. No significant issues were identified.

Power Conditioning: The NIF prototype module was assembled and activated during the past quarter at Sandia National Laboratories, Albuquerque. The module was operated at up to 15 kV for 10s of shots. A prototype embedded controller was installed and tested successfully during operation of the prototype. A request for quotations was issued for procurement of the capacitors for the first article module since these are long-lead components. Bids were received and will be evaluated for an award in January 1998. Test runs were completed on several switches, including two tests of the ST-300 and testing of the Russian reverse-switched-dynistor. In addition, arc-drop measurements were made on the ST-300 switch operating at full current. In response to the approval of ECR 189, preliminary planning and scheduling were done to estimate the ECR's impact on the Title II design process. Tests are now under way on NIF capacitors from four vendors with promising results on each to date.

Beam Transport System. After an intensive campaign to resolve all interface control documents and Mid-Title II action items for the Beam Transport System, over 500 prerelease drawings for the Title II Final Design Reviews (Part 1) were completed in December. These drawings will undergo final checking and approval in the next quarter. Final Design reviews were held for three major subsystems that are on or near the critical path for laser installation, the Laser Bay structures, spatial filter vacuum vessels, and the Switchyard 2 structure. Construction Management began a significant ramp-up in activity, initiating a series of construction planning sessions that will ultimately produce a more detailed Integrated Project Schedule (IPS). A full-time construction planner was hired, and a preliminary laser installation strategy was established and reviewed. Design and environmental assessments of Special Equipment laydown areas were initiated, and construction is set to be awarded in January.

Integrated Computer Control System (ICCS). All Mid-Title II (65%) Reviews for WBS 1.5 are now completed. The Mid-Title II Review for Integrated Safety Systems, which includes the Personnel Access Control System and t-1 Abort System, Communications System, and Facility Environmental Monitor were completed in a joint session; no major issues were raised by reviewers. The Mid-Title II Review for Super-visory Software Applications was also completed with no major issues raised. The Mid-Title II Review for Integrated Timing System was held; reviewer comments are pending. The testbed front-end processors, prototype console, network switches, and Software Engineering Computer System were moved into the new ICCS Testbed Facility in B481/R1206. Network modeling tools were evaluated for use in simulating the ICCS computer network of approximately 800 processors. The MIL3 Opnet Modeler tool was selected because of its flexibility and its adoption for use at other DOE sites. The prototype front-end processor was upgraded from the original Datacube processor to the NIF configuration comprised of a Sun Enterprise 3000 server, which promises to be far more scalable to NIF requirements than the previous implementation.

Optomechanical Systems Management. The Optical Mounts group held the Mid-Title II review in November. Drawing packages for the optical mount prototypes were completed and released for fabrication. Prototype testing activity increased in the Final Optics group, and substantial optical design and analysis work was performed (e.g., ray tracing for optical configuration and ghost analysis). The frequency conversion verification system design was completed (prototype), and all parts are on order, with some parts received. Optical design accomplishments included completion of the target chamber damage inspection system, approval of prototype optics drawings for the preamplifier module (PAM), receipt of final design report for the main laser cavity and spatial filter lens design, release of optics drawings for the output sensor prototype, and release of large-aperture window drawings into configuration management. Detailed product data structures (i.e., drawing trees or indentured parts lists) were assembled, collated, and updated to a uniform format for all line-replaceable units (LRUs) within Opto-Mechanical Systems.

Optical Design. Detailed lens design for the multipass amplifier for the PAM prototype to be built in FY98 was completed this quarter. Fabrication drawings for the prototype were generated, reviewed, approved, and released. The target chamber damage inspection system optical design was also completed, and a comprehensive design report prepared. Optical element fabrication drawings for the output sensor prototype lenses, beamsplitters, and prisms were completed and released through the NIF Product Data Management System for fabrication. A previously reported problem (second-order ghost reflection focusing very close to the Pockels cell) was resolved by shifting the entire periscope structure 120 mm towards the target. In addition, the second stray light workshop was held in November. An update of issues from workshop #1 were presented, the main laser ghosts (including high-order and pencil beams) were reviewed, and the latest results from the extensive modeling of ghost reflections in the final optics were discussed.

Optical Components. The efforts for optics components and production continued on track in the areas of Mirrors, Small Optics, Processing, and Metrology/QA. Some key developments were the completion of efforts to identify all of the small optics required for the NIF in a single spreadsheet, binned into LRUs and types; the modeling of contamination conditions for sol-gel coatings; the completion of demonstrations to vendors and component engineers of the metrology data management system; and the award of the Phase II contract for the LLNL photometer.

Laser Control. The volume of procurements for prototype hardware was increased during the first quarter to provide more opportunities to validate key NIF designs. A few prototypes have already passed NIF lifetime-equivalent tests;. others have generated data that led to important adjustments in their design or in assembly procedures; and many are now in fabrication. Increasing numbers of detailed drawings were also completed as the mechanical designers gained familiarity with the Pro-E CAD tools in the context of detail production. A Pro-E model of the central part of the Transport Spatial Filter (TSF) and the space below it was nearly completed. This model is a key part of defining interfaces in the area. Mechanical and optical design of the input sensor was a major effort this quarter also. Improved packaging now separates the main beamline components requiring the highest level of cleanliness from other components with relaxed cleanliness specifications, placing them in completely separate modules that can be built, installed, or replaced independently.

Target Experimental Systems. Significant accomplishments in the past quarter were the forming of the first two (of 18) plates for the aluminum vacuum chamber at Euroform in France (see Figure 2) and completion of most of the Special Equipment utility designs in the Target Area Building and support pads. The 110-mm-thick aluminum plates were warm-formed (316°C) on a 12,000-ton press between two dish shaped dies, and a preliminary inspection was made using a template. The plates matched contour within 5 mm and no thinning was evident. Prototype testing activity increased in the Final Optics group principally for the actuation system components, debris shield cassette components, and the integrated optics module. Testing of the prototype rail mechanism for debris shield removal was also completed, showing significant particle contamination from

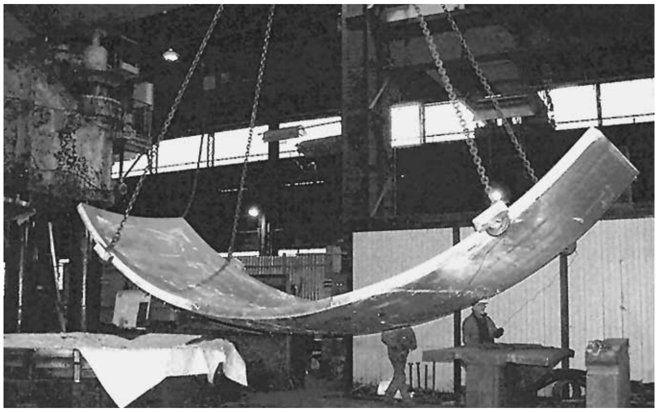

FIGURE 2. Forming of Target Chamber plates at Euroform in France. (05-00-0398-0525pb01)

the rubbing of the slide mechanism with itself. Particle counts indicated more than 1600 particles of 5 μm or larger over a 4-in. wafer, which equates to a cleanliness level of 600 per Mil Std 1240. An ECR was approved by the Level 4 CCB to add a second "cassette" in the final optics assembly (FOA), and the team began implementing the change. This second, removable cassette would be the optical mount for the diffractive optics. A major factor in the decision was a significant reduction in out-year operating costs for a highly flexible target physics program. A complete set of ghost analysis runs was completed for the optical elements within the FOA consistent with the configuration as required by ECR 180. Of the three million ghosts analyzed through 4th order, 6000 had fluences at focus of greater than 1 J/cm^2. Of those, only two families were at or near optical elements. These were mitigated by adjusting the element spacing in the final optics system. Metrology measurements were made of the mounted crystals used in the recently completed frequency conversion experiments. The 18-in. phase-measuring interferometer in Building 298, with an improved setup, was able to record high-quality transmitted wavefront data that can be used for modeling degradation of frequency conversion due to Δn (change in index of refraction) effects.

Operations Special Equipment

During the first quarter, Title II design progressed well. Key activities were the preparations for the Mid-Title II (65%) review of the Optics Assembly Building (OAB) Optical Assembly and Alignment Systems and the Transport and Handling 35% Title II Review. A key milestone was completed by getting the LRU and installation schedule under configuration management, including the addition of refurbishing several LRUs per month. In October NIF Procurement awarded two contracts for the Phase 1 Conceptual Design of the Laser Bay Transport System. By the end of the first quarter, the Phase 1 designs were complete at both contractors (RedZone Robotics, Inc. and Mentor AGVS), and the Conceptual Design documents were received. The assembly of the hardware for the cover removal mechanism for the Bottom Loading (BL) Universal Canister was completed, and "dirty testing" of the cover removal has been initiated. The BL canister nitrogen gas purge testing has also started. Eighty percent of the OAB Special Equipment prototype equipment has been procured, and cleanliness and function testing is beginning.

Start-Up Activities

The updated IPS database was functional on October 31, with over 10,000 activities, and is now being used to status the Project each month. The IPS includes Level 0–4 Project milestones, interfaces, and detailed activities; integrates key technology activities and milestones; and includes FY98 Cost Account Plan schedules. To supplement the IPS, a detailed LRU installation plan (in the form of a chart) has been developed, which describes the number of LRUs of each type to be installed on a monthly basis throughout the Special Equipment installation phase of the Project. Early in the quarter the first bundle working group progressed through an initial discussion and flow diagram of all integrated operational test procedures for first laser bundle start-up. Procedures reviewed during October include the Diagnostic Target Shot procedures, the Precision Diagnostics, the Computer Controls System requirements, Target Area Beam Transport, Final Optics Assembly, beam alignment to Target Chamber Center, and an update on the Main Laser activation steps. Several first quarter Start-Up weekly meetings discussed the coordination with NIF/ICF Program ignition planning efforts. An update on hohlraum energetics experiments and backscatter diagnostics planning was presented, followed by a discussion of start-up test criteria and expected laser performance at completion of a laser bundle start-up.

Optics Technology

Key enabling technology areas are coming to critical demonstration points in the second quarter, and the Optics Technology organization is now shifting its focus from the facilitization contracts, which are proceeding without significant problems, towards those demonstrations and preparation for the pending pilot production effort. Tinsley presented its revised facilitization plan based on a delay until March for the beginning of site preparation due to the current weather. To preserve the pilot production schedule, Tinsley has proposed performing its NIF equipment acceptance testing in its existing facility, and then transferring the equipment to the NIF facility in August 1998. Schott's phase II building is now completely enclosed, which will allow them to complete the construction on schedule without weather delays. Hoya's new facility has the offices, conference room, and elevator completed except for furnishings. The Zygo facility modifications are 94% complete, with most of the work remaining in the shipping receiving area. Assembly of the first relay plane machine was completed; a Zygo review team conducted an acceptance audit; and the machine was found to be acceptable. The contract to retrofit and refurbish the 160" continuous polisher at Eastman Kodak has been awarded, and the work is expected to be complete by May. Tinsley has completed a second high-speed lapping and polishing machine as part of lens development. This machine is the third and final of its type to be built during NIF development at Tinsley and incorporates advancements learned from the design, build, and operation of the previous machines. Many of the long-lead components for the four new 1000-L tanks have arrived at LLNL. One of the four glass vessels is at LLNL, the other three are expected to arrive in late January. All four water bath housings, all support framework/spider systems, and nearly all of the control and diagnostic equipment are on site. LLNL has selected coating vendors for opening negotiations for the coating facilitization contract awards. The first full-sized color separation grating was completed and delivered on schedule to Beamlet in November. The part exceeded specifications with <1% 1ω and 2ω zero order transmission. At 92% transmission in the 3ω zero order, it missed the specification of >95%. No antireflection coating is currently known to be compatible with the NIF 3ω fluence targets of 14 J/cm^2. A plan has been defined to evaluate scandia/silica antireflective coatings from the University of Rochester Laboratory for Laser Energetics and spin-coated sol-gel coatings done at LLNL. Also this quarter, initial inspection of existing 7940/7980 shows <80 μm inclusions have existed in significant quantity in at least some Nova optics. Evidence was also found that <30 μm inclusions have damage in the hottest spot on Nova (input SF7 lens), but these bulk damage sites did not grow to >35 μm at the 1ω fluence of ~15 J/cm^2.

Upcoming Major Activities

During the second quarter of FY98, Conventional Facilities construction will complete the Target Bay mat foundations and the backfill of the mass excavation around the Target Bay. Work on the Optics Assembly Building will begin, and the “Notice to Proceed” will be given for Construction Subcontract Package 9, Laser Building & Central Plant. Special Equipment will continue with several Mid-Title II (65%) Design Reviews, and Title II (100%) Design Reviews will take place in the area of computer systems. In Optics, the activities for bidding and negotiating the optics facilitization contracts will continue.

NOVA/BEAMLET/NIF UPDATES JANUARY–MARCH 1998

R. Ehrlich/S. Burkhart/S. Kumpan

Nova Operations

Nova Operations performed 200 full system shots resulting in 208 experiments during this quarter. These experiments supported efforts in ICF, Defense Sciences, university collaborations, laser science, and Nova facility maintenance. As the technicians hired during the previous quarter gained experience in operating the laser, we were able to begin expanding the shift schedule. In the middle of the quarter, the second shift was moved to end at 10:30 p.m. During the next quarter, the operation of Nova will expand back to a full two shifts per day, with the second shift ending at 12:30 a.m.

During this quarter, 94-cm full-aperture gratings were installed in the Petawatt laser system. This allowed an increase in beam diameter to 55 cm, with a corresponding maximum energy of ~900 J. With the completion of the full-aperture compression system, activation of an adaptive-optic wavefront correction system began. Experi-ments in the Petawatt front-end demonstrated the ability of the deformable mirror to correct for several waves of distortion in a reproducible fashion. Hartmann sensor packages were then deployed in the Nova Output sensor and in the Petawatt diagnostic station following compression. An automatic component status verification system was deployed on the Petawatt system at this time to ensure the proper configuration of components before a full-system shot with the deformable mirror.

A newly redesigned system was built to retrofit one beamline of Nova with an *f*/8 final focus lens for experiments designed to estimate the backscatter levels in NIF hohlraum targets. These experiments during the next quarter will give us confidence that there will be no surprises in NIF hohlraum backscatter levels with reasonable amounts of bandwidth from a high-frequency modulator in conjunction with kinoform phase plates. The experiments will also investigate the effect of a polarization smoothing technique on backscatter levels from various types of targets.

Beamlet Operations

Beamlet completed a total of 121 shots in 44 shot days this quarter. We performed major campaigns on final optics damage at 5 J/cm^2 at 3ω, evaluated extensively the NIF first-boule doubling crystal, executed the final series of pinhole closure experiments at high energy and long pulse, and measured pinhole closure and propagation effects of 1D smoothing by spectral dispersion (1D-SSD). We also began experiments to determine doubling efficiency of the first large fast-growth KDP crystal. Beamlet operations and experimental campaigns are detailed as follows:

- The final optics cell (FOC) and integrated optics module (IOM) were assembled in late December and installed in the Test Mule just before the end of the year. Following alignment, calibration, and the first 5 ramp-up shots, we vented and inspected the medium damage threshold final focus lens (MDT-RFL). We inspected once more the MDT-RFL following the first two shots at the desired fluence (5 J/cm^2), then proceeded with the shot series (see Figure 1). A special optics inspection mechanism was developed for inspecting the MDT-RFL mounted in the Test Mule.
- Eleven shots at 5 kJ (5 J/cm^2) were performed, followed by another Test Mule vent and lens inspection that revealed growing damage as was observed using the on-line inspection system (Schlieren On-Line Imaging of Damage) and by high-resolution near-field photographic film

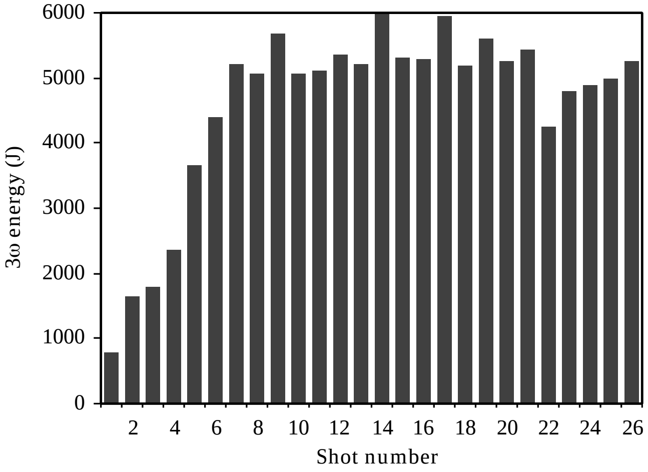

FIGURE 1. Beamlet MDT Lens Campaign, January 1998. (50-00-1098-1955pb01)

images. Eight more shots were done, and then the IOM/FOC was removed for disassembly, inspection, and damage mapping.

- A new frequency doubler, cut from the NIF first-bundle boule, was delivered to LLNL the last week of December. It was coated, characterized, and installed in the second FOC (FOC-B) by the week of January 26, 1998. The MDT lens, from the above damage tests, was installed in FOC-B, and the IOM/FOC assembly was returned to Beamlet in late January for Test Mule installation and alignment. System shots for the Doubler Only campaign commenced at the end of January and continued through the end of February.
- Significant calibration effort was performed to obtain confidence in the doubler efficiency experimental results. The design of the focal plane diagnostics (FPDs) does not allow for a direct measurement of all three wavelengths; instead the 2ω is inferred by subtracting a measurement of the 1ω from the whole-beam calorimeter. In addition, the large FPD attenuation precludes direct calibration, and there were unresolved stray light problems affecting the energy diodes. To circumvent this, a large plate of BG18 (1ω- blocking) filter glass was installed to obtain absolute 2ω measurement of the whole-beam calorimeter from which we scaled all of the Doubler Only experiments. This data linked all the previous measurements to the absolute frequency-doubling conversion efficiency of 73.2% for the whole beam, temporal and spatial variations included. This compared to 72.9% from the plane wave model, accounting for the measured pulse shapes. Following these experiments, the diagnostics were redesigned similar to the Beamlet Phase I system, using prisms and calorimeters to separate and independently measure energy in each of the three colors.
- Hardware design is under way for the French Commissariat à l'Energie Atomique experiments scheduled for June. The experiments include silica plate filamentation experiments at 3ω, full-aperture polarizer damage testing, and high-fluence 1ω mirror damage testing at reduced aperture.
- The final pinhole closure experiments, 20 shots, were conducted during the month of March, including cone-shaped 100-μrad Ta, 100-μrad stainless steel (SS), 100-μrad diamond-oriented gold-plated SS, and a 100-μrad solid Au pinhole. Of course, we still had the 150-μrad SS cone, which has been the workhorse for some time because of its superior back-reflection (none) and closure characteristics. In addition, we tested the French pinhole—a design similar to two short cones in series. The Ta cone pinhole performed the best. It took over 7 kJ in a 20-ns square pulse to close it, and it stayed open up to 11 kJ in a Haan ignition pulse with the nominal SSD. The diagnostics for closure worked very well, with good returns from the streaked pinhole interferometer and the gated optical imager. Data analysis was greatly improved with the addition of numerous Interface Definition Language routines to automatically calculate the contrast ratio for a number of 5- × 5-cm patches for each shot. We also measured the threshold for pinhole closure with background pressure, taking shots up to 3.5 kJ through the 100-μrad cone at 90 mT.
- 1D-SSD experiments were purposely limited to a demonstration of transmission through two different pinholes. Two shots above 15 kJ (15.1 and 15.4) were taken through the 150-μrad pinhole with ±7.5 μrad of 1D-SSD using the Haan ignition pulse. Evidence of pinhole closure initiation was observed on the pinhole interferometer, but the plasma was far enough out of the beam focus to not cause near-field beam modulation. We also propagated 20-ns square and Haan ignition pulses through the 100-μrad Ta cone. The Ta cone was the big surprise in the campaign, as it performed exceedingly well. It transmitted 11 kJ using ±7.5-μrad divergence with the Haan ignition pulse shape. The last

mirror in the mirror tower (M9), damaged during the first 11-kJ Haan ignition pulse shape, incurred a damage spot of about 3 mm and was subsequently replaced. Although the spot is not growing, the modulation is too large for further high-fluence frequency conversion campaigns.

National Ignition Facility

Summary

Overall progress on the NIF Project remains satisfactory for the second quarter of FY98. During this quarter, NIF construction subcontractors recovered four of the estimated six to eight weeks of schedule lost in the November and December El Niño rains, despite the heaviest rainfall on record for the month of February. Implementation of a wet weather construction plan, additional construction equipment, additional manpower, and an extended workweek combined with a second shift generated a sense of urgency and improved productivity through the quarter.

In Special Equipment, 79% of the Mid-Title II (65%) design reviews and 10% of the Title II (100%) final design reviews have been completed. The two major procurements, Beam Transport Stainless Steel and the Target Chamber, are on schedule.

In Optics, the progress on facilitization contracts and development activities remains satisfactory. The first full-scale continuous pour of NIF laser glass has yielded positive results. The potassium dihydrogen phosphate (KDP) rapid growth decision was made early, and the KDP facilitization contracts awarded. Also, the contracts for mirror and polarizer coating facilitization were awarded.

There were no Level 0, 1, 2, 3 milestones due during the second quarter. There were 18 Department of Energy/Oakland (DOE/OAK) Performance Measurement Milestones due this quarter, and 19 were accomplished. There was a total of 30 milestones due in the first half of FY98, and 31 have been accomplished, for an overall variance of (–1). In March, nine milestones were completed, whereas seven were planned. This is based upon DOE/OAK's concurrence with *Revision A* of the FY98 Milestones, which was effective February 28, 1998.

Key Assurance activities during the second quarter to support the Project included assurances preparation for major concrete pours and disposition of mammoth bones. Litigation activities included the following:

- Litigation support to the DOE for the settlement of 60(b) (Agreement to prepare a Progammatic Environmental Impact Study supplement analysis and to conduct specific evaluations and surveillance of potential buried hazardous materials) and the overall litigation against the Stockpile Stewardship Program's *Programmatic Environmental Impact Statement*.
- The NIF Construction Safety Program.
- Interface with the LLNL Institutional surveillance for buried hazardous/toxic and/or radioactive materials.
- Risk Management Plans.
- The *Final Safety Analysis Report*.
- Assurance surveillances and audits.
- Support for environmental permits.

All are on schedule.

The current assessment of Project status remains as stated last quarter; there will be no change to the 4th Qtr. 2001 Level 2 milestone for the End of Conventional Construction nor to the 4th Qtr. 2003 Project Completion date. However, it is still anticipated that there could be a three- to six-week impact to the 4th Qtr. 2001 Level 4 milestone for the start-up of the First Bundle. The current assessment is that there may also remain two to four weeks' impact to other internal milestones for construction. This is an improvement since the first quarter report resulting from the accelerated use of overtime on the construction site. Accelerated activities in addition to the rain mitigation actions taken in the second quarter, which could reduce the First Bundle schedule impact, are currently being assessed in conjunction with construction contractors.

Site and Conventional Facilities

The NIF Conventional Facilities construction subcontractors recovered four weeks of lost schedule during the second quarter despite the heaviest rainfall on record for the month of February. At the end of March, Walsh Pacific (Construction Subcontract Package [CSP]-3, Target Building Mat and Laser Bay Foundations) had recovered one-half of the two months schedule lost in the November and December El Niño rains. As noted above, implementation of a wet weather construction plan, additional construction equipment, additional manpower, and an extended workweek combined with a second shift generated a sense of urgency and improved productivity through the quarter (see Figure 2).

The bids for CSP-6/10, Target Area Building Shell and Buildout, were received in March, bringing to closure the procurement phase of the major Conventional Facilities construction subcontracts. Seven of the eight Conventional Facilities construction subcontracts have been awarded; two of these subcontracts (CSP-1 and 2) are complete, and four subcontractors (CSP-3, 4, 5, and 9) are actively constructing on the NIF site.

FIGURE 2. Target Area retaining wall forms and rebar. (40-60-0198-0084#46pb02)

FIGURE 3. Finishing the Target Bay slab. (40-60-0398-0616#20pb01)

Construction work in place at the end of the second quarter is approximately 9%.

The Conventional Facilities Title II engineering design ended on schedule in February, and Title III engineering support to construction began in earnest concurrent with the ramp-up of subcontractors and craftspersons at the NIF site.

Construction Milestones. Several important milestones were achieved on the NIF site in the second quarter. The critical path backfill of the retaining wall along gridline 10/12 was completed (FY98 DOE/OAK Performance Measurement Milestone). This was important for two reasons. First, the completion of backfill allowed footings and tie-beams in the Laser Bays to be completed, a prerequisite to start of structural steel erection, which is, in turn, on the critical path of construction activities for the Laser Bay. Second, the completion of the Target Building retaining wall backfill was the final construction work by Teichert under CSP-2.

Another significant milestone achieved by Walsh Pacific (CSP-3) was the placement of the Target Bay mat slab (FY98 DOE/OAK Performance Measurement Milestone); this 3300-cubic-yard continuous pour occurred over an 18-hour period in late March (see Figure 3). This critical path concrete work in the Target Building is the first of three major mat slab pours by Walsh Pacific that are prerequisite to the start of work in the Target Building by Nielsen-Dillingham, CSP-6/10. Other work completed by Walsh Pacific included forming, rebar, installation, and placement of concrete in the Target Building retaining wall and footings; the Target Building wing walls; and the footings, short pilasters, and tie beams within the Laser Building core.

Nielsen-Dillingham (CSP-4) continued steel fabrication in Oklahoma City during the second quarter, with anticipated arrival on site in mid-April. All critical submittals and shop drawings have been reviewed and approved. Dillingham (CSP-5) also completed the Optics Assembly Building (OAB) concrete footings six days ahead of schedule (FY98 DOE/OAK Performance Measurement Milestone). The work on contract includes: completed footing and foundations, poured basement walls, continued installation of the grounding loop for building steel, erected structural steel column stubs on the entire perimeter, and started basement wall. The Nielsen-Dillingham CSP-6/10 bids were opened and the contract was awarded in March.

Hensel-Phelps (CSP-9) and their subcontractors have fully mobilized their trailers on site. A full platform proposal that will shorten the subcontractor’s duration in the Laser Building was negotiated this quarter at no cost to the NIF Project. Hensel Phelps will begin site utilities in April, including: storm drain and sewer lines at the east side of the site, tie into mechanical bundle at the northeast side of the site, and site temporary power.

Mammoth Bones. The excavation of the mammoth bones in the area of the Laser Building 1 retaining wall footing, adjacent to Switchyard 1, was completed in February. DOE confirmed in March that bones located adjacent to the Diagnostics Building and Switchyard 2, outside the building footprint, will not be removed at this time. Change orders will be issued to subcontractors by Conventional Facilities to protect the bones for future recovery. Survey information and maps identifying the locations of the bones have been recorded for future reference.

Special Equipment

This quarter, a major focus was to successfully bring closure to outstanding requirement issues as part of the Mid-Title II (65%) design reviews. With the completion of the second quarter, a majority of the

Mid-Title II design reviews were completed, and more of the final (100%) design reviews were held. Reviews of the Beam Transport procurement packages also began.

Mid-Title II reviews were held for the Laser Amplifier, the Target Positioner, the Optical Pulse Generation (OPG), Optical Assembly and Alignment Systems, Alignment Control, Precision Diagnostics, Roving Mirror and Roving Assemblies, Power Diagnostic and Back-reflection Sensor/Portable Sensor, Energy Diagnostic, the Final Optics Assembly (FOA), the Target Chamber Vacuum System, Target Area Structures, and Relay Optics/3ω Energy. Final design reviews were held for the Supervisory Control (Framework) and the Computer Systems. Design review reports were prepared and released for the Pockels Cells, the Beam Transport, the Target Positioner, the Amplifier, the OPG, and the OAB reviews.

Laser Systems. Nearly all Laser Systems design issues have been resolved, and detailed drawings are being produced in all areas. Substantial progress was made on prototypes during the second quarter. The preamplifier prototype was procured and assembled in preparation for testing during the third quarter. Tests on the Amplifier Module Prototype Laboratory (AMPLAB) amplifier prototype were completed for the 2-slab-long configurations. The 4 × 1 Pockels cell prototype was assembled and tested, demonstrating the necessary switching performance for the NIF. The detailed design of the power conditioning first-article prototype was completed, while the performance models were validated by tests on the existing prototype capacitor module. Design documentation is being produced at a rapid pace consistent with completing in time to procure hardware for the first beam bundle.

Optical Pulse Generation. A substantial effort during the past quarter focused on resolving the remaining issues required to complete the OPG design. Experi-ments and modeling quantified the modulation due to FM-to-AM conversion from the modulators in the Master Oscillator system. A decision was made to use polarizing fiber to minimize the modulation, while system propagation modeling began to quantify the impact of the residual AM on laser performance. The rmaining hardware for the prototype preamplifier module arrived, and assembly of this complex subsystem began. Perfor-mance of important subassemblies was valid-ated, in-cluding commercial diode arrays, the regenerative amplifier, and the optoelectromechanical beam- shaping module produced by Allied Signal in Kansas City. Optical design of the preamplifier beam transport system was completed, enabling the team to freeze the design and begin detailed drawing production.

Amplifier. Since the key features of the amplifier design were frozen in the first quarter, the design team is now in the process of creating detailed fabrication drawings. During the second quarter, many of the computer-aided design (CAD) models were sufficiently completed that they could be exported to a subcontractor for detailing.

A parallel experimental effort, centered in the AMPLAB, worked to address the few remaining open issues and provide a final physics validation of the design. The 4 × 2 × 2 AMPLAB gain and wavefront experiments were completed during the second quarter, and the facility is currently being configured to measure three-slab-long gain and wavefront to complete the data set required to validate the amplifier model. The three-slab-long measurement is expected to show that most of the wavefront error is produced by the end slabs in the amplifier chain. This would explain the concern raised earlier this quarter regarding a discrepancy between the expected and measured wavefront error on the AMPLAB. Analysis of the data is ongoing, but so far indicates that the amplifier will meet or exceed its gain requirement.

In response to the issue raised earlier this quarter, the cleanliness tiger-team, consisting of NIF amplifier, cleanliness, and optics personnel as well as LLNL analytical chemists, continued to characterize the nature, source, and effects of the contamination observed in AMPLAB. A detailed plan was developed to complete the tests necessary to demonstrate that the amplifier can be installed and operated cleanly.

Pockels Cell. During the past quarter, the plasma electrode Pockels cell (PEPC) detailed design has progressed in parallel with activation and testing of the 4 × 1 prototype cell. The prototype drawings, also considered the Title II drawings, were entered into the Project Data Management system and placed under configuration control. Several interface control documents (ICDs) were updated to reflect changes since the 65% review. Parts for the prototype control system were ordered. The controls approach will be validated through integrated testing with the 4 × 1 prototype. The prototype was assembled and tested for the first time during the second quarter. Minor problems with potting and simmering were encountered and solved. By the end of March, the prototype was operating, and simultaneous measurements on all four apertures indicated that the cell exceeds the minimum NIF requirements for switching efficiency in both the “on” and “off” states. The remaining operational prototype effort will test the cell against the remaining system requirements and validate the controls and diagnostics designs via integrated testing and operations. The mechanical prototype is assembled, and preparations are under way for mounting and alignment tests.

Power Conditioning. The power conditioning effort during the past quarter was focused on completing the design of the first article so that parts could be ordered and on using the existing 2 × 2 × 5 capacitor prototype module to refine and validate a detailed circuit model. The model was then modified to reflect the design of the 2 × 3 × 4 first article and predict its performance. Several meetings of the design team were held to resolve the issues regarding the first article design. Among the decisions made were the following: the use of coaxial cable instead of twin-line, the architecture of the first article module (2 × 3 × 4), the grounding strategy for the bank/amplifier system, and the details of the preionization pulse requirements. A scale model of the first article module was completed and is being used to develop maintenance and safety procedures for the bank, as well as to help the design team evaluate the architecture. The life test of the baseline (ST-300) switch commenced in order to demonstrate adequate life and performance at the elevated currents associated with 24-capacitor operation.

Beam Transport System (BTS). Final checking and documentation for critical path components were highly focused activities in this quarter. The installation schedule drove all resource priorities. The first two procurement packages, for the Laser Bay steel material and spatial filter vacuum vessels, were completed and reviewed, including checked and signed drawings, engineering calculations, and all Title II deliverables. The BTS structural/mechanical analysis team completed the Title II analyses and final analysis reports for the BTS Laser Bay structures, the Bldg. 298 laydown area grading activity is under way, the amplifier cooling system fan units have begun fabrication and are on schedule, and the stainless steel plate is on schedule.

- The spatial filter vacuum vessel designs were completed, and drawings were signed and released into Configuration Management (CM). The fabrication specification was completed and reviewed. Mill production of stainless steel is nearing completion and is on schedule.
- Discussions with Los Alamos National Laboratory (LANL) regarding the proposed Roving Mirror system design, space allocation, alignment, installation sequence, and cleaning issues for the switchyard enclosures were continued. BTS has finalized its decision to perform design and installation of enclosures using internal rather than external resources to allow more schedule flexibility for the Roving Mirror changes proposed by LANL system.
- Ports were added to the Laser Bay interstage beam tubes for clean air purge in the event of in situ maintenance. Seal testing was initiated to evaluate three candidate materials (solid silicone, silicone foam, and expanded Teflon tape) and a number of bolt patterns at both switchyard and Laser Bay pressure differentials.
- The PEPC team recently made a change to use self-contained, local dry pumps to provide backing turbomolecular pumps for the vacuum system. Therefore, a separate backing line to the PEPC is no longer needed from Auxiliary Systems.
- Leak rate measurements for one design of the beam tube seals was completed to validate the design of the gas-handling system.
- The Switchyard 2 structural support structural drawings are about 80% complete, and the structural steel quantity takeoff (spread sheet) is 95% complete. It includes everything but LM5 support subframes because some member sizes are not available.
- Finite-element analysis plots of forces and moments necessary for the completion of the concrete pedestal reinforcement design calculations for the Laser Bay were generated. Pedestal design is nearing completion. Steel-concrete interface force data for the pedestal embedment plates was prepared.
- Tests of o-ring, flat gasket, and formed gasket seal designs for the spatial filter lens prototype were conducted. All three seal designs met the design requirements. These test results provide high confidence in proceeding to final, detail drawings for the spatial filter lens cassettes (see Figure 4). The prototype testing has shown that formed gaskets can be used in place of o-rings at lower cost and similar performance.
- A modified transport mirror attachment design was tested during February. This modification contacted the bore in the back of the mirror at its midplane, which reduced the distortion induced on the front face. Interferometer tests confirmed that a significant reduction was achieved. Improvements to address two problems, plastic deformation of the attachment and creep of the elastomer within the attachment, have been identified.

Integrated Computer Control System (ICCS). Title II 100% Design Reviews were conducted a month early for the Computer System and the Supervisory Software Frameworks.

- The 100% design review for the computer system and network held in February featured 153 drawings, all of which are under configuration control. The network design

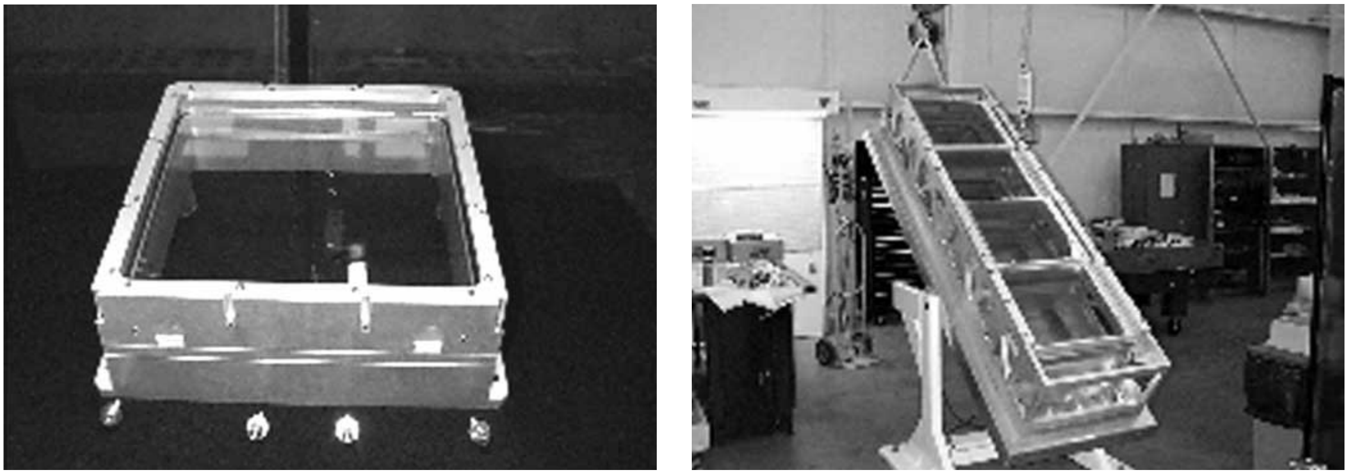

FIGURE 4. A single spatial filter lens assembly is shown above on the left. Four such assemblies are installed into a cassette, which has a strong back for stiffness/handling (shown on right). (50-00-1098-1989pb01 and 50-00-1098-1990pb01)

has evolved since the 65% review to become a hybrid topology of switched Fast Ethernet and Asynchronous Transfer Mode networks. Analysis of expected traffic over the full-shot cycle combined with simulation study shows that substantial performance margin exists in the design. The prototype operator console was delivered and installed in Bldg. 481-1206 for conducting ICCS testbed demonstrations.

- The Title II 100% Review of the Software Frameworks was delivered in February. The review featured a number of presentations on the framework including front-end processor (FEP) preparation, operations databases, system management, status monitoring and reporting, CORBA distribution strategy and measurements, and results from the discrete event simulation for the status monitor performance.
- The report for the 65% Design Review for the integrated timing system was released. In total the reviewers generated 46 comments, of which 7 were level one, 35 were level two, and 4 were level 3. The review committee recommended that an additional prototype of the timing distribution backbone be pursued to demonstrate precision timing requirements and ensure continuing vendor involvement leading to NIF deployment.
- The Control Logix integrated safety system beta unit was received from Allen-Bradley and activated for testing. This unit represents the next generation of higher-performance programmable logic controllers and will form the basis for the NIF Industrial Control Systems.
- The Preliminary Timing Analysis of NIF Beamline Alignment was finalized and used to demonstrate Alignment Control's ability to meet Software Subsystem Design Requirements (SSDR) alignment time specifications in support of the 65% review. This analysis defines the step-by-step alignment procedures from the Preamplifier Module (PAM) through the Target Chamber and includes how shared resources (such as the Output Sensor and Target Chamber) impact system performance.

Optomechanical Systems Management. Title II design progress was very good. Spatial filter lens cassette prototype testing was completed. Mirror attachment design testing continued with moderate success. Transport mirror sizes were determined. Most of main laser cavity optics final drawings have been released. The FOA Mid-Title II (65%) design review was held. The final optics configuration was updated to incorporate ECR180. Major pieces of FOA prototype hardware were received. The CAVE (Crystal Assembly Verification Equipment) became ready to begin manual measurements.

Optical Design. Title II optical design progress during the second quarter included the following:

- The final, planned update to the main laser design optical configuration drawing was released. The optical design of the main laser cavity is complete.
- The optical design of the OPG system was presented by the responsible optical engineer at the Mid-Title II (65%) review in February. Important results were reported for the optical stability

analysis, the wavefront specifications for optical components, the optical layout (under CM), and the optical design performance.

- Detailed optical design studies of the telescopes in the preamplifier beam transport section (PABTS) of the OPG were completed and showed that a lengthening of the relay telescope was necessary to reduce fluence on lenses within the telescope. As part of the system design, the telescope in the input sensor package was also redesigned to better balance the energy loading.
- Good progress was made on releasing final main laser optics drawings into CM. The following drawings have been released: amplifier blank, spatial filter lens, cavity mirrors and polarizer, switch window, and diagnostic beamsplitter. The remaining cavity optics drawings (switch crystal and amplifier finishing) are being updated by the optics manufacturing organizations.
- The Title II mirror sizes for the transport mirrors were determined. The alignment scheme (i.e., which mirrors would be used to control pointing to the target and centering at the final optics) had to be changed to obtain mirror sizes acceptable to the various interfacing groups, generally decreasing in size. As a result, the final drawings (nine) for the mirror blanks were released.
- Two out of six FOA optics drawings are under CM (target chamber vacuum window and focus lens). The final sizes of the diffractive optics plates and debris shields were established and the Title II drawings should be released in April.
- The defect-induced damage analysis calculations for the NIF vacuum barriers investigated the beam modulation at spatial filter lenses (vacuum barriers) arising from defects in optical components. The results showed that the presence of defects modulates the beam slightly more than fabrication phase errors, but that this modulation is below damage thresholds. The results confirm that the polarizer and LM3 are the most sensitive locations for defects.

Optical Components. Several potential qualified suppliers have expressed strong interest in supplying the BK-7 mirror and polarizer substrate materials for the NIF. In contrast to the other materials, BK-7 is a commodity glass requiring no special facilitization or development efforts. The statement of work was written for these substrates in conjunction with the release of the Title II mirror and polarizer substrate drawings.

Significant progress was made in NIF small optics in the second quarter. A list of prototypes and a delivery schedule were developed, along with a vendor survey from which a qualified bid list will be developed for production optics. The Vendor Qualification Plan was also completed and released on schedule.

The small-sample cleanliness verification system was completed, as was a comprehensive technical review of the large-optics processing plan. This review included a status of the following areas: all optics processing support facilities for the NIF, QA for optics processing, staffing and training, database documentation, facility and process cleanliness control, and mechanical handling equipment and fixtures. The requirements document for the Metrology Data Management System, which will be used to assist inspection and quality assurance (QA) of the optics at the vendors and LLNL, was updated based on input from the optics component lead engineers and the vendors.

Laser Control. Considerable progress has been made in completing and reviewing parts of the laser control design. In addition, various prototype components were ordered, received, and assembled, with more on the way.

- The Transport Spatial Filter area now has a fully integrated design that encompasses the mechanical, optical, and electronic systems for the preamplifier module, injection beams, alignment and diagnostic beams, input sensors, output sensors, and beam enclosures.
- Solid modeling of the Input Sensor package is essentially complete, and some detail drawings are also finished.
- Signal level requirements for beam control light sources were analyzed in more detail using a complete NIF transmission model for all optical paths from the light source locations to the corresponding detectors. The model compared well with the transmission elements of current beam propagation codes, and the two methods are believed to be equivalent.
- Substantially all of the mechanical parts for the Output Sensor prototype have been received, and assembly is being planned. Similarly, all purchased parts for the sensor test stand are in hand while fabrication parts are on order.
- The optical design of the Laser Optic Damage Inspection (LODI) System was modified to accommodate 3ω light. When the Schlieren focus stop is removed, LODI can be used to record near-field images of light that have made a round trip to the final optic and back. This will likely be part of an on-line system for measuring the net 3ω reflectivity profile of the 1ω transport mirrors.

Target Experimental Systems. The Target Experimental System has continued Title II design according to schedule, for the most part.

- All 18 target chamber plates have been formed and shipped to Precision Components Corp. (PCC) for edge machining. The first sphere plate edge machining was done at PCC, with the long sides of the plate receiving the weld groove configuration. The land of the weld joint will be at a 5064 mm (199.38 in.) radius on all pieces (see Figure 5). This will facilitate alignment and use of semiautomated welding equipment.
- Stainless steel louvers appear to work for both the x-ray panels and beam dumps in the target chamber first wall. Tests showed that either B4C or stainless steel louvers pass the requirement, which is the debris shield contamination rate limit. Stainless steel louvers are substantially cheaper than B4C louvers, and since the base material does not matter, there is no strong reason to go to the additional expense of B4C louvers.

  Work is proceeding to test a prototype stainless steel louvered beam dump on Nova. The fixture is designed and is being reviewed with Nova personnel. The stainless steel louver without a vertical member has been tested on 2-beam, and a larger panel with 45° louvers with vertical members will be tested on Nova.
- The 65% Title II Design Reviews for the target chamber vacuum system and the target positioner were held this quarter. Creation of detailed mechanical drawings for the Target Bay vacuum components assemblies and detailed design of the positioner are proceeding.

FIGURE 5. Shown is the radiused weld prep that has been machined on one of the target chamber sections. (40-00-1098-2033pb01)

- A Diagnostics Working Group Meeting was held at Jackson Hole, Wyoming, to present the status of the NIF design and discuss the diagnostics to be placed on the NIF and other laser facilities. Data Acquisition, Calibration facilities, X-Ray Diagnostics, and Neutron Diagnostics were also discussed. Participants included representatives from LLNL, LANL, Sandia National Laboratories (SNL), Laboratory for Laser Energetics (LLE), and Atomic Weapons Research Establishment (AWE), who are also developing a Web page to share diagnostic design information. It will soon be password accessible by diagnostic users.
- The design of the diagnostic instrument manipulator (DIM) is proceeding. AWE has designed and is starting the fabrication of a test setup to verify the design of the rails that mount the insertion tube and the z-axis motor design. Detailed drawings of this test setup have been received. AWE is reviewing the DIM development schedule and LANL has volunteered the Trident laser facility for evaluating the prototype DIM.
- The Q31T mirror support frame, the largest and most complex, is located in a position within the Target Area Building that experiences the most severe environmental conditions. For this reason, it has been extensively analyzed to validate the proposed structural design, and detail drawings are being prepared so it can be a model for the remaining frames.

Final Optics Assembly. Title II second quarter progress for the FOA is summarized below.

- The Mid-Title II (65%) FOA design review was presented in February. All mechanical subsystems were reviewed: integrated optics module (IOM), final optics cell (FOC), debris shield cassette, actuation system, alignment fiducial arm, 3ω calorimeter chamber, vacuum isolation valve, thermal control system, and vacuum/venting system. The optical configuration was described, and a scientific update on frequency conversion, with special attention paid to the performance error budget, was also given. Analysis results presented included structural, seismic, thermal, and computational fluid dynamics.
- The optical configuration was revised to implement the requirements imposed by ECR180 (additional diffractive optic cassette). Extensive ghost analysis and optical chief ray tracing provided detailed input to establish the revised configuration.

- Work has focused on incorporating ghost mitigation measures (e.g., absorbing glass) into the IOM. The ghost analysis has indicated that two sides and both ends of the of the IOM require mitigation. It is highly desirable to use glass that is textured appropriately to diffuse or scatter the incident light, thereby reducing the fluence on subsequent surfaces. Work has also been proceeding on ghost control in the FOC. Two sides of the cell are “illuminated” by stray light at sufficient levels to require protection. The baseline scheme involves covering the sides of the cell and the retaining flanges with absorbing glass. Key test data is needed for the damage limits of various materials (aluminum surfaces, ceramics, and absorbing glass) to complete the design.
- Major pieces of FOA prototype hardware were received: the calorimeter chamber, three integrated optics modules, large test stand, and debris shield cassette hardware. The test stand was installed in Bldg. 432, and the pumping system was located at the base of the stand, as shown in Figure 6. It will permit testing of the prototype hardware in an orientation consistent with installation on the target chamber. The vacuum isolation valve will be installed after the valve body is caustic-etched, and the revised bell crank mechanism is fabricated. The calorimeter chamber is ready for installation thereafter.
- All hardware for the CAVE has been delivered and assembled in Bldg. 432 (see Figure 7). Specifically, the following items were installed: optical table, temperature-controlled clean room, high-power laser, and large reference mirror. The laser operational safety procedure and interlocks were approved so that operations can begin.

Operations Special Equipment. Title II design is progressing well. Hardware prototyping is providing excellent cleanliness data and design validation. During the second quarter, the group completed the Transport and Handling (T&H) 35% Review, the OAB Mid-Title II (65%) Review, and an Informal OAB Corridor Review.

- Line-replaceable unit (LRU) refurbishment meetings with various LRU owners continued in order to develop requirements for refurbishment. Requirements for LRU and equipment movement in the OAB corridor were documented. The drawing package of the corridor is now complete.
- The detailed designs of the bottom-loading, top-loading, side-loading, switchyard, and Target Area delivery systems are progressing well. The 35% Review was completed this quarter.

FIGURE 6. The full-scale FOA test stand (large steel structure in center of photo) was installed in the Bldg. 432 high-bay in March. A CAD representation of the FOA has been superimposed to illustrate the soon-to-be-installed hardware. The actual vacuum isolation valve is shown on a support stand at the bottom of the photo. (40-00-1098-2032pb01)

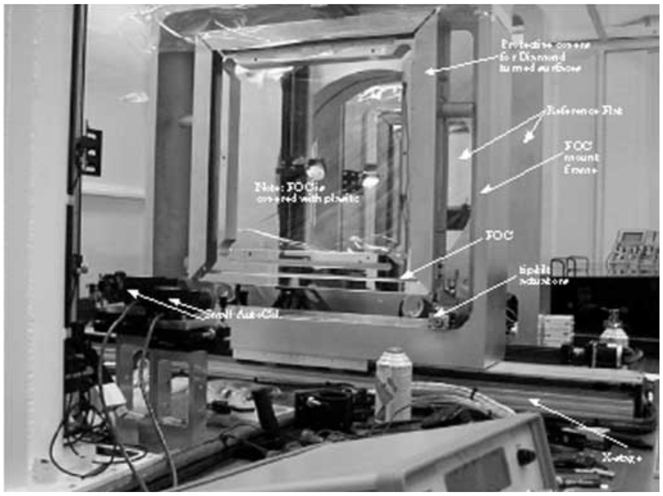

FIGURE 7. The CAVE FOC mount, the reference flat, horizontal slide, and autocollimators for tracking tip/tilt as the mount is translated. (40-00-1098-2031pb01)

- The interface and Phase II requirements review was held this quarter with RedZone Robotics, Inc./AGV Products, Inc. to clarify the Laser Bay transporter deliverables and the requirements of the design. Permission was given to the vendor to start procuring long-lead items for the fabrication of the first vehicle.
- The assembly and testing of the T&H prototype hardware is progressing well. The "clean" testing of the cover removal mechanism for the bottom-loading canister has begun and will be completed next quarter. The assembly of the components for the insertion mechanism is complete, and dirty testing of the mechanism has begun. The hardware for the scissors mechanism and vacuum cover has been fabricated, and assembly will start in April.
- The OAB hardware designs and the simulation model were presented in February at the Mid-Title II (65%) design review. The review was highly interactive, key areas of interest were discussed with the interface partners, and all comments have now been addressed.
- The software requirements specifications were completed for the FEPs for bottom-loading, top-loading, side-loading, and switchyard delivery systems. The control points (sensors, actuators) for all T&H prototype delivery systems were specified. A draft interface specification was completed identifying data interfaces between the Laser Bay transport system computer systems and the T&H FEPs and Supervisory System. A "proof of concept" graphical user interface of an OAB integrated desktop was presented at the OAB 65% review and received very positive feedback.

Start-Up Activities

Integrated Project Schedule (IPS) Assessment. The month-end March status of the IPS showed no impact to Level 0–3 milestones. Current schedule issues are (1) the coordination challenge of interfacing Conventional Facilities multiple subcontractor activities with Special Equipment activities, (2) restructuring the Optics schedule module in the IPS from process-based (development/facilitization/pilot/production) to component-based (windows/lenses/mirrors/polarizers/etc.) activities, and (3) adding equipment installation details to the IPS.

Start-Up Planning. A draft Start-Up Plan for the first bundle has been completed on schedule. The purpose of this plan is to outline the sequence of integrated system Operational Test Procedures, which constitute start-up of the first bundle of eight beamlines. These integrated tests will be conducted once all first bundle special equipment in Laser Bay 2 has been installed and Acceptance Test Procedures have been completed. After start-up has been successfully completed, the first bundle will be ready for ICF/NIF Program experimental operations.

Advanced Operations Planning. A draft *NIF Operations Procedures Plan* document has been completed. The NIF Start-Up and Operations Planning Group is responsible for providing the management and technical oversight necessary to ensure a smooth project transition from the construction and equipment development phase of the NIF to integrated beamline operation in a fully functional facility.

Optics Technology

Facilitization efforts are proceeding well. The initial evaluation of the Schott laser glass melting campaign at the end of the first quarter was very promising. The glass was formed at full size without any major problems with inclusions or fracturing. Minor problems with the melter and batch feeding system will be addressed when the melter is rebuilt for the pilot production campaign in the first quarter 1999. Though not all of the specifications were met during this campaign, the assessment both at Schott and LLNL is positive. Hoya started and completed its final subscale campaign at the production facility in Fremont, California. The glass met nearly all the NIF specifications, but OH content needs to be reduced slightly. Fine annealing of both the Schott and Hoya glass will be complete in the third quarter, so the glass can be evaluated for homogeneity.

Facilitization of the remaining four rapid crystal growth tanks was accelerated during the second quarter due to the early decision to select rapid growth as the baseline process for NIF crystals. Several crystals were fabricated from development boules for frequency conversion testing on Beamlet; the optical quality and damage threshold meet NIF specifications.

Finishing facilitization at Zygo is on schedule and going extremely well. The NIF facility was formally dedicated in February 1998. The start of the Tinsley building construction was delayed from November 1997 until April 1998, primarily due to the extended rains. Aside from the building, most of the equipment design and construction at Tinsley is on schedule.

Coatings facilitization contracts were negotiated and signed with Spectra Physics and LLE in the second quarter. Veeco Process Metrology, formerly Wyko, delivered interferometry unit Nos. 2 and 3 to LLNL and Hoya, respectively. Facilitization efforts in other metrology areas, including photometry and surface inspection, also went well.

Upcoming Major Activities

During the third quarter of FY98, Conventional Facilities will complete the CSP-3 Target Bay and Mat Foundations work and begin the CSP-4 erection of the Laser Building steel. In the OAB, the concrete foundations will be completed, and the steel work will begin. In Special Equipment, the 65% and 100% design reviews will continue at a faster pace, and procurements will be initiated for some of the Beam Transport items such as the Spatial Filter Vacuum vessels. In Optics, the contracts for mirror and polarizer substrates should be placed, and the vendor facilitization activities will continue.

NOVA/BEAMLET/NIF UPDATES APRIL–JUNE 1998

R. Ehrlich/P. Wegner/S. Kumpan

Nova Operations

Nova Operations performed 229 experiments during this quarter. These experiments supported efforts in ICF, Defense Sciences, university collaborations, Laser Science, and Nova facility maintenance. At the beginning of June, the operation of Nova expanded back to a full two shifts per day, with 2.5 hours of overlap between shifts. Nova now operates four days per week continuously from 6:30 a.m. to 12:30 a.m. This will allow the operations group to achieve the goal of 900 experiments in FY 1998.

Several new systems and diagnostics were added to Nova. The temporary installation of the $f/8.5$ lens system on one beamline was successful. Experiments were successfully performed utilizing this system both with and without an array of wedged KDP crystals for studying the effect of a polarization smoothing technique on the backscatter levels of various targets. New diagnostics, such as a driven wave Thomson scattering measurement system, were fielded. Another new system was added in the laser bay, which allows beamline 10 to be used as a backlighter. This increases the number of beamlines that can propagate the separate backlighter pulse to four.

Many improvements were made to the Petawatt system. Beginning in April, the first full-power target experiments were performed with the Petawatt deformable mirror. Using the sensor packages, it was determined that there are ~4 waves of static distortion in the Nova chain and several waves of thermal distortion due to heating of the amplifier disks. The mirror successfully corrects for these distortions by running a probe beam through the chain to the Hartmann sensor, and actively correcting the wavefront up to ~20 minutes before a shot. Averaging software was developed to keep the mirror from overcorrecting for turbulence occurring on a fast time scale. Pump-induced distortions are on the order of 1.8 waves peak-to-valley, and are corrected for by creating a precorrect file from the previous shot, which is applied immediately before the system shot. Because the cumulative wavefront correction is applied early in the amplifier chain, it was necessary to increase the diameter of the spatial filter pinholes early in the amplifier chain to avoid clipping. This allows high spatial frequencies to propagate through the chain, generating small-scale modulation in the near-field irradiance. This modulation causes a significant fraction of the beam energy to scatter outside the central focal spot.

Prior to using the wavefront control system, the focal spot at target chamber center was many times diffraction limited, with multiple hot spots within the central peak due to thermal distortion of the amplifier disks. With the deformable mirror, a single hot spot ~10 μm in diameter (full-width-half-maximum) is reproducibly delivered on target. This spot typically contains ~28% of the total energy in the central peak, corresponding to a maximum intensity of ~4×10^{20} W/cm^2 to date.

Beamlet Operations

During the third quarter of FY 1998, Beamlet continued to provide a testbed for validating the laser physics and engineering foundations of the National Ignition Facility (NIF). We completed a total of 128 full-system shots, 72 of which were dedicated to testing prototype NIF frequency converters, 25 to testing prototype fused-silica final optics at high 3ω fluence, and 16 to completing high-power, high-B-integral 1ω beam propagation experiments with angularly dispersed bandwidth as required for 1D smoothing by spectral dispersion (SSD). At the end of the quarter, we began a series of experiments for the French Commisseriat d'Energie Atomique (CEA) and completed a 15-shot campaign to measure thresholds for 3ω filamentation and damage in high-quality fused silica.

The frequency conversion work on Beamlet involved extensive testing of NIF production crystals, both conventional growth and rapid growth, in a 37-cm-aperture final optics cell (FOC) in the NIF-like vacuum environment of the Beamlet final-optics-assembly test mule. The purpose of the work was to validate the design of the NIF frequency converter and verify the physics models on which a detailed error analysis of its performance is based. As part of these tests, we measured (1) the second-harmonic conversion efficiency of a converter incorporating the first rapidly grown 37-cm type-I KDP doubler, (2) the third-harmonic conversion efficiency of a converter consisting of conventionally grown crystals from NIF production boules, and (3) the third-harmonic conversion efficiency of a converter consisting of the rapid-growth doubler and the first rapid-growth 37-cm tripler. Maximum efficiencies (whole beam, time integrated) were 70.5%, 75%, and 73% respectively measured at drive irradiances of between 3.6 and 3.9 GW/cm^2 in 1.5-ns square pulses. In each case, the measured efficiencies were within a few percent of modeling, assuming values for component transmissions measured prior to the experiments.

A small number of additional frequency conversion experiments were done to evaluate the effects of increased bandwidth with angular dispersion on 3ω efficiency, under conditions relevant to beam smoothing. Tests with 80 GHz (3Å) of 1ω bandwidth critically dispersed and 135 GHz (5Å) of bandwidth critically dispersed and 3× the critical dispersion condition showed reductions in efficiency to be less severe by ~30 to 40% than what was expected based on 2D modeling. The importance of choosing the correct dispersion direction was also demonstrated by reversing the sign of the dispersion along the tripler optic axis and measuring a corresponding reduction in efficiency of as much as 5%.

Tests to measure the effects of increased bandwidth and dispersion on 1ω beam quality in the laser amplifier were more extensive. The purpose of the measurements was to determine how the conditions for SSD reduce the operating margin against B-integral induced-beam breakup. The tests were conducted with 500-ps pulses using 167-μrad pinholes in the cavity spatial filter and with no pinhole in the transport spatial filter. The pulses were propagated through unpumped booster amplifiers to produce the high B-integrals expected at the end of a long, saturating ignition pulse. At B integrals in the booster amplifiers up to ~25% higher than the NIF limit of 1.8 rad, no difference in near-field beam quality was observed for the baseline SSD condition of 80 GHz critically dispersed, for which the divergence is ±7.5 μrad. Onset of beam degradation was observed when the divergence reached ±25 μrad, at which point the near-field irradiance contrast measured at a B of 2.1 rad was equivalent to the contrast measured at 2.3 rad without SSD, suggesting a reduction in operating margin of ~10%.

Full-aperture tests of high-damage-threshold silica components were also conducted for the first time this quarter. The goal of the campaign was to test a NIF-like FOC and debris shield at average 3ω fluences of 6 J/cm^2 in 3-ns square pulses for 20 shots. The initial shot sequence consisted of a five-shot ramp and eight shots at 6 J/cm^2, with only the FOC containing frequency conversion crystals and a final focus lens installed in the test mule. Optics condition during this part of the campaign was quite good. After installation of a debris shield and seven additional shots at 6 J/cm^2, extensive damage occurred on the output surface of the tripler and the input surface of the lens. Evidence suggests that the damage was related to a back reflection from the debris shield, which was misdirected onto the Al wall of the FOC.

The first of the French CEA campaigns was completed this quarter. The purpose of the campaign was to test fused silica windows with a large-aperture, high-quality 3ω beam to determine thresholds for filamentation and damage that could be extrapolated to the target chamber vacuum windows on the LMJ. Two parts were tested (Suprasil 312 and Herasil 1SV) in the test mule vacuum chamber at a plane 2 m downstream of the *f*/20 3ω focus, which was spatial filtered. Onset of filamentation occurred at an aperture-averaged intensity-length product of between 25 and 30 GW/cm as measured at a pulse duration of 200 ps. High-fluence testing up to aperture-averaged fluences of 13 J/cm^2 in 3-ns produced damage that was significantly less than expected from off-line tests.

National Ignition Facility

Overall progress on the NIF Project remains satisfactory for the third quarter of FY98. NIF Conventional Facilities construction made good progress, and a total of eight DOE/OAK Performance Measurement Milestones were completed. In June, Walsh Pacific (CSP-3) finished its major concrete work in the Target Building and Switchyards essentially on schedule. Nielsen Dillingham's (CSP-4) steelwork in the Laser Bays started in April, about six weeks later than originally planned. This delay was anticipated during the bid period for CSP-9, Laser Building Finish & Central Plant, so the milestones were adjusted by four to six weeks to compensate. The critical path for Conventional Facilities, which runs through CSP-9, is delayed by roughly two to four weeks, but the fourth quarter 03 Project completion date is being held.

In Special Equipment, 89% of the Mid-Title II (65%) design reviews, and 24% of the Title II (100%) final design reviews have been completed. Design reviews continue to be successfully held, and drawing production continues, although at a rate slower than planned. Some reviews and the follow-on procurement activities are now beginning to lag the schedule dates, which reduces the available schedule float for these activities. Efforts are now under way to streamline the review process to maintain the FY98 Title II completion schedule. The Beam Transport Vessels and Enclosures procurement was awarded early in June, and the Target Chamber contract is on schedule.

In Optics, facilitization is moving well at all NIF vendors as they prepare for pilot production in late FY98 or in FY99. Zygo and Corning will both begin pilot production in the fourth quarter in portions of their facilities while they complete facilitization tasks in other areas. Schott, Hoya, and Tinsley will begin their pilots in the first quarter of 1999. KDP rapid growth and finishing pilots have already started at LLNL, and the external-vendor rapid-growth pilots are set to begin in early FY99 at Cleveland Crystal and Inrad. Facilitization at the University of Rochester Laboratory for Laser Energetics and Spectra-Physics is on schedule to begin their pilots later in FY99. The longest lead substrate material, polarizer substrates, has already been received for pilot. The first NIF production optics orders were awarded to Schott and Ohara for the polarizer substrates, and to Ohara and Pilkington for LM3 mirror BK7 substrates.

Key Assurance activities during the third quarter to support the Project included Assurances safety support and QA surveillance of major concrete pours including the initiation of shielding concrete pours. Litigation activities included litigation support to the DOE for the settlement of 60(b)—Agreement to prepare a Programmatic Environmental Impact Study supplement analysis and to conduct specific evaluations and surveillance of potential buried hazardous materials—and the overall litigation against the Stockpile Stewardship Program's *Programmatic Environmental Impact Statement*; the NIF Construction Safety Program; interface with the Institutional surveillance for buried hazardous/toxic and/or radioactive materials; Risk Management Plans; the *Final Safety Analysis Report*; assurance surveillances and audits; and support of environmental permits. All are on schedule.

There were no Level 0, 1, 2, 3 milestones due during the third quarter. There were 26 DOE/OAK Performance Measurement Milestones due, and 21 were accomplished. There was a total of 56 milestones due through the end of the third quarter, and 52 have been accomplished, for an overall variance of 4. This is based upon DOE/OAK's concurrence with Rev. c of the FY98 Milestones, which was effective May 1, 1998.

The current assessment of Project status remains similar to that stated at the end of the second quarter; that there will be no change to the fourth quarter 01 Level 2 milestone for the End of Conventional Construction, nor to the fourth quarter 03 Project Completion date. However, it is still anticipated that there could be a three- to six-week impact to the fourth quarter 01 Level 4 milestone for the start-up of the first bundle. Due to the status of Laser Bay steel erection, the current assessment is that there may be a four- to six-week impact to other internal milestones for construction. The Project Office is working with Nielsen Dillingham to determine how best to accelerate the steel work early in the fourth quarter. The Integrated Project Schedule is also being reviewed to find potential work-arounds to minimize impact to the first bundle.

Site and Conventional Facilities

NIF Conventional Facilities construction made good progress during the third quarter and completed a total of eight DOE/OAK Performance Measurement Milestones. Of these, five of six due in the third quarter plus two remaining from the second quarter were completed, and one due in the fourth quarter was completed early. In June, Walsh Pacific (CSP-3) finished their major concrete work in the Target Building and Switchyards essentially on schedule (plus nine rain days), as a result of several months of accelerated double shift work (see Figure 1). Nielsen Dillingham's (CSP-4) steelwork in the Laser Bays started about six weeks late in April, was delayed by rain in early May, then began to accelerate in late May and early June. However, efforts to further accelerate the schedule in June did not materialize. Therefore, due to the lack of progress on CSP-4 steelwork in the Laser Building, there is approximately a four to six week lag in the completion of internal milestones for this subcontract. This delay was anticipated during the bid period for CSP-9, so the milestones were adjusted by four to six weeks in CSP-9 to compensate for the delays coming from CSP-4. However, the critical path for Conventional Facilities that runs through CSP-9 is delayed by roughly two to four weeks. In addition, the field team is closely watching progress to ensure that the facility will be essentially dried-in by the start of the rainy season.

FIGURE 1. Switchyard 1 concrete pour. (40-60-0598-1213#7pb01)

FIGURE 2. Looking north from Switchyard 1. (40-60-0598-1007#3pb02)

Efforts to accelerate roofing activities under CSP-4 may be undertaken to ensure the dry-in of the facility.

June was generally a positive month for the NIF Conventional Facilities construction effort; clear weather allowed work to proceed at full speed. Walsh Pacific (CSP-3) completed its work and demobilized from the site. Nielsen Dillingham (CSP-6/10) began work in the Target Area, Switchyards and Diagnostics Building, and has made excellent progress to date. Although access to the work area was delayed for Nielsen Dillingham for CSP-6/10 due to Walsh's late departure, the team anticipates full recovery of the schedule. Work in the Optics Assembly Building (OAB) made good progress in the third quarter. The erection of structural steel began several weeks early, placing the work on the OAB slightly ahead of schedule. The site utility work is progressing at a fairly slow pace; multiple prime contractors on the site are creating some challenges to the team's ability to open excavations that do not choke the site circulation. The work has not progressed per the initial schedule, however, there has not yet been an impact to the critical path of the Conventional Facilities work. Significant, visible progress has resulted from field efforts in June.

Three FY98 DOE/OAK Performance Measurement Milestones were achieved on the NIF site in April: the issuance of the Notice to Proceed for CSP-6/10, the start of Laser Bay Core Structural Steel Erection (see Figure 2), and the completion of Laser Bay Footings. One DOE/OAK milestone, the completion of Storm & Sanitary Sewer Lines, was delayed until October. This adjustment does not affect the critical path on either Conventional Facilities or the Project. One milestone, Switchyard Mat Slabs Pour, was achieved in May. Four milestones were achieved in June: Start Concrete F/R/P/C East Wall for Switchyard 2, achieved with the erection of forms; Start Overhead Platform Set-up for Laser Bay 2, achieved with delivery and staging of the platform materials; Start Concrete F/R/P/C for Target Bay Cylinder, achieved with erection of forms; and OAB Start Structural Steel Erection, originally scheduled for July, also achieved in June. The milestone not achieved was the Complete Structural Steel Erection for the Laser Bays, currently estimated for completion in August, seven weeks later than originally planned.

- All contract work by Walsh Pacific, CSP-3, was completed in June except for the curbs that sit on top of the footings between grids 28 and 30 (between the Laser Building and the OAB). This work was removed from CSP-3 and added to CSP-5 to allow for better access between the Laser Building and the OAB. The total concrete placed was 6872 yards during the third quarter. This contract is considered to be 100% complete.
- Steel erection of the Laser Building Core by Nielsen Dillingham, CSP-4, was completed in June, and bolting and plumbing is approximately 25% complete. Erection of Laser Bay 2 is

approximately 75% complete, but bolting and plumbing has not started.
- Four isolation pads, slab on grade, and return walls bordering the OAB equipment pads were placed in three separate pours by Nielsen Dillingham, CSP-5. The Special Equipment granite slab was placed on the spatial filter tower alignment pad.
- Work began in earnest for Nielsen Dillingham, CSP-6/10, during June. The formwork for the Target Bay 18-in. and 30-in. columns was put in place with rebar. The first concrete pour for the columns was completed utilizing a 52-m pump truck and the 5000-psi shielded concrete. The second pour for the remaining columns in the Target Bay was also completed. All of the first three pours were completed to the –22.75-ft level.
- The majority of work performed in June by Hensel Phelps, CSP-9, was related to the site utilities. Material for the overhead platform to be used in the Laser Bays was received, and staging began in June. Site utility work is continuing, including installation of mechanical utility bundles at the East side of the site up to the Central Plant and installation of chilled water piping, hydronic piping, domestic water, and sewer lines around the OAB.

Special Equipment

Design reviews continue to be successfully held, and drawing production continues, although at a rate slower than expected. Procurement packages are being reviewed, revised, and released. Detail planning for FY99 is well under way, and reviews of the FY99 Cost Account Plans have been started.

Mid Title II (65%) design reviews were held for the Final Optics Damage Inspection System, the Pulse Synchronization System, the Laser Injection, and for the Operations Special Equipment Control System Supervisory Controls. Final (100%) design reviews were held for the Target Chamber Vessel, the Line Replaceable Unit (LRU) Assembly Verification System, the Vacuum System, the Supervisory Control (Applications), Target Area Auxiliary Systems, and the Communications/Environment Monitor System. In addition, Final Documentation and Procurement Reviews were held for the Beam Transport Enclosures for the structural supports for the Transport Spatial Filter (TSF), Cavity Spatial Filter (CSF), and Preamplifier Module Support Structure (PASS). Design review reports were prepared and released for the Supervisory Control (Framework) 100%, the Final Optics 65%, the Computer Systems 100%, and the Target Area 65% reviews. Changes to the required content for the 100% design reviews are being considered to reduce the amount of preparation and presentation time. This is based on the successful completion of most of the 65% reviews focusing on the design, and intent to focus the 100% reviews on the procurement readiness and design basis book completion for that subsystem.

Laser Systems. The Laser Systems detailed designs are progressing roughly according to plan. Drawings are being completed at a rapid pace, and manufacturing prototypes or first-article prototypes of various assemblies are being procured and tested. The emphasis of prototype testing has shifted from optical performance to more engineering-like concerns such as cleanliness, vibration, installation, assembly, and kinematic mounting.

- During the third quarter, the Preamplifier Module (PAM) prototype was assembled, and testing began. The electronics bay was installed and tested, and the regenerative amplifier was activated. Alignment of the multipass amplifier is in progress in preparation for energy extraction tests. This prototype will be used during the next quarter to validate the PAM design relative to the system requirements. Numerous technical issues with the design of the Master Oscillator Room (MOR) hardware were also addressed. Stability issues with the baseline oscillator design motivated the identification of several commercially available alternative oscillators. The most promising of these have been ordered to validate their performance relative to their specifications. The FM-to-AM conversion noted during the last quarter motivated a change in the fiber used in the MOR design from a polarization-maintaining fiber to a polarizing (PZ) fiber. The PZ fiber has been specified and a test-run ordered from 3M for testing. The prototype arbitrary waveform generator system was coupled with the electro-optic modulator to produce the baseline Haan optical pulse from the MOR system (see Figure 3). Alignment testing of the prototype PAM was completed during the past quarter. The procedure was defined, and the rails were successfully aligned. Maxwell Physics International presented a successful design review for the PAM power-conditioning unit.
- During the past quarter, four tiger teams were established to analyze and interpret amplifier performance data collected using the AMPLAB prototype. Computer codes for reducing AMPLAB gain and wavefront data were revised and tested. Much of the wavefront data were reduced and compared with model predictions. Reduction of the gain data is under

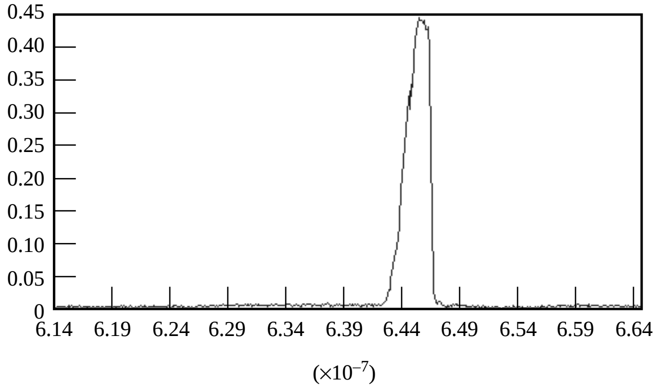

FIGURE 3. Optical pulse with a contrast ratio of 175:1. (40-60-1198-2258pb01)

way. Additional thermal recovery experiments were performed on the AMPLAB after insulation was applied to the outside surfaces of the amplifier, beam tubes, and mirror towers, to improve thermal stability; this data is being analyzed. Detailed hardware designs are proceeding at a rapid pace, and a prototype amplifier Frame Assembly Unit was ordered and is being fabricated. The slab holder design was modified to address slab abrasion and assembly difficulties experienced on the prototype. A management review was conducted for the conversion of Building 381W into the Frame Assembly Unit Assembly Area. The plan was approved, and the Program will cover the costs for the conversion, including the clean room.

- The Plasma Electrode Pockels Cell (PEPC) prototypes underwent numerous mechanical and optical tests during the third quarter to validate the design. The kinematic mount design was tested to demonstrate adequate repeatability, capture range, and reliable operation of the mechanisms. The design performed very well overall, and minor modifications were noted for the production hardware. Vibration testing was completed to provide data for system stability performance models. A detailed tolerance analysis was completed for the PEPC, accounting for insertion/removal, alignment, structure and manufacturing tolerances. Optical performance of the cell under nominal conditions demonstrated that the design exceeds requirements for both "on" and "off" states. The design of the PEPC assembly fixture was completed, and the drawings are being reviewed. The PEPC front-end processor (FEP) prototype was deployed in the PEPC Lab to test compatibility of the controls with the harsh EMI environment of the PEPC.
- The Power Conditioning System Mid-Title II (65%) design review was held in April, and the design was commended by the review committee. A full prototype of the Power Conditioning System module was completed with the procurement of parts for the first-article module. Actual procurement of the first-article components will provide for firm cost estimates for production. Nearly all components arrived during the past quarter, and assembly and installation has begun. A variety of critical fault modes were simulated using the prototype module, including capacitor and bus faults. The system performed as expected and minimal damage to the hardware was sustained. Most notably, the 1.4-mega-ampere bus fault validated the performance of the module enclosure, blast doors, and fire prevention strategy. The ST-300 switch testing was completed in May. Testing of the ST-300E at greater than 540 kA indicates that switch lifetime will be in excess of 1500 shots.

Beam Transport System. In this quarter, all major structural and vessel packages for upcoming procurements were finalized and reviewed. The majority of laser bay steel structures were issued for bid. Contracts for the laser bay steel-mill order and the fabrication of spatial filter vacuum vessels were awarded. Shipment of 1000 tons of stainless vessel plate was initiated. Over 500 drawings were completed and released under Configuration Management. Much progress was made in streamlining the submittal process to facilitate the timely release of procurement packages. Construction Planning activities developed into focus groups for the PASS, the War Zone (i.e., the optical system in the TSF optical plane area), Periscope (the structure that supports the PEPC, polarizer, laser mirrors LM2 and LM3), and Switchyards to establish more detailed links in the Integrated Project Schedule.

- Production of the spatial filter stainless plate is near completion with final product completion slipped to July and final invoicing anticipated by the end of August. Shipment of plate material to vessel fabricators is in progress and approximately 60% complete. Title II procurement review was completed for the spatial filter vacuum vessels, including approval of end vessel and center vessel engineering safety notes. Contracts were released in June for vacuum vessel fabrication.

- The detailed drawings for the Switchyard Beam Tubes are 95% complete. The horizontal quads remain to be detailed and should be completed by early July.
- The Roving Mirror Diagnostic Enclosure design is proceeding. Substantial progress was made incorporating updated interfacing structures and assemblies into the Pro-E model. The updated assembly details allow for development of part details based on real fit and dimensional constraints.
- Design development was concentrated on the large interstage components consisting of docking frames at the spatial filter end vessels and at the Switchyard wall to ensure fabrication and delivery do not impact critical path closure of facility openings. Planning and preliminary development of options and methods for cleaning beam tube enclosures is progressing.
- During this quarter the Spatial Filter Vacuum System Title II 100% Design Review was completed.
- The Switchyard #2 structure drawing package was completed and submitted into Configuration Management. The Title II Procurement Review for SY#2 was scheduled for early July, and the draft Statement of Work and fabrication specification were distributed for comment.
- The Power Amplifier, Main Amplifier, Laser Mirror 1, and Periscope support structure design drawings were completed. The Laser Bay Support Structures Fabrication Specific-ation is completed. The CSF Optical Bench, TSF Optical Bench, Injection Structure, and PASS design calculations were completed. Thermally sprayed aluminum was chosen to coat the interior of the Laser Mirror 1 and the Periscope after examining many paints, ceramic, and thermal metallic applications. The aluminum coating will be mechanically finished to a 125-rms finish to accommodate cleaning.
- A review of thermal analysis in the Laser Bays was presented. A significant conclusion was that the fluorescent lights under the Laser Bay beam cavities will adversely affect the wavefront of the laser. The solution was to provide motion detectors to power these lights only when needed, minimizing the thermal effects. In addition, a laser alignment control system override may be needed to shut lights off on demand to allow the structures to thermally stabilize.
- The 100% Title II review for the LRU Assembly Verification System was presented in May. The comments received were helpful and did not reveal any major issues.
- Good progress was made in developing and demonstrating an acceptable transport mirror attachment design. At an internal review in April, it was recommended to proceed with two concepts—an expansion arbor and an undercut. These have been tested at subscale. The results for both were very encouraging, with mirror surface deformations less than 20 nm.
- Testing of actuators is producing useful information for final design. The reliability, availability, and maintainability (RAM) testing of the harmonic drive actuators is well under way (>2 million cycles) and is showing that design to be robust. Testing of the friction drive actuator, planned for use on the periscope LRU, has revealed that there is some slippage between bearings and races that is load dependent. This error is being quantified to determine whether the controller can accommodate it or whether a design change will be necessary (i.e., use the harmonic drive actuator).
- Testing of prototype hardware continued. The shutter/beamdump (shown in Figure 4, below left) tests indicated that a design modification is needed to prevent the gate valve from binding during operation. Linear bearings will be used. RAM testing of this LRU will begin in July. The LM4 (switchyard mirror, below right) LRU is undergoing modal testing to confirm the finite element analysis of the individual mirror mounts, the frame assembly, and the kinematic mounts.

Integrated Computer Control System. Title II design progress is satisfactory. Five out of eight scheduled 100% reviews have been completed. Three reviews were completed in the third quarter: the Video Distribution System, a prototype of which was demonstrated at the review; the Supervisory Software, followed by two weeks of advanced training in object-oriented software engineering (construction of the first phase of the Production Prototype for demonstration in October 1998 has started); and the Communications System and Facility Environmental Monitor, also projected to meet deployment cost goals.

- Title II work is complete for computer systems. Installations of the NIF Testbed server computer, network diagnostic equipment, and numerous software items were completed in June, including graphical user interface tools, network management software, and security upgrades. Significant upgrades to the capability of the Rational Ada-95 compiler and ORBexpress

FIGURE 4. The shutter/beamdump testing, shown at left, and the LM4 switchyard mirror, shown on the right. (40-60-1198-2259pb01) (40-60-1198-2404pb01)

object request broker for Solaris supervisory and FEP systems were successfully delivered as a result of outstanding collaboration between the vendors.

- The design for the first Production Prototype of the NIF Computer Control System software was featured at the 100% review. The prototype will be implemented during the fourth quarter to be demonstrated and submitted for testing in October 1998.
- Prototype testing of the t-1 Abort System on the programmable logic controller platform was performed. The system was simulated for one laser bay, and the terminal-to-terminal response time of the system was measured to be 1.8 ms. Although an additional 5 to 15 ms is expected when all overhead is accounted for, these results are well within the 70-ms real-time processing requirement of the system. The Industrial Controls Requirements and Design Description document was revised to reflect the final design, and the detailed failure modes and effects analysis was completed for the t-1 Abort System.
- Optics damage inspection data was generated from Beamlet experiments, locating an optic containing a broad spectrum of flaws at several positions in the beamline that was imaged repeatedly with various pinhole configurations, camera integration times, and other system configuration variations.
- A deployment model of the Control System software framework was created that allocates computer processes and key framework objects among the generic FEP, supervisory workstation, file server computers, and control points. A specific deployment model of the first production prototype was then created that depicts the vertical slices (i.e., the subsystem architecture from FEP level to supervisory level) to be built for all supervisory applications and participating FEPs.

Optomechanical Systems Management. Title II design activity is moving towards completion in several areas. The LRU Assembly Verification System completed its 100% design review, and the drawing package was released under Configuration Management (CM). Optical design prepared for its upcoming 100% review. Internal reviews of subsystems in final optics resolved lingering, detailed design questions. The final optics assembly (FOA) prototype hardware (full-scale) was assembled, and integrated testing began. The shutter beamdump hardware was received for validation testing, and the transport mirror assembly was assembled and underwent modal testing.

Optical Design

- The final optics damage inspection system design was modified to use only fused silica components. This reduces the susceptibility of the system to damage due to background radiation (neutron-activated) in the target chamber. The design was further improved to reduce the sensitivity to element decenter and tilts. The optical design of the final optics damage-inspection system was presented at the 65% review for that system with no optical design issues identified.
- The final optical design detail for the transport mirrors was described in a memo. Target area mirrors LM6 to LM8 should be offset slightly to maximize use of the mirrors' clear aperture. This information was communicated to mechanical design groups in optical mounts and target area structures for inclusion in their detailed Pro-E models.
- Ghost workshop #3 was held in May to discuss the extensive analysis that has been performed on stray light in the FOA. Numerous threatening ghosts near the mechanical structures have been identified, their fluences estimated, and areas for absorbing materials or baffles identified.
- Optical fabrication drawings for the transport mirrors were released (blank, finished, and coated). The fused silica blank drawings were revised based on a request from Optics Manufacturing. Thus, 60 drawings needed for large optics manufacturing are under CM. The release of the six KDP crystal drawings needed for Title II is being paced by resolution of detailed specifications and associated metrology for the doubler and tripler.

Optical Components. The first NIF production optics order has been placed with the awarding of polarizer and LM3 mirror BK7 substrates. Due to long lead times, polarizer substrates for pilot production were ordered more than a year ago from Schott and Ohara. Mirror BK7 substrates were awarded to Ohara and Pilkington for pilot production with fixed price annual options for all of production.

- Mirror substrate blank drawings have been revised and released based on final dimensions and specifications. Firm fixed price contracts were awarded in June for mirror substrates for the NIF mirror pilot, with firm fixed price annual options for production of all the glass required for the NIF. Competitive bids were received from four glass companies, and awards were made to two vendors: Ohara and Pilkington. Each received a contract in June for one-half of the pilot quantity of mirror substrates.
- The polarizer substrate blank drawing was revised and released based on final dimensions and specifications. Firm fixed price contracts were awarded to Schott and Ohara in June for polarizer substrates for the first half of NIF production, with firm fixed price options for the remaining half of production to be awarded in FY01.
- Extensive testing of a variety of materials by laser exposure, flashlamp exposure, and cleaning has shown that burnished, thermally sprayed aluminum meets all performance requirements for the interior of the laser by a wide performance margin.

Laser Control. The last of the 65% design reviews were completed in May, and Laboratory activity supporting prototype testing continued to increase.

- The 65% design reviews for Alignment Systems, Final Optics Damage Inspection, and Pulse Synchronization were presented during the third quarter for a total number of 22 Beam Control reviews during Title II. All remaining reviews will be at the 100% level.
- Initial measurements of optics transmission degradation in vacuum and in static nitrogen or argon environments suggest that parts in static gas are less vulnerable to outgassing than those in vacuum, and that the specification for outgassing in vacuum enclosures may have to be tightened.
- Most of the input sensor optical component drawings have been released and are being sent out for prototype fabrication. Mechanical fabrication will take less time, and most mechanical drawings are in checking. Some prototype mechanical parts are already on order, including the two-position shutter and optics insertion device that will also be used in other locations.
- The first prototype light source unit was assembled for the LM3 centering location. It will provide two pairs of 1.05-μm beams for comparison with similar reference sources at LM1 and the FOA.

- The optical configuration drawing for the Output Sensor was completed. Assembly of the prototype Output Sensor was begun early in the quarter and is now complete. The test stand for the sensor package was also completed, and the package and test stand are now undergoing integrated testing.
- The lab setup for integrated testing of all power measurement components including Output Sensor fiber launch optics, fiber bundles, fiber bundle-to-photodiode coupler optics, photodiode, signal dividing transformer, and transient digitizer was assembled in the Optical Sciences Laboratory.
- A prototype local-energy node board including the latest dynamic range enhancements was prepared for use with the Preamplifier Module prototype. Its performance will be verified by calibrated test equipment available in Nova.
- The Raytheon deformable mirror prototype was delivered and is ready for testing in the NIF Wavefront Systems Laboratory. The ThermoTrex deformable mirror prototype has not been delivered, but the acceptance tests at ThermoTrex were completed. Finite-element models of both vendor mirrors were generated at Livermore to calculate influence functions for inclusion in the wavefront correction modules of the NIF propagation codes.
- The completeness of the NIF beamline aberration model was improved by the addition of mounting and gravity sag aberration estimates. The LLNL-developed finite-element model influence functions for the Raytheon mirror were put in proper form for use in the adaptive optics part of the propagation code, and actual calculations incorporating these changes have recently begun.

Target Experimental Systems

- The Target Chamber Final Design Review was successfully completed in May. Comments from that review have been collected and initial replies issued. The majority of the 18-sphere plate sections have had the weld joint configuration machined at Precision Component Company. The first three plates were shipped to Pitt-Des Moines in Pittsburgh for a trial fit to evaluate the effectiveness of the shipping cradles, fitting gear, handling procedures, and overall matching of the three plates that will form the bottom of the target chamber.
- Construction work on the target chamber temporary enclosure, built on the E7 parking lot, continues with the completion of the 60-ft-diam, 62-ft-high enclosure. The enclosure is similar to an oil storage tank. It is made from 0.25” steel plates, seven courses high. A polar crane, HVAC, insulation, lights, and a removable roof will be added.
- The prototype beamdump was placed on Nova, and samples changed out weekly for three weeks of mostly gas-bag shots. An additional fused silica optic was added to the samples for off-line laser damage studies. The beamdump survived without excessive stainless steel ablation. Then, the prototype beamdump was placed back on Nova for a week of hohlraum shots. After a week of high-yield shots, the beamdump will be removed from the chamber and additional analysis performed.
- The investigation of the trade-offs between increased protective disc sizes for the target positioner and the need to clad some portion of the cryostat itself has been carried forward. Although a larger protective disc, which can completely shield the cryostat, gives rise to more ablation than the combined ablation from a smaller disc and the cryostat, the difference may not be enough to warrant periodic recoating of the cryostat; as the total ablation of relatively benign B_4C is still less than the amount of debris from the target assembly and the first wall. It now appears that a sufficient quantity of cryogens for several days’ holding can be accommodated in a cryostat of a geometry that can be completely shielded from target x rays.
- A web page has been developed to share diagnostic design information with representatives from LLNL, LANL, SNL, LLE, and AWE. The web page is still under review for content and organization and will soon be password accessible by diagnostic users.
- A design review for the NIF Grounding and Shielding Plan review was conducted in April, and no significant problems were identified in the review. The new draft of the NIF Electrical Grounding, Shielding & Isolation Plan has been entered into Project Database Management for review. A detailed analysis of electrical noise induced in cables in the Target Bay was conducted, and the design for the Target Chamber Ground Monitor System is being developed using commercial ground fault monitor/alarms systems.
- As a result of revised calculations performed by CSA for the seismic loads applied to the top of

the pedestal and the target chamber to floor restraints, there has been some concern that the loads may exceed cited loads that were given to Parsons in an interface control document (ICD) in August 1997. Considerable design and analysis effort has been expended to resolve the differences between the existing calculations.

- A revised tritium usage projection for NIF has modified plans for implementation of the tritium-related systems. The schedule for implementation of all environmental protection elements has been extended.
- The 100% Design Review for Target Area Utilities & Cable Trays was held in June. No significant design action items were identified. All Title II deliverables have been completed and submitted to the Project Office.

Final Optics Assembly

- Significant progress was made in understanding and projecting the frequency conversion performance for the NIF final optics design. At a scientific review held in April, the converter design, its requirements, and error budget were presented. Requirements from this budget have since been flowed down to metrology equipment, crystal fabrication, coating performance, and mount tolerances.
- As a result of the intensive Beamlet experiments and the change-out/testing of different optical components, the single prototype final-optics cell has been assembled and disassembled many times. This heavy use has proven the robustness of the mechanical design and led to development of very detailed procedures for clean assembly.
- Major pieces of prototype hardware were assembled in the high bay of Building 432: the vacuum isolation valve, the calorimeter chamber, debris shield modules, four optics modules (one manufactured as a welded assembly and three by a casting process), and the large test stand. The integrated testing of the full-scale assembly began. The orientation of the FOA shown in Figure 5 simulates installation on the bottom half of the target chamber. Planned tests include mechanical fit-up and handling, vacuum pumping rates, cleanliness evaluations, and in-situ operation of debris shield cassette.
- The first round of debris shield cassette testing for cleanliness was completed. Preliminary results indicate that some minor design modifications are needed to eliminate sag and "walk"problems as the slide exits the Nylatron edge guides.
- The design progress toward final, detailed FOA design drawing packages was good for several subsystems. The final optics cell is in excellent shape, the vacuum isolation valve is nearly complete, and the alignment fiducial arm design drawings are in checking.
- Good progress was made on CAVE (crystal alignment and verification equipment). The "first light" milestone was met in April. Semi-automated measurements of frequency conversion of a doubling crystal (2ω rocking curve) were completed in May. The control software for fully automated, full-aperture scanning measurements is proceeding well and will be operational next quarter. Detailed, engineering subsystem verifications (e.g., stability of mounts, performance of autocollimators) are under way.

Operations Special Equipment

Title II design progress is proceeding well. Hardware prototyping continues to increase in volume and in data collected. Several internal key milestones were accomplished this quarter.

- An integrated 3D model of the Laser and Target Area Building (LTAB), OAB, and corridor is in

FIGURE 5. Prototype FOA hardware being assembled in the high bay of Building 432. (40-60-1198-2260pb01)

progress for a Material Flow design review. The process to bring manageable-size files together and maintain a high level of detail has been developed by using a series of benchmark tests, resulting in a process that allows the designers to use Intergraph files with 3D Studio, gain a huge time savings, and maintain a high level of detail for modeling.

- The detailed design in the bottom loading (BL), top loading (TL), side loading (SL), switchyard, and target area delivery systems is progressing well. The docking structure for the BL system has been initiated and will be used for the canister docking as well as for the insertion testing of the PEPC, Spatial Filter, and Periscope LRUs.
- The Final Design Review for the Laser Bay Transport System with RedZone Robotics/AGV Products was completed this quarter.
- The assembly and testing of the prototype hardware is progressing well. All components are in for the flashlamp cover removal mechanism and assembly was started in May. Load testing of the permanent carriage for the BL universal system was completed in May, and some redesign is expected due to the results. A vacuum cover removal operation was completed with the TL scissors/latching mechanism as well, and the system performed flawlessly.
- The OAB hardware designs and the simulations continue to progress well. All ICDs with optical mounts, amplifier, and alignment systems groups are revised and signed. A top-level assembly model for the OAB was completed this quarter, and the docking station and assembly stand concepts are complete for the amplifier and the generic docking ports.
- The Supervisory Controls team has made excellent progress, completing the Mid-Title II (65%) Review in June, with strong project endorsement and interactions. The software requirements specification and rational rose model for the supervisory server was completed. A prototype implementation of the supervisory server framework and event services, integrated with the FEP control software, is in progress.

Start-Up Activities

- The month-end June status of the Integrated Project Schedule showed no impact to Level 0–3 milestones. Work continues with the Conventional Facilities group to establish a baseline for CSP-9 and CSP-6/10. Once baselines are established, Project Milestone dates and definitions will be adjusted.
- As part of the FY99 CAP planning process, Start-Up has completed definition of the FY99 workplan to develop the present First Bundle Operational Test Plan into a complete set of Operational Test Procedures. Additionally, the Start-Up Preliminary Staffing Plan for the First Bundle was completed in detail. A detailed list of activities for the Start-Up group was laid out for FY00 and FY01. The composition of the Start-Up Laser Operations teams was defined, in addition to the scientific support staff, who will provide expert assistance and handle data processing and evaluation of the operational test data.
- Optics Processing is the first of 12 to 15 functional areas to work with Start-Up in preparing operations training materials following a performance-based training method. A schedule driven by Project milestone dates and Title II 100% design review dates has been developed to determine the order in which Start-Up will work with various groups to prepare training materials and operations procedures.
- Start-Up staff has been working on the conceptual design of a metrology station to measure wavefront errors in mounted optics. This continued through May and June with the goal of a conceptual review held the first week in June. A solid concept was developed to test LM4, LM5, LM6, LM7, LM8, amplifiers, and PEPC.
- A plan has been developed laying out all NIF operational readiness requirements through the end of the project and beyond. This plan is presently being reviewed internally and will be discussed with DOE within a few months.

Optics Technology

Facilitization is moving well at all NIF vendors as they prepare for pilot production in late FY98 or in FY99. Zygo and Corning will both begin their pilots in the fourth quarter in portions of their facilities while they complete facilitization tasks in other areas. Schott, Hoya, and Tinsley will begin their pilots in the first quarter of 1999. KDP rapid growth and finishing pilots have already started at LLNL, and the external-vendor rapid-growth pilots are set to begin in early FY99 at Cleveland Crystal and Inrad. Facilitization at LLE and Spectra-Physics is in good shape to begin their pilots later in FY99. The longest lead substrate material, polarizer substrates, has already been received for pilot production, and orders are in place for mirror and polarizer substrate production.

- The last two crystal growth stations at LLNL became fully operational, went through their first validation tests, and are now being used for growth runs. Coating development at LLNL was completed and the first convex aluminum platform was coated with the improved process. Six tanks are now running as part of the LLNL pilot.

- Fabrication of the Finishing Diamond Flycutting Machine by the Moore Tool Company in Bridgeport, Connecticut, is progressing well. Moore Tool plans to ship the machine by the end of July 1998, after debugging the major mechanical and control systems. The flycutter design and most major assembly are complete. LLNL site preparations for accepting the Moore machine are also complete.
- LLNL has agreed to Corning's proposed plan to accelerate pilot and production of fused silica in FY99 to take advantage of the current world slump in the fused silica market, driven by a drop in the semiconductor industry. Corning will be ready to ship pilot glass in October, matching the original schedule and eliminating a previously expected slip of three months. Corning demonstrated a new inspection technique that will allow them to detect solid inclusions much smaller than their current 80-μm limit. If required, this technique may be used as a factory quality control tool to ensure 3ω glass meets the proposed new 3ω inclusion specification.
- Tinsley is making excellent progress on their NIF Lenses and Windows Finishing Facility building. Although the new NIF building will not be completed until November, pilot production of NIF optics will begin in October (completing a DOE/OAK Performance Measurement Milestone). High-volume demonstration runs will be carried out in the current facility using NIF equipment and NIF processes to fabricate lenses for the NIF. Production of pilot optics will switch to the new building when available midpilot.
- Initial acceptance testing of the cleaning line equipment for Zygo's facility was done at the equipment manufacturer, Forward Technology. Installation at Zygo is approximately 80% complete. Zygo has been evaluating cleaning detergents on small material samples with their existing equipment.
- Facilitization at Spectra-Physics is proceeding on schedule. The interferometer isolation pad was poured and is curing. Interestingly, NIF construction has delayed availability of concrete at Spectra-Physics. Walls for the metrology labs are in construction as are air-handling systems. Facilitization at LLE is proceeding on schedule. Construction has begun on conditioning labs, and the contract was awarded for the 1ω interferometer at LLE. The counter rotating planetary hardware at LLE has also been assembled and cleaned.
- A WYKO white light microinterferometer was installed and performance verified during June. The unit is being used to verify the etch depth of samples from etch monitor development. Modifications are being made to enable this instrument to also provide roughness and power spectral density waviness II measurements for mirrors, lenses, windows, crystals, and amplifier slabs.

Upcoming Major Activities

During the fourth quarter of FY98, Conventional Facilities will complete the CSP-4 erection of the Laser Building steel and much of the roofing and siding. In the Target Building, the concrete walls for the switchyards and the Target Bay cylinder will begin to rise. The OAB steel work will be completed, and the building will be dried-in. In Special Equipment, the majority of the 65% and 100% design reviews will be completed, and procurements will continue to be initiated for Beam Transport items such as the Laser Bay Structures. In Optics, preprocurement reviews will be held for the major components, and the vendor facilitization activities will continue.

NOVA/BEAMLET/NIF UPDATES JULY–SEPTEMBER 1998

R. Ehrlich/P. Wegner/S. Kumpan

Nova Operations

Nova Operations performed 256 experiments during this quarter, which was enough to exceed the goal of 900 experiments during FY98. These experiments supported efforts in ICF, Defense Sciences, university collaborations, Laser Science, and Nova facility maintenance.

While continuing to make minor improvements to the capabilities of Nova, we began the process of planning the decommissioning of the Nova facility during the upcoming fiscal year. Nova will be shut down to make room in Building 391 for National Ignition Facility (NIF) Project activities. Some of the laser components from Nova will be reused in the NIF facility; the remaining components will be made available for use at other facilities.

The operation of the Petawatt Laser Project was substantially improved with the installation of a set of mirrors that allows beamline 6 to bypass the 46-cm amplifiers without physically removing them from the space frame. This saves several hours during the process of converting that beamline to and from the Petawatt configuration, allowing Nova to use beamline 6 for Petawatt shots and ten-beam target shots during the same day. Also during this quarter, we initiated the installation of hardware required for a campaign of cryogenic ten-beam target shots, which are among the 585 experiments planned for next year.

Beamlet Operations

The fourth quarter of FY98 saw Beamlet complete its mission as laser physics and engineering test bed for the National Ignition Facility (NIF). The last Beamlet shot was fired on July 31, capping a highly productive four-year period of NIF laser technology and component development activities, including over

ω (the third harmonic). Shutdown activities commenced immediately thereafter.

The damage testing of the CEA polarizer was conducted with “p” polarized light at a beam size of 34 cm. The polarizer was conditioned off-line prior to the test. Minor damage sites a few hundred microns in size were observed after the first shot at an aperture-averaged fluence of 1.9 J/cm^2 in a 9-ns square pulse. This was the only damage observed, however, and it did not grow on subsequent shots at fluences up to 11.9 J/cm^2. Two CEA mirrors were also damage tested. One of the mirrors was unconditioned and the other had two levels of conditioning applied in different regions of the aperture. Both mirrors were exposed to aperture-averaged fluences of 20 to 30 J/cm^2 in 3-ns square pulses, which was achieved by positioning the mirrors 3.5 m downstream of the Beamlet final focus lens at a beam size of 17.8 cm. The only damage occurred midway through the testing of the first mirror and was caused by contamination.

The high-energy tests of NIF prototype final optics achieved third-harmonic fluences of up to 8 J/cm^2 and NIF-equivalent energies of up to 9.6 kJ in 3-ns square pulses. The purpose of the test was twofold: (1) to validate the design of the NIF final optics cell (FOC) at high fluence and (2) to operate an integrated NIF-like final optics package, including diffractive optics, to obtain data for estimating component lifetimes on the NIF. Tests of the FOC alone confirmed that it can be operated at full fluence without the large-area damage previously observed and attributed to a mismanaged back reflection. Isolated damage was observed, however. Results of the integrated tests revealed problems with color-separation–grating (CSG)-induced beam modulation and damage associated with the sol-gel coating being nonconformal with the grating—an effect previously identified as being responsible for reducing CSG diffraction efficiency. Improved CSG designs under development are expected to eliminate this problem.

Disassembly of the Beamlet Facility began on August 3. Approximately two-thirds of the laser was designated to be shipped to Sandia National Laboratories (SNL), New Mexico, for use as a backlighter on the "Z pinch" facility. The remaining one-third was packaged and turned over to various groups of the NIF Project. The disassembly was completed by October 1, and the facility was turned over to Lawrence Livermore National Laboratory's (LLNL) Plant Engineering Directorate for transition to the NIF Frame Amplifier Unit Assembly Area. Over 350 crates were shipped to SNL, varying in size from 2 ft square to the largest crate containing the front-end frame which was 7 ft tall, 8 ft wide and 51 ft long and weighed ~18,000 lbs. The large amplifiers are still on site, in storage, awaiting clean disassembly and eventual transfer to SNL.

National Ignition Facility

Overall Assessment

Overall progress on the NIF Project remains satisfactory for the fourth quarter of FY98. The current top-level assessment of Project status remains similar to that stated at the end of the third quarter 1998; that there will be no change to the fourth quarter 2001 Level 2 milestone for the End of Conventional Construction, nor to the fourth quarter 2003 Project Completion date. However, the NIF Project Office now anticipates that based upon the status of Conventional Facilities, CSP-4, work on the Laser Bay Core and the status of Special Equipment design and procurement, there could be an impact of 6 to 8 weeks in the fourth quarter 2001 completion of the Level 4 milestone for start-up of the First NIF Bundle. The impact of current field conditions on this important milestone, which is to be completed in three years, continues to be evaluated on a weekly basis at the Project Top Ten Scheduling meeting.

For NIF Conventional Facilities, fourth quarter 1998 was a period of relatively high productivity. Work completed in the field progressed from 17.5% at the end of June to over 28% by the end of September. Efforts on the site rapidly accelerated as the average manpower on site increased to over 180 and will approach 300 by the end of the first quarter 1999. The structural steel erection, bolting, and plumbing has been completed for the Laser Bays and Core sections, and roofing and siding is in process, but the progress on critical interfaces to CSP-9 is approximately eight weeks behind schedule. Efforts to accelerate the Laser Bay steelwork during the fourth quarter 1998 did not materialize due to labor difficulties with the ironworkers, but the Laser and Capacitor Bay areas will be sufficiently "dried-in" prior to the start of the rainy season. The concrete walls have been poured to about ground level in the Target Area and Switchyards, and installation of the Target Chamber on its pedestal is on schedule for March of 1999. The Optics Assembly Building (OAB) structural steelwork is complete and is generally on schedule.

In Special Equipment, at the end of the fourth quarter the Mid-Title II (65%) Design Reviews were 93% complete, and final Title II (100%) Design Reviews were 60% complete. There were four Special Equipment Title II (100%) Design Reviews planned for FY98 that remain to be completed in the first quarter 1999. Design closure and drawing production were slower than planned, but critical path designs were generally on schedule. Major awards have been made for the spatial filter vacuum vessels and vacuum beam tubes, the Laser Bay structures, and for the Switchyard 2 structural steel tubing.

In Optics, facilitization was in final stages at most vendors as they started or prepared to start pilot in early FY99. All laser glass contracts were either in place or will be placed at the beginning of the new fiscal year. Nd was in hand at both Schott Glass Technologies and Hoya Optics for their pilots. Potassium dihydrogen phosphate (KDP) rapid-growth facilitization at Cleveland Crystals, Inc. (CCI) and Inrad has gone well, and they have made excellent progress growing their first crystals, up to 27 cm in size. Corning was nearing completion of facilitization. The accelerated fused silica pilot was awarded early in September and has begun. Tinsley continued to make excellent progress on their finishing facility, and they demonstrated outstanding performance with the first four lenses, which will be used on the NIF first bundle. Zygo was making good progress with their facility, including resolution of the pitch problem discussed in previous reports and initial hiring for pilot production. The University of Rochester Laboratory for Laser Energetics (UR-LLE) and Spectra-Physics continued to make good progress preparing for their pilots.

Key Assurance activities during the fourth quarter were all on schedule, including construction safety support, litigation support to the Department of Energy (DOE) for the settlement of 60(b) (e.g., quarterly reports), and the *Final Safety Analysis Report*. The *Pollution Prevention and Waste Minimization Plan* was completed in August, one month ahead of schedule, achieving a Level 2 DOE milestone.

There were 39 DOE/OAK Performance Measurement Milestones due in the fourth quarter, and 33 were accomplished. There were a total of 95 milestones due through the end of FY98, and 85 have been accomplished.

Site and Conventional Facilities

The fourth quarter of FY 1998 was a period of high productivity for NIF Conventional Facilities. Work completed in the field progressed from 17.5% at the end of June to over 28% by the end of September. Efforts on the site are rapidly accelerating as the average manpower on site has increased to over 180 and will approach 300 by the end of the first quarter 1999.

Bolting the core steel was the main focus on the Laser Building so that as much of the deck as possible could be released to CSP-9 to allow for rough-in and concrete placement to start in September. Bolting and plumbing of Laser Bay 1 lagged due to the lack of ironworkers, but by the end of September, the entire crew completed work on the core and started work on Laser Bay 1, which should be completed during the month of October.

Roofing operations started in September and made significant progress. In the three-week time frame that the roofing subcontractor worked, the entire Laser Bay 2 roof was dried-in along with nearly half of the Laser Building core area. The roofing subcontractor accelerated its schedule to complete all the roofing on the Laser and Target Area Building (LTAB) in an eight-week time frame.

A primary focus of work for October will be to continue to “dry-in” the building and to protect the site to the fullest extent possible from the upcoming winter weather. The site storm drainage system has been completed and is ready to receive runoff from the Laser Building and OAB roof drains. The Target Building will not have the roof constructed and will be open to weather this coming winter. Regrading and surface treatment of the site to allow for proper drainage will occur in October to permit access and laydown through the coming winter. *Storm Water Pollution Prevention Plan* requirements are scheduled to be completed during October. The *NIF Site Winterization Plan* will be reviewed by wet weather specialists, EarthTech, and finalization of the plan will occur in October.

- FY98 DOE/OAK Performance Measurement Milestones completed this quarter included: “OAB Start Structural Steel Erection,” achieved in June; “Laser Bays: Complete Structural Steel Erection,” completed in August; and “Power Available,” completed in August.
- Nielsen Dillingham (NDBI) completed erection of structural steel for the OAB Corridor and is substantially complete with all steel erection for CSP-4 Phase I.
- Activities increased in the OAB in September as more trades manned the site. Midstate Steel nearly completed their work, including the roof truss punch list. Magnum Drywall mobilization occurred in September; they installed studs around the perimeter of the building and, by the end of the quarter, were ready to start sheathing installation (see Figure 1).
- Work by CSP-6/10 continued in all four areas of the Target Building. The target pedestals have been constructed up to the ring at elevation –8′-9″ (see Figure 2). The radius wall up to elevation –3′-6″ is formed on one side with rebar, and embed/blockout installations are nearing completion. The radius wall pour from elevation –21′-9″ to –3′-6″ is taking longer than expected, but the complexity and need for precision of the blockouts and embeds is very critical. This pour and the similar one higher up on the radius wall from elevation 48′-0″ to 68′-3″ are the most difficult pours on the project; therefore, the extra

FIGURE 1. Installation of metal studs in the OAB. (40-60-0998-1855#11)

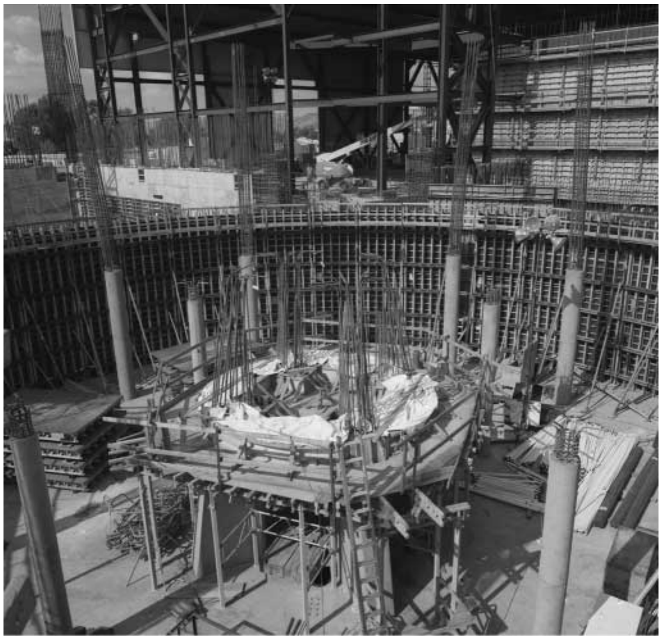

FIGURE 2. Shoring and forming for the target bay pedestal. (40-60-0998-1942#08)

time required to assure they are correct is justified. Despite the extra time used, the milestone for installation of the Target Chamber has not slipped. The first lift for Switchyards 2 and 1 walls up to elevation 3′-6″ have been completed on all three sides. Forms for walls in Switchyard 2 are being jumped for the next lift in October. The south wall of the Diagnostics Building basement was placed in September. Currently, CSP-6/10′s schedule meets the critical milestone dates for installation of the Target Chamber and Switchyard structures.

- The bulk of the Site Utilities scheduled for this year were completed in the fourth quarter by Hensel Phelps (HPCC). The Site Utilities are continuing (but are winding down): including installation of temporary/permanent ductbanks around the OAB, south side of the site, and sectionalizing switches and vaults north of CB4. Complete installation of the storm drain system will occur in October. In addition, HPCC completed erection of Central Plant structural steel as well as completed forms, reinforcing, and placement of Cooling Tower walls. The placement of concrete on the metal deck was completed for parts of Core Areas "A" and "B" elevations 28′ and 47′-6″. Within LB2 and CB4, HPCC began installation of underslab precast duct in LB2 and began installation of underslab conduit in CB4. The installation of LB2 overhead platform up to Column Line 24 was completed and HPCC began installation of mechanical, fire sprinkler, and electrical rough-in off of the platform. Work by CSP-9 in the core area was under way at both mezzanine levels. CSP-9 overhead rough-in work in Laser Bay 2 (utilizing the overhead platform) was off to a good start and progress appeared to be at or above the originally scheduled pace.

Special Equipment

Design Reviews continued to be successfully held at both the Mid-Title II (65%) and final Title II (100%) design levels. Design closure and drawing production were slower than planned, but critical path designs were on schedule. Awards were made for the Laser Bay structures.

During the fourth quarter, many of the Special Equipment Title II Engineering activities were brought to an end. Title II 65% Design Reviews were held for the OSECS Safety Interlock and Video Surveillance System and for the Transport and Handling System. The final (100%) Design Reviews were held in July and August for the Alignment System, Pockels Cell, the Mechanical Utilities, the Optical Design, the Gas Handling System, the Laser Auxiliary System, and the Safety System. Ten final (100%) Design Reviews were conducted in September, including Final Optics Damage Inspection/Pulse Synchronization, Output Sensor/Relay Optics, Optical Mounts, Target Positioner, Target Area Structures, Main Laser Alignment, Optical Pulse Generation, Power and Back Reflection Sensor/3ω Energy/Portable Sensor/Energy Diagnostics/Power Diagnostics, Target Chamber Vacuum, and Laser Amplifier. Final Documentation Reviews were held for the Switchyard 2 Support Structures Procurement Documents, the Switchyard Tube Enclosures Design and Procurement, and for the Laser Bay Support Structures Concrete Pedestals.

Laser Systems. The optical pulse generation (OPG), plasma electrode Pockels cell (PEPC), and amplifier subsystems each held well-received 100% Title II Design Reviews during the fourth quarter. The fabrication drawings are now complete, or nearly so, in each of these areas. The emphasis is now shifting to procuring and assembling hardware for the first bundle. In the Power Conditioning area, assembly of the First Article module essentially realized the baseline capacitor bank design for the NIF. Over 1000 shots were accumulated at full NIF current levels.

- The OPG 100% Title II Design Review was completed in September. This milestone represented a shift in the team's focus from design to procurement and fabrication. The current plan calls for an integrated test of the OPG hardware in Building 381 prior to reinstallation in the LTAB. A major focus of the OPG team during the past quarter has been identifying and testing a distributed feedback (DFB) oscillator connected to a high-gain fiber amplifier to provide the required input pulse to the master oscillator fiber distribution system. DFB oscillators from two vendors were evaluated and both demonstrated excellent single-mode operation. The requisite power and noise levels were achieved using a high-gain, double-pass fiber amplifier. Testing of the Stimulated Brillouin Scattering (SBS) fail-safe circuit (intended to prevent propagation of a pulse with inadequate bandwidth to prevent SBS) began during the last quarter and produced encouraging results. A new circuit approach in the arbitrary waveform generator was tested and was shown to reduce the electrical noise to a level consistent with meeting the stability requirement during the “foot” of the Haan pulse shape. This change allows the vendor to proceed with the final design of the pulse shape generator for the NIF. The prototype preamplifier module demonstrated all of its key performance requirements including energy and phase error during this quarter, adding substantial credibility to the design.

- The 100% Title II Review of the Amplifier was held as scheduled in September. The 13-volume Amplifier design basis book was prepared, reviewed, and submitted to the NIF document center. Approximately 95% of the drawings of the Amplifier components were submitted to the NIF Project Database Management system, and approximately 30% of the assembly, interface, and assembly equipment drawings were completed. All interface control documents were completed and are under configuration control, though some will be modified as the interfacing system designs evolve. Approximately 75% of the supporting calculations were completed, and many but not all of the design implementation plans were prepared. The failure modes and effects analysis and reliability, availability, and maintainability analyses were updated for Title II. A 700-shot cleanliness test was completed using the AMPLAB amplifier. The results indicated that damage growth on a slab in the amplifier is consistent with achieving the recently modified operational contamination damage levels proposed by the Project Scientist (beam obscuration <1% and no damage site larger than 1 mm). This result indicates that NIF contaminant levels can be achieved at installation and that in operation, the slab damage levels are within acceptable replacement limits.
- The PEPC subsystem also completed a very successful 100% Title II review during the fourth quarter. There were very few action items generated by the reviewers, and responses have been completed for all of them. All of the mechanical drawings for the PEPC subsystem are complete, and the procurement process is under way at an aggressive pace to attempt to benefit from a slack period for machine shops that traditionally support Silicon Valley companies. During the past quarter, the emphasis was on demonstrating acceptable switching performance over a 100-ns time window to enable appropriate timing of target backlighter beams. The requirement was met after minor modifications to the switch pulse termination resistors to sharpen the rise and fall times of the pulse, effectively broadening the “in spec” portion of the pulse. Control system software testing has begun in the prototype laboratory to demonstrate proper controls operation and robustness for operation in the Pockels cell electromagnetic interference environment.
- The NIF First Article capacitor module was assembled during the fourth quarter. Roughly 1000 full-current shots were completed, and the lifetime of the switch under NIF-like operating conditions is consistent with predictions. Late delivery of the flashlamp load, coils, and cables consistent with the baseline design resulted in the use of the old prototype parts for these initial tests. Therefore, the waveshape and charge voltage are not yet representative of the NIF. Module operation consistent with the amplifier requirements is planned for the first quarter of FY99. An environmental, safety, and health (ES&H) review of the module design and operation concluded that the gaseous effluent from the switch contains sufficient ozone and nitrogen compound levels that an outside exhaust vent is needed. The noise level and other safety-related controls were found to be acceptable.

Beam Transport System. In this quarter, major fabrication contracts were awarded, mill order material was shipped, and production of Laser Bay structures and vessels was ramped up after completion of shop drawings and quality assurance submittals. Shop operations during this period included welding fixture fabrication, plate cutting, and structural member preparation. These 11 contracts are currently on schedule to meet the installation milestones.

The Beam Transport System acquired government excess material-handling equipment for upcoming installation activities, including an Oshkosh diesel prime mover, a 45-ton Taylor forklift, and a 60-ton capacity battle tank trailer. These assets are now at LLNL for the cost of shipment and are fully operational.

Laser Bay concrete structure and Switchyard 2 structure design drawings were released for construction change order quotations from the existing Conventional Facilities contractors. The mill order for Switchyard 2 tube steel was awarded in August. Auxiliary Subsystems completed the Title II Design Reviews for the Gas Handling System, Amplifier Cooling System, and Conventional Utilities. All amplifier cooling fan units have been received and are currently stored in the laydown area awaiting installation into the LTAB. Other activities include the following:

- Production of the stainless steel plate neared completion. Vacuum vessel fabrication activities are proceeding with the three selected contractors. Two contractors completed preliminary documentation, and their fabrication activities are proceeding on schedule. Fabrication plans and procedures are being reviewed and revised with the third contractor to ensure compliance with the specifications and drawings.
- The drawing packages for the Switchyard 2 beam tube enclosures are complete, and the procurement requisition is prepared and submitted for request for proposals (RFP) release. The specification for the Switchyard and Interstage Beam Enclosures was updated and revised, incorporating design review comments and other recommended changes learned during ongoing fabrications for the vessels and beam tubes.
- The Airlock/Sliding Door feature of the Roving Enclosure was removed to reduce costs. Roving Enclosure design will continue to include features that can accommodate future installation and conversion on a "Not to Preclude" basis.
- Design detailing is proceeding on the interstage docking frames at the Spatial Filter (SF) end vessels. Engineering review and design checking remain to be performed. Design development and detailing is behind schedule on the large interstage components at the switchyard wall. These structures must be fabricated and installed into the Laser Building before closure of the facility holdouts.
- The Title II 100% Design Reviews for the Amplifier Cooling System, the BTS Auxiliary Subsystems, Gas Handling system, and the Mechanical Utilities, which included Fire Protection as well as Lighting and Power subsystems, were completed.
- The mill order for Switchyard 2 tube steel was awarded in August. The Title II 100% procurement review was held in preparation for the change order proposal solicitation from the CSP–6/10 contractor.
- The Cavity Spatial Filter Optical Bench, Transport Spatial Filter Optical Bench, Injection Structure, and Preamplifier Support Structure Safety Notes were completed. Contracts were awarded for the Main and Power Amplifiers, Laser Mirror 1 structures, Cavity and Transport Spatial Filter optics benches, Injection Structures, Preamplifier Support Structures, and Periscope structures.

  The Optical Mounts Title II 100% Review was held in September. Final designs were presented for spatial filter lens cassettes, the injection system, cavity mirror/polarizer mounts, shutter/beamdump, Switchyard transport mirrors, and Target Area transport mirrors.
- A full-size rectangular test mirror with "holes" drilled in the back was mounted and evaluated interferometrically (the mirror was tested vertically and in the down-facing orientation shown in Figure 3). This test is part of the validation plan for the transport mirror attachment concept and mount design. The preliminary results indicate that the observed distortion is less than predicted from finite-element analysis. The results to date indicate that the so-called "expanding mandrel" design will hold the mirror sufficiently well.

FIGURE 3. Transport Mirror Mount testing at use angle. (40-00-0199-0193pb01)

Integrated Computer Control System. Title II design progress is satisfactory. Seven out of a total of eight scheduled 100% reviews have been completed. Two reviews were completed during the fourth quarter: the Integrated Safety System and the Automatic Alignment System.

- At the end of September, the controls team accomplished the last of the FY98 Cost Account Plan milestones. These milestones, scheduled some fourteen months ago, were transformed into a much larger software delivery: the first integrated production prototype (code named Nightlight), consisting of incremental deliveries of 8 supervisory and 15 (out of 18) front-end processors (FEPs) (see Figure 4).

This prototype (the first of seven planned) had several major goals:

- Risk mitigation by early execution of important functions.
- Testing frameworks in actual use within applications.
- Gaining experience and confidence with software tools and engineering processes.
- Activating the independent software testing capability.

The theme of this first prototype was the vertical slice: the execution of initial functionality in each subsystem using either emulated or prototype hardware. Most slices included both supervisory and FEP functions; a few were limited to FEPs only. Almost all slices made use of the reusable frameworks upon which all controls software will eventually be built. Those that did not concentrated upon important application-specific behavior. In addition, significant new work was done on frameworks prototyped or designed earlier in the Project. Among these were the message logger, the sequence control language, the graphical user interface, the sample (or generic) application, and the shot life cycle.

To date, the vertical slices for target diagnostics, laser diagnostics, PEPC, integrated timing system, special imaging sensors, graphical user interface, and the sample application have been demonstrated—the first of three steps that certify completion of the software delivery: (1) demonstration to a project management team member, (2) placing the software under configuration control, and (3) independent testing of the software.

Due to the complexity and importance of the shot director and power-conditioning slice, its delivery has been delayed to the end of October. Because effort was redirected toward the graphical user interface portion of the sample application, the industrial controls vertical slice was also delayed to the end of October. The remaining slices are expected to be demonstrated in early October.

A major goal of Nightlight was validation of the distributed software architecture and the implementation process. While not every goal was achieved in this release, the important risks were successfully addressed and confidence was gained that the software needed to control the first bundle can be incrementally completed by repeating this process.

FIGURE 4. Nightlight software demonstration at the test bed operator console. (40-00-0199-0194pb01)

- The example supervisor software that will serve as a pattern for all eight NIF subsystems was constructed and tested. This demonstrates how the supervisory architecture is to be deployed and how each program is connected to the database, framework services for configuration, system manager, monitor, message logging, and graphical user interfaces. The new generic supervisor is analogous to the generic FEP that has been in use for several months. The new component adds a number of features needed by supervisor-level code: public and private internal objects for upper-level controls, communication with one or more graphical user interfaces, and bidirectional connections between distributed objects.
- Berkeley Nucleonics presented a satisfactory design review for the prototype Integrated Timing System delay generator in September.

About 200 units are needed for the NIF. They have selected an acceptable optical receiver and are progressing on the basis that it will meet requirements, while also testing a discrete design intended to reduce propagation delay as a function of optical power level.

The version of the timing FEP for Nightlight is complete and delivered to the software test team. It consists of a computer crate containing actual NIF hardware, except that a similar 4-channel delay generator was substituted for the custom 8-channel NIF delay generator currently under development. The Nightlight FEP provides a complete vertical slice of the architecture using the supervisory frameworks (system manager, configuration server, generic FEP, and graphical user interface) to create devices for trigger channels, trigger diagnostics, and precise trigger diagnostics. The software provides the ability to set delays, enable/disable channels, create epochs and activate triggers as well as measure and read the resultant delay using two types of time interval meters. The release demonstrates integration under both Solaris and VxWorks operating systems.

- The 100% Design Review of the Integrated Safety System was conducted in July, and the Automatic Alignment 100% Design Review was presented in August. System operations for optics inspection were analyzed and documented in the *Preliminary System Analysis for the Damage Inspection Control System*. In summary, the inspection of vacuum-loaded optics in the spatial filters and final optics assembly (FOA) will require slightly more than two hours. Amplifier cooling time and the brief target chamber center keep-out period extend the maintenance access time to as long as three hours following the shot. Inspection time is dominated by mechanical actions times. For example, repositioning the roving mirror assembly accounts for 24% of this time.
- Integration activities have concentrated on the project-wide tasks required to develop and test Nightlight. Preliminary planning also began on deployment of integrated software for the second production prototype (“Penlight”) that will feature software operation and testing in the Preamplifier Module and input sensor prototype labs.

Optomechanical Systems Management. Title II 100% Design Reviews were held for Optical Design and Optical Mounts. Detail drawing checking and final approval is lagging in Optical Mounts (spatial filter lens cassettes have been completed; others are in creation or checking). The Title II Design Review for Final Optics was delayed about one month to allow for additional scientific evaluations of the final Beamlet campaign results. About 60% of the detail drawings for Final Optics are approved or in checking.

Optical Design. Design and analysis activity has been focused on completing the detailed optical design, manufacturing tolerances, and specifications for small optics subsystems (e.g., output sensor relays and preamplifier beam transport).

- The Optical Design Title II 100% Review was held in July. The presentation included the review for compliance, Main Laser system optical design, Switchyard/Target Area mirror system optical design, final optics optical design status, large-aperture optics specification and drawings, and stray light control.
- Some follow-up ghost analysis was conducted for the Main Laser, diagnostic system, and the final optics. In the Main Laser model, mechanical elements (e.g., beam tubes) were added so that the analysis of stray light paths could be completed. A worst-case target back reflection was modeled in the FOA to determine ghost fluences in the 3ω calorimeter chamber. A simplified model of the 1ω diagnostic system was constructed; a second-order ghost analysis provided useful feedback for the final optical design.
- The optical model for the FOA was completed; the configuration will be described in an upcoming revision of the configuration drawing. Final revisions included detailed ray tracing of the 1ω diagnostic reflection from the focus lens and transfer of optical design data to Pro-E.
- The “Small Optics Summit” was held in September. Representatives from 66 optics and optomechanics manufacturers attended this very successful one-day event. The morning session comprised presentations from the responsible engineers who will deliver line replaceable units (LRUs) containing small optics (≤150 mm diameter) to the NIF. In the afternoon, the vendors set up displays in a tent, allowing NIF Project and other LLNL personnel to come by and ask questions about the capabilities of each supplier of interest to them.

Optical Components. All NIF optics Title II Design Reviews were held in September except the KDP Crystals. The reviews focused on progress to date of facilitization at vendor sites and at LLNL and validated readiness to proceed with Title III and with pilot production.

The contract for 13.5 metric tonnes of Nd salts was negotiated and is ready to place early in October with FY99 funding. This will support the first production runs of laser glass for Hoya and Schott. The NIF Amplifiers (slabs), NIF Lenses, NIF Mirrors, NIF Polarizers, and NIF Windows 100% Title II Design Reviews were completed in early September. The NIF QA/Metrology and NIF Processing Title II Design Reviews were completed in early September as well.

Laser Control. Four Title II 100% Design Reviews were presented in August. Taken together, they covered Main Laser alignment, the output sensor package, the beamline to output sensor relay optics, final optics damage inspection, pulse synchronization, power sensors, the 3ω energy module, portable streak camera, backreflection sensor, FEPs for energy diagnostics, power diagnostics, and special charge-coupled device sensors.

- The last of the input sensor drawings, namely the sensor assembly drawing and the test stand base plate and rails are now expected to be completed in October.
- Updated cost estimates for the beamline centering references were found to be higher than the plan, and efforts were made to simplify their implementation. A significantly less expensive approach to the centering reference on the FOA was identified.
- Optical design was begun for the spatial filter tower test stand that will be used for assembly and test in the OAB.
- Assembly of the Target Alignment Sensor hardware began. If performance meets expectations, this unit will be designated for use in the initial operation of the NIF.
- The number of FEPs was reduced in the plan from 108 to 100 to implement a decision removing motors from those mirror mounts in the Switchyard and Target Bay that are not part of the closed-loop control system.
- The optical alignment section of the acceptance test plan has been verified on the prototype. Other parts of the test plan, including motion tests of the motorized components, will be checked for suitability when the motor control electronics are added to the test stand.
- Efforts began to establish test capability for accurately measuring the reflectivity of 1ω sol-gel coatings in the 0.1% range. A preliminary capability was demonstrated using recent sample sol-gel samples.
- End-to-end tests of the power measurement instrumentation were completed in August. The results, which included a demonstrated precision of 1.5%, were documented during September and satisfy the appropriate part of the NIF power balance error budget.
- Disassembly of the precision diagnostics prototype systems in Beamlet was completed, and components were readied for storage.
- Tests on the LLNL deformable mirror prototype went very smoothly. The mirror clearly met the range specifications and showed a preliminary residual error of about 0.04 waves (rms surface) compared to the specification of 0.025 waves. The LLNL mirror is currently the only one of the three prototypes whose performance compares reasonably with NIF requirements; it will appear as the baseline for this review.
- The adaptive optic was identified as a high-risk system component to be reviewed by the Project Risk Management Group. This group will review test data, modeling results, and other aspects of deformable mirror status as a basis for recommending a plan to complete development activities.

Target Experimental Systems. All 18 sphere plates have had their weld joint configurations machined on the edges and the inside surfaces smoothed (grinding marks removed) and have been shipped to LLNL. The last three are en route. The first three plates were installed on a welding fixture inside the temporary enclosure and welded to form a subassembly. PCC moved from the machining of the sphere plates to the fabrication of the weld necks. All of the cylindrical pieces are completed and the flanges are now being welded to them.

- The 60-foot-diameter, 62-foot-high, cylindrical enclosure, built on the E7 parking lot, which is to be used for the construction of the target chamber, was completed. It is now being used for the welding of the first three sphere plates that form the bottom of the chamber. Yet to be installed is the HVAC for the building, planned for October.
- The chamber gunite shielding (hereafter known as shotcrete) design was reviewed by LLNL. An alternative design was proposed and analyzed by Project personnel. The result was a system that would provide shielding but not become a structural member (composite) with the target chamber. This simplified design was discussed with two potential shotcrete installers who felt

it was a very workable installation. The system consists of wire mesh attached to the chamber with studs on a 1.3-foot spacing. Additional limited rebar will be used around the weld necks, which will be isolated from the shotcrete by a barrier. This concept greatly reduced the amount of engineering and installation time for the shielding.

- The prototype stainless steel beam dump was removed from the Nova chamber at the end of July, and another fused silica optic was placed in the chamber after the prototype was removed to use as a baseline in the optic damage tests. The stainless steel beam dump showed no signs of catastrophic damage, and there was no evidence of excessive amounts of elements of stainless steel in the chamber.
- The target chamber vacuum 100% Title II Design Review was held in September. The first revision of the equipment specifications for the target chamber cryogenic high-vacuum pumps, gate valves, tritium gas-roughing pump, and turbodrag high-vacuum pumps was completed.
- The target positioner 100 % Title II Design Review was held in September.
- A web page has been developed to share diagnostic design information with representatives from LLNL, SNL, LLE, Los Alamos National Laboratory, and Atomic Weapons Research Establishment (AWE), U.K. The web page is internally accessible to LLNL experimenters and will soon be password accessible to NIF diagnostic users at other DOE sites. Discussions are taking place with a working group of people from other test facilities and labs to establish standards for diagnostics and their associated control and support equipment so that diagnostic can be used at multiple test facilities.

  Software Requirements Specifications (SRS) and Software Design Descriptions (SDD) documents for Embedded Controller Software and FEP Software have been started. These will form the foundation of the Target Diagnostics FEP and controller SRS and SDD documents.
- The Diagnostic Instrument Manipulator (DIM) drive system is now being manufactured. The trolley is finished and has been fitted onto the bench. The electronic rack has been finished and is awaiting checkout. The DIM extension tube was being fabricated in the United States. The extension tube will be completed by the end of September and shipped to AWE early in October.
- In September, the 100% Title II Design Review was conducted for the engineering of the major mirror frame structural components. This included the target chamber pedestal, the mirror frame supports and enclosures, the seismic restraints, and the FOAs.
- The peer review team met with the NIF team in August and reviewed the revised calculations for the seismic loads applied to the top of the pedestal and the target chamber to floor. They agreed with calculations presented and supported the use of a steel encasement around the upper ring beam to increase the load-bearing capacity and increase the safety factor. The steel encasement was fabricated and delivered and is awaiting incorporation into the pedestal.
- The Tritium Environmental Protection Systems work has been delayed until 2004 to be able to prepare for the introduction of tritium into the facility in 2005. The exception to this delay is the stack monitoring system, which will be in place for first bundle.
- The prototype 2 degree-of-freedom Integrated Optics Module (IOM) handling fixture (see Figure 5) was successfully tested on the FOA test stand in Building 432. The fixture was tested at angular orientations of 130°, 135.5°, 150°, and 156.5°, which represent the positions of IOM units on the lower half of the target chamber. These initial tests have validated the basic concept. All drive mechanisms, alignment features, and installation procedures worked as planned. Deflection of the IOM translation arm was within tolerance with no interference with adjacent IOM units. All tests were conducted with a 125% test load of 1050 pounds.
- The FOA 100% Title II Review presentation was delayed by approximately one month until November to allow more time for scientific review of the last Beamlet tests using the final optics cell (FOC). The Project Scientist has been leading the scientific review of the data and establishing priorities for future work. The last series of shots (high-damage-threshold campaign) tested frequency conversion crystals, focus lens, and diffractive optics plates in a configuration similar to the NIF optical design. (There are some differences between the optomechanical configuration in Beamlet and the baseline NIF configuration.) Optical damage was expected and was observed; however, it is taking some time to reduce the data, understand the mechanisms, and determine the contributing factors.
- The frequency conversion technical management plan has succeeded in establishing a firm understanding of frequency conversion performance

for the NIF final optics design (i.e., significant factors, status of technology, error budget). Requirements from a detailed error budget have been flowed down to metrology equipment, crystal fabrication, coating performance, and mount tolerances. There is very good correlation between analysis predictions and experiment.

- The ghost analysis of the IOM was completed during the quarter. The baseline absorbing material is a PTFE (Teflon) product with a trade name of Spectralon. This material selection is based on adequate damage threshold, fabrication/installation ease, and cost. Extensive ghost mitigation measures have been incorporated into the FOC final design. Additional measures can be implemented if future tests and First-Bundle operation indicate that they are needed.
- Integrated testing of the fully assembled FOA prototype hardware began in the high bay of Building 432. The vacuum/venting sequence evaluations will confirm (or suggest modifications to) the final design details of the debris shield module, pumping rates, and so on.
- A modification to the FOA debris shield cassette frame is shown under test in Figures 6 and 7. (The tests are conducted in a clean, enclosed hood with particle measurement wafers beneath the hardware.) Particulate generation has almost been completely eliminated with this design, which uses a solid stainless steel guide bar.

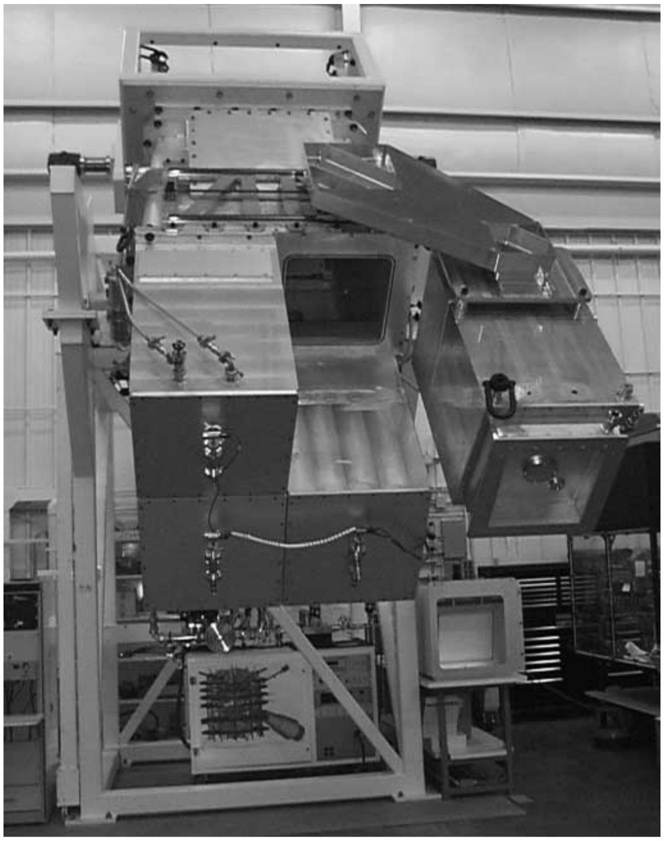

FIGURE 5. IOM 2-dof fixture with IOM in fully retracted position. (40-00-0199-0195pb01)

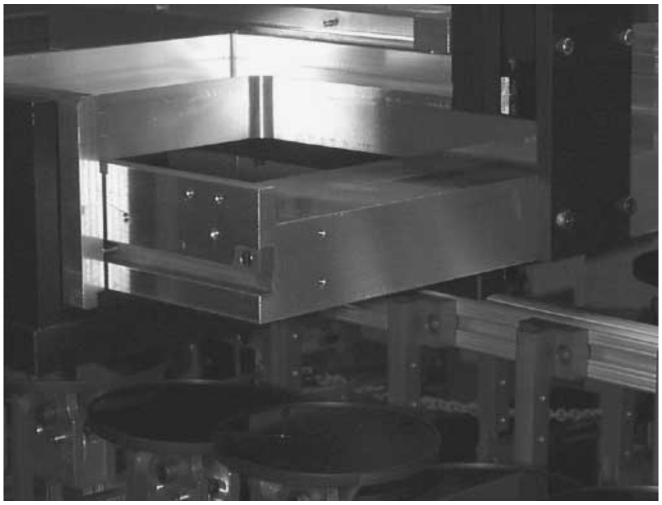

FIGURE 6. Debris shield cassette frame. (40-00-0199-0196pb01)

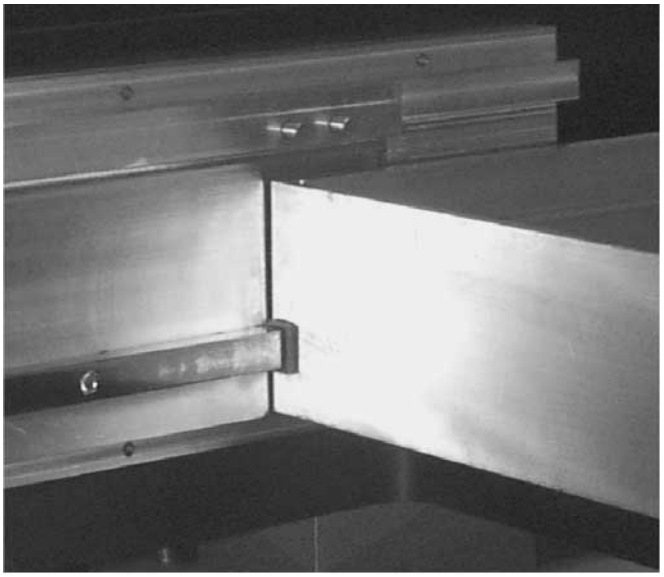

FIGURE 7. Cassette frame guide bar. (40-00-0199-0197pb01)

Operations Special Equipment

This has been a successful quarter with good progress in detailed design and prototype testing. Several DOE milestones were completed, including large procurements and design reviews. Preparations are currently under way for hardware installation in the OAB scheduled for October 1998.

- A number of significant changes for the OAB were agreed to in August during an LRU storage review. The IOM assembly area, Cave, and shutter assembly have been moved to Building 391. Space available in the OAB resulting from the location changes will be used for storage of LRUs. A complete 3D model of the animation sequence is being developed for formal review. This 3D integrated model will show extensive stay-out zones and will hopefully prevent major interference and space conflicts for the OAB, the corridor, and the LTAB aisles.
- The Transport and Material Handling 65% Design Review was successfully completed in August. Also an installation schedule is being developed for the T&H systems going into the Laser Bay Facility.
- The 65% review for T&H FEP controls was completed. The SRS for Bottom Loading, Top Loading, and Side Loading are nearly complete, which includes the requirements specification for the electronics, sensors and actuators, I/O boards, and software.
- The contract was awarded in August to AGV Products, Inc. for the fabrication of the hardware and software of the Laser Bay Transport System. Fabrication has begun, parts have been ordered, and the contract for the large fabrications has been awarded.
- Detailed design, prototyping, and procurement are in process for the Optical Assembly and Alignment Design. All drawings and procurements for equipment that will be installed in the OAB during October/November are complete. A new installation plan was also completed for equipment to be installed between October and November.

Start-Up Activities

- Level 0-3 Integrated Project Schedule (IPS) milestones are on track. The Target Area construction, CSP-6/10, is currently ahead of schedule. With the inclusion of the subcontractor baseline schedule for Conventional Facilities CSP-6/10, the IPS now contains all facility construction baseline schedules. An Engineering Change Request has been submitted that modifies the Project milestone dictionary to be consistent with CSP-9 dates and definitions, excluding the core area of the Laser Bay for which work-arounds are still under evaluation. First-bundle installation details in Laser Bay 2, which have been in planning off-line for several months, have now been added to the IPS database.
- A significant effort was devoted to preparing for the detailed review of the NIF First Bundle Start-Up Plan in July. The review was held for a committee that included reviewers from the NIF Project, the ICF-NIF Program, SNL-Albuquerque, UR-LLE, and LANL. The major goals of the review were to inform the Project staff on the detailed plans for First-Bundle Start-Up and to collect detailed feedback on the operational test procedures and their interfaces. Both goals were successfully achieved. A draft revision of the First Bundle Start-Up Test Plan was completed and is presently being proofed and edited. This draft revision included a review of all sections except the “Beam Transport to Target-Chamber Center and Final Optics Assembly Tests” and the “Beam Smoothing Tests.” Further revision of the “Amplifier-Gain Test” section is being considered to add a subsection to discuss an on-line amplifier cleanliness test. Once the revision is completed, the Start-Up Plan will serve as the basis for the FY99 planning activities, including the writing of detailed operational test procedures. It will provide the interfaces to the Master Test Plan and contain sufficient information to create a resource plan and detailed schedule for execution of the first bundle start-up testing.
- The computer controls software acceptance test team’s largest effort was developing system test procedures for the ICCS Nightlight release due in October. Five formal test procedures were drafted for OPG, PEPC, Laser Diagnostics, Automatic Alignment, and Power Conditioning/Shot Director. The technical staffs from NIF hardware and software development reviewed four of these test procedures. The fifth procedure, Laser Diagnostics process, has progressed more slowly due to key development staff focusing on non-laser diagnostic tasks. The procedure is expected to be completed in early October.
- The NIF Laser Operations Model is a code that will be used by Beam Controls and Diagnostics to set up the correct operating and diagnostic parameters to achieve power balance based on performance parameters of the individual beamlines and their components. This model

will also provide critical information to support start-up planning and execution.

- Performance-based training (PBT) infrastructure development continues, and 16 functional areas have been identified for the development of training materials. Operations procedures are identified as part of this process. A detailed schedule has been developed using Project milestones so that training materials will be available when needed. Thus far, the first two (of three) phases of the PBT process are complete for the Optics Processing area, and the first phase is complete for the OAB area.
- A draft sequence for conducting facility readiness reviews is being prepared for review by the Project Manager. Planning for readiness reviews is being coordinated with the ICF/NIF Program, which is responsible for ICF facilities that are not part of the LTAB or OAB, but which will support NIF equipment testing, assembly, or development. Start-up has hired an ES&H specialist from the AVLIS program to provide part-time help planning readiness reviews.

Optics Technology

- Facilitization was in final stages at most vendors at the end of the fourth quarter as they started or prepared to start pilot in early FY99. All laser glass contracts are either in place or will be placed when the new fiscal year begins. Nd was in hand at both Schott and Hoya for their pilots. KDP rapid-growth facilitization at CCI and Inrad has gone well, and they have made excellent progress growing their first crystals, up to 27 cm in size. Corning was nearing completion of facilitization. The accelerated fused silica pilot was awarded early in September and has begun.
- Tinsley continued to make excellent progress on their finishing facility. They demonstrated outstanding performance with the first four NIF SF1 and SF2 lenses, which will be the first nonprototype optics they have made, and that will be used on the NIF First Bundle. Zygo was making good progress with their facility including resolution of the pitch problem discussed in previous reports. Initial hiring for pilot production has begun. LLE and Spectra-Physics continued to make good progress preparing for their pilots.
- Metrology issues with the interferometers have been resolved, and the final units have been ordered from Wyko.
- Postprocessing equipment has been arriving weekly to support the laser glass pilot run that starts in October. The laser glass pilot contracts were in place for the October start-up. Schott plans to ship the first laser glass slab to Zygo by January or February 1999. The cladding glass pilot/production run is scheduled for January 1999.
- At Hoya, the full-scale furnace frame has been constructed and the bricking has begun. Several melter components, the lehr, and several fine-annealing ovens have been shipped from Japan. Hoya's batch mixing room is nearly complete. Laser glass and cladding glass pilot contracts are in place. Hoya starts their pilot in October with 200 slab equivalents of cladding glass being produced in Japan, which will support first-bundle needs. Their laser glass pilot run is scheduled for January 1999 with the first laser glass slab shipped to Zygo for finishing by April 1999.
- A deuterated potassium dihydrogen (DKDP) boule grown at LLNL reached NIF size at the end of September. The boule is large enough to yield 17 NIF tripler crystals, demonstrating substantial improvement in our ability to control inclusion formation. Optical quality was very good, but 3ω laser damage threshold has yet to be measured. A 15-cm KDP crystal rapidly grown with constant filtration achieved the highest 3ω laser damage threshold of the year and would be expected to have negligible damage at maximum NIF fluences. Both CCI and Inrad grew KDP boules >25 cm in their shakedown runs using NIF production equipment.
- The Moore Tool Company continued to assemble the diamond turning machine at LLNL. Their efforts did not proceed as rapidly as estimated, and it appears that they will need the month of October to make the machine ready for acceptance tests beginning in November. Several items associated with the fly cutter and drive spindles, X and Z slides, and the temperature control must be addressed before the acceptance tests can begin.
- Corning has completed installation of the new overarm lapping machine and begun installation of the polisher. Their new Zygo 24" interferometer is in-house and will be operational by mid-October. The fused silica pilot was awarded to Corning in early September.
- Tinsley's lens and window finishing facility building construction has continued on schedule. Beneficial occupancy and installation of manufacturing equipment is planned for November and December. All manufacturing equipment for the facility has been accounted

for and is nearing completion. Most equipment has been run and tested in Tinsley's existing facility and has been used during an early pilot production to produce NIF specification lenses. An award was made to Kodak to construct the NIF Flexible Finishing Facility, which will be designed to augment flats finishing capacity for NIF amplifiers, mirrors, and fused silica windows and to provide a backup for the critical 3ω focus lens.

- Zygo's automated cleaning equipment passed its acceptance tests. LLNL's software for power spectral density (PSD) was installed and run successfully on the first 24" Zygo interferometer. Cavity measurements demonstrated the instrument has an acceptably low noise floor level. The first NIF demonstration amplifier slab has been processed through both phases of edge-cladding bonding, edge machining, and automated beveling.
- Facilitization work at LLE focused on design efforts to reduce the deposition time by the removal of "hot" substrates, planetary design in the 54" chamber for complete devotion of the 72". coater to NIF work, and mount designs for the laser conditioning stations. All of the facility modifications were completed at Spectra-Physics including the cleaning, coating, and metrology areas. The large NIF chamber was returned to operating condition and resumed process optimization activities.
- A NIF-size color separation grating (CSG) was successfully fabricated with the prototype long hydrofluoric etch station. This full-sized optic achieved a 3ω transmission of 89.4% with a sigma of 0.3%, which is significantly lower variability than CSGs previously etched by hand.
- The facility modifications for the Building 391W phase I Optics Processing Research and Development Area were completed. Balancing of the air-handling systems and certification of the clean room is under way. Beneficial occupancy is targeted for mid-November.

APPENDIX E

PUBLICATIONS AND PRESENTATIONS OCTOBER–DECEMBER 1997

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