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INERTIAL CONFINEMENT FUSION

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To all of you, thank you for your talents and dedication.

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The Appendix provides more details of the objectives of the Nova Technical Contract as presented at the 1990 National Academy of Sciences review.

ICF PROGRAM OVERVIEW

Introduction

Lawrence Livermore National Laboratory's (LLNL's) Inertial Confinement Fusion (ICF) Program is a Department of Energy (DOE) Defense Program research and advanced technology development program focused on the goal of demonstrating thermonuclear fusion ignition and energy gain in the laboratory. During FY 1995, the ICF Program continued to conduct ignition target physics optimization studies and weapons physics experiments in support of the Defense Program's stockpile stewardship goals. It also continued to develop technologies in support of the performance, cost, and schedule goals of the National Ignition Facility (NIF) Project. The NIF is a key element of the DOE's Stockpile Stewardship and Management Program.

In addition to its primary Defense Program goals, the ICF Program provides research and development opportunities in fundamental high-energy-density physics and supports the necessary research base for the possible long-term application to inertial fusion energy (IFE). Also, ICF technologies have had spin-off applications for industrial and governmental use.

Highlights of ICF's FY 1995 Program accomplishments included the following:

- Completed experimentation on Nova to fulfill the National Academy of Science (NAS) Nova Technical Contract[1] ignition target physics goals for indirect drive, and continued weapons physics experiments in support of stockpile stewardship.
- Received approval of Key Decision 1 (KD1) for the NIF Project. On October 21, 1994, Energy Secretary Hazel O'Leary announced her endorsement of KD1, which affirms the Project's mission need and authorizes its transition from conceptual design to preliminary engineering design. Secretary O'Leary also stated that LLNL is the preferred site for the Project because of its resident technical expertise and the existing technical infrastructure.
- Completed the initial Beamlet laser experiments to verify the NIF design performance, and initiated aggressive developments in laser optics and target area technologies to support NIF performance, cost, and schedule goals.

Target Physics

In FY 1995, the Target Physics Program completed a milestone in ignition physics and started a major change in mission and organization. For the past several years, the Program has been oriented toward completing the Nova Technical Contract (NTC) defined by the 1990 NAS report.[1] In particular, the report defined specific experimental goals that address fundamental issues of indirect-drive ICF. Together with Los Alamos National Laboratory (LANL), we have made successful completion of the NTC our highest priority. During the past year, the Inertial Confinement Federal Advisory Committee (ICFAC) concluded that the Target Physics Program achieved a major mission because: (1) the NTC is essentially complete, (2) there has been significant progress in establishing a robust target design for the NIF, and (3) major progress has been made in achieving adequate target surface finish of cryogenic ignition targets. Because of this success, we plan to increase our efforts on direct-drive ignition physics, ignitionless Science-Based Stockpile Stewardship (SBSS) with lasers, and advanced ICF technologies, especially with short-pulse lasers.

X-Ray Drive Ignition Physics

This section discusses progress in three major areas of x-ray drive ignition research that we explored during FY 1995:

- Target experiments using Nova to improve our understanding of ignition target physics,
- NIF ignition design optimization, and
- Demonstrating that cryogenic targets with adequate surface finish can be built.

Target Experiments Using Nova. During the year, successful experiments were conducted by LLNL in collaboration with scientists from LANL and the Centre d'Études Limeil–Valenton, France. Results from these experiments include: (1) demonstrating ways of reducing stimulated Brillouin scatter (SBS) and stimulated Raman scatter (SRS) from NIF-scale plasmas, (2) understanding and controlling symmetry shifts from those predicted by calculations in Nova implosions, and (3) understanding the difference between predicted and measured yields on Nova implosions with hydrodynamic growth factors ~150. In addition, we have demonstrated reduced hohlraum wall loss using material mixtures.

In hohlraum and laser–plasma physics, investigations have concentrated on reducing the levels of SBS and SRS from "gas-bag" plasmas and gas-filled hohlraums. For the gas bags over the range of NIF intensities (5×10^{14} to 2.5×10^{15} W/cm^2), the measured levels of SRS and SBS meet the NIF specifications of <15% for energetics. For more details, see the articles entitled "Laser–Plasma Interactions in Large Gas-Filled Hohlraums" on p. 97 and "Laser–Plasma Interactions in NIF-Scale Plasmas (HLP5 and HLP6)" on p. 305 of this report.

We have also measured that laser-beam smoothing and enhanced Landau damping in the Au-wall plasma reduce SBS and SRS to 1 to 2% levels in Nova scale-1, gas-filled hohlraums compared with higher levels originally seen without beam conditioning. These measurements were made with only one beam of Nova—only one beam is fully diagnosed for accurate backscatter measurements—but we expect that the conclusion will not change for all 10 beams.

Implosion symmetry studies on Nova have been extended in an effort to understand and control symmetry shifts in gas-filled hohlraums similar to present NIF baseline designs. These experiments were performed by varying the hohlraum length and the beam together, similar to previous symmetry experiments. See the article entitled "Nova Symmetry: Experiments, Modeling, and Interpretation (HLP3 and HLP4)" on p. 293 of this report. The experiments demonstrate that the symmetry is reproducible, and for unsmoothed laser beams, the hohlraum length for a given capsule distortion is offset from the calculation and the empty hohlraums by ~150 ± 25 μm. This offset is largely explained by a shift of the emission pattern at the hohlraum wall towards the laser entrance holes, as measured by directly observing the position of the soft x-rays produced by the laser with a gated soft x-ray framing camera.

Experiments in gas-filled hohlraums to measure soft x-ray hot spot motion simply using a beam smoothed with a binary random phase plate (RPP) were in agreement with LASNEX modeling predictions. With a RPP, the x-ray wall emission patterns for gas-filled hohlraums were very similar to those for empty hohlraums. Three-dimensional (3-D) wave fluid calculations show that at ~2×10^{15} W/cm^2, an unsmoothed laser beam in a transversely flowing plasma would be expected to filament and be deflected, whereas a smoothed laser beam would not filament nor be deflected. The experimental results are consistent with these calculations. We plan to implement beam smoothing on all 10 beams of Nova for an integral test of these results on implosions.

Nova implosion experiments have concentrated on implosions with hydrodynamic growth factors of ~150 [defined as the growth of a small pertubation on the outside surface after Rayleigh–Taylor (RT) instability growth during acceleration, feed through the shell and inner-surface perturbation RT growth during deceleration]. These high growth factors are achieved by doping the plastic capsules with materials (Br or Ge) with high x-ray absorption coefficients that act as a preheat shield thereby increasing capsule performance. For high-growth-factor implosions (HEP4), calculations including the 3-D effects of low-order capsule wall thickness variations (P_1) reproduce the smooth capsule HEP4 experimental neutron yields. Without these effects, the calculated yields are a factor of 2 to 4 too high. These calculations also offer a possible explanation for the experimental yield variation since the effect of the P_1 variation depends on its orientation relative to the intrinsic hohlraum asymmetry. See the article entitled "High-Growth-Factor Implosions (HEP4)" on p. 271 of this report for more details.

Modifications to Nova will make it possible to achieve NIF-like time-dependent symmetry control for HEP4 experiments. Current experiments on Nova with a single ring of five discrete spots on each end of the hohlraum have an $m = 5$ azimuthal variation in flux and cannot control the polar time-dependent flux variation in asymmetry. Kinoform phase plates, similar to those being developed for NIF,[2] provide an approach that will allow us to obtain two rings on each side of a Nova hohlraum. Each ring will be much more uniform in the azimuthal direction than with current Nova illumination. The rings can have independent pulse shapes by using two oscillators that produce different pulse shapes for different halves of each Nova beam.

In addition, Nova experiments similar to those that verified wall loss of x rays in Au[3] have shown that a mixture of Au and Gd results in a lower hohlraum wall loss of x rays than with Au alone. This reduction occurs because of the overlaps of peaks and windows in opacity for the two materials. Projecting these results to NIF hohlraums made using these materials, the reduced wall loss is equivalent to 100- to 200-kJ reduction in laser energy required for ignition.

NIF Ignition Design Work. For NIF, a broad set of target designs has been established. The point design for NIF is a plastic ablator capsule, requiring 1.3 MJ of laser energy absorbed in the hohlraum. Designs have been developed that use a variety of other ablator materials and that ignite using significantly lower laser energy. In addition, many parameter variation studies have been done on the point design to study the effects of outer surface finish and inner cryogenic ice surface finish of the capsule and time-dependent drive asymmetry and their coupling.

Integrated calculations, in which the entire target is modeled from laser deposition through thermonuclear burn, have now been done with good ignition performance at laser energies as low as 900 kJ. For details, see the article entitled "Ignition Target Design for the National Ignition Facility" on p. 215 of this report. These smaller targets are simple geometric scales of the point design at 1.3 MJ, with details of the design adjusted to recover symmetry and pulse shaping.

The point design performs well in modeling that includes all of the following:

- Surface roughness perturbations of 20 nm rms on the CH ablator surface and 0.5 μm rms on the deuterium–tritium (DT) ice inner surface.
- Irradiation asymmetry as determined from integrated calculations.
- Additional irradiation asymmetry that is greater than would result from laser pointing and power balance specifications and is compatible with reasonable experimental precision in a campaign to measure the time-dependent asymmetry.
- Variations in the time-dependence of the total x-ray flux that, once again, are larger than would result from laser power balance specifications and are consistent with an experimental campaign to measure the time-dependent flux.

A sensitivity study was done in which laser powers and pointing were varied in integrated calculations, including both the capsule and hohlraum (see p. 215 of this report). Generally, the tolerance is a factor of several larger than the expected deviations (which are dominated by expected experimental uncertainties—the deviations from laser power imbalance and pointing uncertainty are significantly smaller).

For NIF targets, variation in beam pointing and cone-to-cone pulse shapes can be used to control P_6 flux variations. Using this control, the level of P_6 identified in earlier designs has been reduced. With this reduction, the tolerable pointing variations are increased a factor of 2 to 3 to about 200 μm for the NIF inner beams and 350 μm for the outer beams. This is well within the individual NIF beam pointing specifications of 50 μm. Average ring locations can be specified with even better accuracy because of the significant number of beams in each ring.

NIF Target Fabrication. A smooth surface finish is required for the inner surface cryogenic ice to minimize growth of perturbations, which could degrade the implosion. For the NIF point design, an ice surface finish of ~3 μm rms is required if this is the only source of perturbation growth. When the effects of outer-surface roughness and time-dependent asymmetry are included, an ice surface finish of ~ 1–2 μm rms is required. In FY 1995, an aggressive, collaborative program was conducted with LANL to demonstrate the NIF goal of ~1 μm rms for surface finish of the inner ice layer in a curved geometry. During the past year, improved experimental design and diagnostics have demonstrated surface roughnesses <1 μm produced by native beta layering. To increase the margin for ignition, we are developing several techniques to reduce the DT roughness even further. Three techniques to control DT roughness are (1) applying a heat flux across the gas–solid interface by resistively heating with microwaves the DT gas in the center of the target, (2) increasing the bulk heating rate of DT by pumping the collision-induced infrared (IR) absorption band of the solid, and (3) controlling the DT crystal size with a foam substrate.

Native beta layering produces smooth, thick DT layers (with 1 μm rms surface roughness) because the tritium decay volumetricly heats the solid DT. This volumetric heating causes thicker parts of the layer to have a higher temperature than the mean, producing an increased sublimation, thereby reducing surface roughness. DT roughness is controlled by the increase in surface temperature with increasing layer thickness. The increase in surface temperatures with thickness competes with the anisotropic surface energy of the crystalline layer to determine the final surface finish. We can reduce DT surface roughness by increasing surface temperature gradient. This is done either by applying a heat flux across the gas solid interface or by increasing the volumetric heating rate.

We have demonstrated that increasing surface heat flux can improve surface roughness in D_2 experiments. Interferometric measurements of the surface roughness of D_2 layers on flat substrates show that the surface roughness decreases rapidly with increasing surface heat flux, achieving smoothnesses of ~5× less than obtained using native beta layering. We have also measured the surface roughness of D_2 and DT layers in a curved toroidal geometry with the NIF-scale radius of curvature, using shadowgraphy. Again we find that the surface roughness decreases with increasing heat flux, precisely the same as in the surface roughness measurements on flats. These experiments show that D_2 has the same surface roughness as DT when the heat flux is the same as the native DT value. We will apply this technique to NIF capsules by resistively heating the DT gas in the center of the target. An experiment to measure the DT roughness vs resistive heating is under way at LLNL.

We have also shown by measurements and calculations that IR heating reduces the surface roughness of solid hydrogen layers. By pumping the collision-induced IR absorption band in solid hydrogen, we convert IR light into bulk heating, which allows us to control surface temperature and layer thickness. This technique can also be used to smooth solid D_2 layers as well as DT for the NIF. We have measured bulk heating up to

30× the DT value by native beta layering, limited only by IR laser power. Vibrational relaxation rates suggest we can generate up to 600× the volumetric heating rate in DT by IR heating.

The final technique we are developing to improve surface finish is to control the nucleation and crystal size by using only a thin, DT layer above 100 μm of DT-filled CH foam. Interferometric measurements show that thin D_2 layers over foam are significantly smoother than without foam. A thin layer of DT over a fine cell foam will likely have a surface roughness less than 0.5 μm rms without any external heating. Calculations have shown that a CH foam-lined plastic target will perform as well as one without foam, as long as there is at least 10 μm of DT above the DT-filled foam for the ignition hot spot.

A common feature of all NIF capsule fabrication technologies, except machined Be, is a 2-mm-diam, thin-walled polymer mandrel upon which ablator material is deposited. From our study of Nova capsules, we have demonstrated that (1) the capsule surface finish rms is dominated by the lower (longer-wavelength) modes and (2) that the origin of these modes is the underlying polymer mandrel and not the ablator material. Thus, a key technical challenge for the production of high-quality NIF-scale capsules is the development of techniques that can produce high-quality, 2-mm-diam polymer mandrels.

Current solution-drop-tower techniques that are used for Nova-scale polymer mandrels are limited to mandrel production in diameter sizes less than 1 mm. Thus, several different capsule fabrication technologies are being developed to meet the needs of NIF ignition targets. The most straightforward method is to extend the size range of microencapsulation techniques used currently for Omega targets at the Laboratory for Laser Energetics at the University of Rochester from 0.9 mm to 2 mm. These techniques have been shown to produce shells with very smooth outer surfaces, but, especially on larger, thicker-walled shells, there are often interior wall defects (voids). To solve this problem, we have developed a decomposable mandrel technique in which the flawed microencapsulated shell is overcoated with a thermally stable polymer and then heated. This heating decomposes the mandrel to gaseous products that diffuse through the thermally stable overcoat, leaving a hollow shell whose quality depends only on the outer surface of the initial mandrel. We are also working with scientists at the Lebedev Institute in Moscow to adapt their drop-tower technique, which uses a solid polymer feedstock as opposed to LLNL's solution droplets, to the production of NIF-scale shells. The current size range using this technique is about 1 to 1.5 mm. We are also examining interfacial techniques in which a 2-mm droplet of an oil phase is suspended in an aqueous phase, and mutually reactive components in each phase polymerize at the surface to form a solid shell. Comparison of the surfaces of shells produced by these techniques to the requirements for NIF capsules leads us to expect that one or more of these techniques will provide the needed 2-mm mandrels for NIF targets.

For the CH point design, we are confident that the existing plasma polymerization techniques used for Nova capsules will meet the needs of NIF targets. As an alternative to hemishell machining and bonding for the Be point design, we are exploring the use of metal sputtering techniques. We have demonstrated that NIF-scale ablator thicknesses of Be can be sputter deposited on plastic mandrels. The surface finish of these coatings must be improved. To accomplish this, the sputtering techniques offer several options, such as substrate biasing or chamber pressure modification. One key advantage of the sputtering technique is that the overcoated shells are permeable to hydrogen. In addition, the technique is easily modified to allow graded inclusion of higher-Z metallic dopants such as Cu.

Advanced Code Development

For more than 20 years, LASNEX has been the workhorse for ICF 2-D design done at LLNL, LANL, and Sandia National Laboratories (SNL). To meet the more advanced needs for problems that are inherently 3-D in nature, new hydrodynamics codes (ICF3D and HYDRA) are currently under development. Recently, about half of this effort has been aided and accelerated by the DOE's Accelerated Strategic Computing Initiative. In addition, we continue to improve our plasma–physics codes (e.g., bZOHAR and F3D) and others (WARP3D and BASIS).

3-D Hydrodynamics Codes. ICF3D is radically different than LASNEX in that it is written in C++ and has entirely new treatments of hydrodynamics that are considered to be more flexible and accurate. We envision that eventually it will include full physics, namely the usual high-energy-density physics of hydrodynamics, radiation flow, and burn product transport. This would also include laser transport, non-local thermodynamic equilibrium (LTE) atomic physics, material strength, electromagnetic fields, electron transport, and eventually even approximate plasma–physics simulation capability.

Increased accuracy will be achieved in three ways: replacing finite difference with finite element numerical methods, using the most optimal coordinate system for a given problem, and adaptively refining the mesh to better resolve important features.[4] Robustness and ability to handle complicated geometries will be achieved by an unstructured grid with mesh reconnection and arbitrary Lagrange Eulerian methods. We have made considerable progress on this code in FY 1995, including running its hydrodynamics package in massively parallel mode on up to 128 processors of the T3D machine. The tests performed to date on this parallelization have shown very efficient scaling and speed of the problem by going to the many processors in parallel. The challenge will be to parallelize the other components of the code, such as radiation and electron transport.

We developed HYDRA, a simplified 3-D radiation–hydrodynamics code to analyze Nova experiments, since 3-D issues are a challenge in interpreting capsule implosions. This code has had a tremendous amount of success explaining 3-D planar RT experiments and in discovering the 3-D effects on implosion capsule yield of the coupling of capsule low-mode asymmetries with Nova hohlraum low-mode drive asymmetries. See the article "Three-Dimensional Simulations of Ablative Hydrodynamic Instabilities in Indirectly Driven Targets" on p. 168 of this report for one application of the HYDRA code.

Plasma Physics Codes. We are actively developing a variety of plasma physics codes to help explain important phenomena at scales too small to be treated properly or efficiently by the hydrodynamics codes. Currently, ZOHAR is our 2-D 3-velocity particle (electron and ion) in cell (PIC) code—used both for the fundamental understanding of laser–plasma interactions in conventional ICF targets and for the fundamental understanding of high-intensity relativistic interactions for the fast ignitor concept.[5] Also, understanding the fundamentals of plasma physics is an important constraint on achieving high radiation temperature (T_r) on NIF. Although a 3-D version of this code has not been developed, we have produced a hybrid plasma code, bZOHAR, for studying SBS and filamentation. In bZOHAR, the ions are treated as particles but the electrons as fluids, allowing the study to calculate for much longer times in the problem. We can therefore investigate the nonlinear development of SBS, crucial in understanding the actual levels to expect of SBS in the NIF hohlraum targets.

At yet another level of description, closer to the hydrodynamics scale, is F3D, a 3-D laser propagation fluid code that treats filamentation, beam steering and smoothing, and models for SBS and SRS. It has played a central role in understanding present Nova plasma–physics experiments and extrapolations to the NIF. Enhancements under way include a better nonlinear hydrodynamics package that will help us better model the startup phase (window and gas burn-through) of Nova and NIF gas-filled hohlraums, beam deflection in gas-filled hohlraums, and a variety of challenging tasks involving channeling for the fast ignitor.

Other Codes. WARP3D is a 3-D PIC code used in the design of accelerators such as heavy-ion accelerators that could one day be the driver in a facility superseding the NIF. For applications of this code, see the article entitled "Progress Toward a Prototype Recirculating Ion Induction Accelerator" on p. 179 of this report. WARP has other stockpile stewardship applications as well. It is used to design accelerators for x-ray radiography for the Advanced Hydrodynamics Testing Facility. Furthermore, it has been identified as an important code in evaluating designs for the accelerator production of tritium.

BASIS is a sophisticated computer science shell in which most of the above-mentioned hydrodynamics and plasma–physics codes reside. It makes each of these applications programmable by its user and supplies common facilities such as a portability layer, input/output, graphics, dump files, and time history collection. Nevertheless, it is becoming obsolete for current technologies, due to its limitations of running the large, monolithic Fortran 77 program on a single computer. In the future, programs are going to be written in a variety of languages, both standard and with experimental parallel extensions, and are going to run on a variety of different hardware, both distributed and massively parallel. Using object-oriented technology, we can respond to the need to make programs programmable by the users in a heterogeneous hardware and software environment. We are currently in the technology evaluation phase, which we expect to complete in FY 1996, having at least some form of the prototype working by the end of FY 1996, and moving to a production system in subsequent years.

Direct-Drive Ignition Physics

In November 1995, the DOE Office of Research and Inertial Fusion requested that the Office of the NIF include direct drive in the NIF preliminary (Title I) design. This coincided with the completion at the University of Rochester of the upgraded Omega facility. As a result, the Target Physics Program at LLNL will play an increasing role in exploring the technical issues of direct-drive ignition targets. LLNL has maintained a collaborative program with the University of Rochester on direct drive for several years.

In FY 1995, we demonstrated and documented[6] a way of simply modifying the NIF beam layout to achieve a low-mode asymmetry of illumination of direct-drive targets (~1%). This modifies the target area illumination symmetry, which involves moving 24 of the 48 quadruplets of beams (16 from the outer rings and 8 from the inner rings) to rings close (~15°) to the equator. This modification could be made in a relatively short time.

We continued efforts to understand the growth of RT instabilities with directly driven targets. Experiments demonstrated that the longer wavelength and increased brightness of an x-ray laser over x-rays from a laser–plasma can be exploited to measure small areal density modulations in the initial phases of laser imprinting. This is the second use of an x-ray laser as a tool to be used for diagnosis of a high-density plasma using either the coherence or high-brightness properties of the x-ray laser.

Ignitionless Science-Based Stockpile Stewardship (SBSS)

For many years, the ICF Program has supplied Nova shots for LLNL's Defense and Nuclear Technology (D&NT) and Physics and Space Technology (P&ST) Directorates for experiments to benchmark weapons design codes. In FY 1995, this work continued with approximately 220 Nova shots supplied to scientists in D&NT and P&ST for experiments in hydrodynamics, equations-of-state (EOS), opacity, radiation flow, atomic microphysics, and x-ray laser diagnostic development.

In FY 1995, the ICF Program identified experiments of direct relevance to weapons, where there is a natural overlap with ICF in which scientists from the ICF Program will participate with D&NT and P&ST scientists. The areas identified so far as the so-called ignitionless SBSS projects are the high-temperature hohlraums, the EOS of cryogenic hydrogen isotopes, and the growth of hydrodynamic instabilities in regimes of high pressure and relatively low temperature where the strength of material modifies growth rate.

Advanced Technologies and Enhancements

In addition to the conventional hot-spot ignition schemes, there are schemes that rely on a high-energy laser to form a core without a hot spot, and then a high-intensity laser to ignite the compressed plasma, i.e., the fast ignitor concept.

Since 1992, we have pursued a laser technology development program to develop a petawatt capability for Nova. In FY 1995, the technology for large gratings developed sufficiently to install a 100-TW short-pulse laser, an engineering prototype of the Petawatt laser, on the Nova 2-beam target chamber (see discussion and Fig. 4 on p. xviii). Target experiments and diagnostic developments are ongoing to study the fast-ignitor concept.

The Target Physics Program has a history of technology transfer (the Micropower Impulse Radar was a direct result of diagnostic development for Nova[7]). In FY 1995, a program element was created within the Target Physics Program to pursue the dual goals of developing technology for ICF Target Physics as well as technology diversification. Also, a new program element (Target Area Technology) was established to coalesce technology development required for the NIF Target Chamber. This program element works on NIF cryogenic targets, first-wall survival issues, and NIF diagnostic development. The NIF diagnostic effort is in conjunction with SNL, LANL, and University of Rochester scientists and is coordinated through a joint central diagnostic team.

National Ignition Facility

On October 21, 1994, the Secretary of Energy issued KD1 for the NIF, thus reaffirming the Justification of Mission Need issued on January 15, 1993, formally approving the NIF Project and establishing LLNL as the preferred site. With this decision, the DOE and the Administration requested FY 1996 congressional line-item funding for the Project. The Justification of Mission Need emphasizes the importance of the NIF to the mission of the National ICF Program—achieving controlled thermonuclear fusion in the laboratory. This important goal, endorsed in a recent government-sponsored report by JASON,[8] supports the DOE mandate of maintaining nuclear weapons science expertise in required areas for stockpile stewardship and for understanding nuclear weapons effects.

During the past year, the role of the NIF in supporting vital U.S. goals for national security was further strengthened. On August 11, 1995, the President announced the continuation of the nation's moratorium on underground testing of nuclear weapons and the U.S. intention of signing a zero-threshold comprehensive test ban treaty in 1996.[9] (The current moratorium on underground testing of nuclear weapons, beginning in 1991, remains in effect.) The confidence expressed by the Secretaries of Energy and Defense in the ensemble of science-based stockpile stewardship facilities was referenced by the President as strengthening the confidence in his decision to seek a zero-threshold treaty.

Consistent with KD1, DOE Defense Programs and the Laboratory Project staff began several activities in FY 1995 to support a Project start in FY 1996, including the following:

- Establishing a DOE Office of the NIF and a Project organization;
- Supporting the DOE study public process (with public participation) to determine nonproliferation impacts of the NIF and initiating the National Environmental Policy Act (NEPA) process for its siting, construction, and operation;
- Preparing the key industrial contracts to support preliminary and final design;
- Establishing interfaces with potential user groups outside the ICF community;
- Initiating specific advanced conceptual design work to optimize the NIF; and
- Drafting key Project documents required for a Strategic System Acquisition.

During FY 1995, the NIF Project organization met all the milestones required to maintain the Project baselines, described in "The National Ignition Facility Project" on p. 110 of this report.

LLNL's Role in Project Organization and Management

In January 1995, DOE Defense Programs chose a Director of the Office of the NIF, reporting to the Assistant Secretary for Research and Development. A Memorandum of Understanding was signed in May 1995 delineating the responsibilities of this Office and that of the Office of Research and Inertial Fusion—the Defense Program's scientific, technical, and administrative organization responsible for the ICF Program. In particular, the ICF Program has the responsibility of developing the laser, optics, and target area technologies required for the NIF.

The DOE national laboratories team is responsible to all stakeholders in executing the NIF Project. This team includes the Director of the Office of the NIF at DOE Headquarters in Washington, DC; the DOE Field Project Manager at DOE Operations in Oakland, CA; and the National Laboratories' Project Manager and Project Deputies. The current Project organization is consistent with both the Project Charter originally issued in March 1993 and the Memorandum of Agreement signed in August 1993 between the participating ICF laboratories: LLNL, the lead laboratory; LANL; SNL, Albuquerque; and the Laboratory for Laser Energetics at the University of Rochester. As during the conceptual design phase, the National Laboratory Project Manager, chosen by the LLNL Director, has other laboratory Project Deputies originally appointed by their respective ICF Programs.

NIF's Role in Nonproliferation and the NEPA Process

To be responsive to the public, the Secretary of Energy initiated two public processes at KD1:

- To have the DOE Office of Arms Control and Nonproliferation review the impact of the NIF on the nation's policy towards the nonproliferation of nuclear weapons.
- To incorporate the NIF site selection, construction, and operation according to NEPA as a part of the Programmatic Environmental Impact Statement (PEIS) for Stockpile Stewardship and Management.

Nonproliferation and Key Decision One Prime (KD1´). This review has been referred to as the Dellums process because it was designed in response to inquiries made by the Congressman who initiated the Key Decision One Prime (KD1´) process. The Secretary made it a requirement for proceeding to the final design phase of the Project. During 1995, open meetings were held by DOE in Washington, DC and Livermore, CA to first seek public input on the scope of the study and then to receive public comment on the draft study. The schedule of these meetings was broadly announced in the *Federal Register*, and their formats were similar to those used in NEPA reviews. The DOE *Draft Report* was also reviewed by other government organizations, such as the Defense Department, State Department, Arms Control and Disarmament Agency, and by a group of independent experts. The DOE *Draft Report* was issued for public comment in October, and public meetings were held in Washington, DC on September 21, 1995 and in Livermore, CA on September 28, 1995. The two major conclusions reached by the DOE *Draft Report* were as follows: the impact of the NIF on proliferation is manageable, and the NIF can be made acceptable and can contribute positively to the U.S. policy on nonproliferation. The Secretary of Energy accepted these conclusions, issued the final document,[10] and made a positive KD1´ decision on December 20, 1995.[11]

Programmatic Environmental Impact Statement (PEIS). The PEIS Notice of Intent was published in June 1995,[12] and Argonne National Laboratories was chosen by DOE as the NEPA document preparer for the NIF section of the PEIS. PEIS public scoping meetings were held at eight Defense Program sites across the country between June and August 1995 (Kansas City, Savannah River, Oak Ridge, Pantex, Los Alamos, Albuquerque, Livermore, and the Nevada Test Site). The *Implementation Plan* will be published in January 1996. NIF will be handled as a Project Specific Analysis (PSA) in the PEIS, reflecting the status of the Project. The NIF PSA contains the necessary information on all the proposed Defense Program sites—Livermore, Los Alamos, Sandia (Albuquerque), and the Nevada Test Site (in North Las Vegas as well as in Mercury)—for site-specific design, construction, and operation of the facility. Public meetings on the draft PEIS are scheduled to begin in April 1996. It is anticipated that the NEPA process will be completed in the fall of 1996, and a Record of Decision for the siting of NIF to be announced at the end of 1996.

Industrial Outreach

In February 1995, LLNL's Laser Programs Directorate held an Industrial Stakeholders' Briefing Meeting in collaboration with the NIF Laboratory Project Office, representing the participating ICF Laboratories. The meeting, paid for by the industrial participants themselves, attracted 350 individuals from 240 companies representing 35 states. It offered a first-time opportunity for manufacturers and vendors to review NIF requirements with Project technical staff. Follow-on actions included source solicitation and preparatory procurement actions for the following:

- Architect/Engineering (A/E) firms—for the Laser and Target Area Building (LTAB) and the Optics Assembly Building (OAB),
- Construction Management Services,
- Master Task Agreements for Engineering Services—for preliminary and final design phases of the Project, and
- Optics facilitization.

After a rigorous source evaluation process, Ralph M. Parsons of Pasadena, CA and A. C. Martin of Los Angeles, CA were selected as the A/Es for the LTAB and OAB, respectively. Similar processes are under way for the other procurement actions. Final contracts will be signed when the Project is formally funded in FY 1996.

User Groups

In concert with the NIF mission statement, a Project Scientist's Advisory Panel was established to solicit input on the facility from a broad user community. White papers were generated by the ICF direct-drive community, weapons physicists, the Defense Nuclear Agency and Defense Programs' radiation scientists, IFE groups, and the university-dominated high-energy-density community. The Project is considering how to handle features desired by these communities beyond those required to achieve ignition and gain using indirect or x-ray drive as specified in the NIF *Primary Criteria and Functional Requirements*. In particular, DOE has formally requested the NIF Laboratory Project Office recommend a direct-drive option for the NIF (see Fig. 1).

Advanced Conceptual Design

In preparation for completing the advanced conceptual design by February 1996 and starting the preliminary design early in FY 1996, the Project reviewed key technical areas, including structural–vibrational issues, amplifier configurations, beam isolation, and final optics design. A review was held in July 1995 and attended by key Core Science and Technology staff from the participating ICF Laboratories and members of the French Program from Centre d'Études de Limeil–Valenton, France.

Project Documentation

Many key Project documents were generated during FY 1995: a Fire Hazards Analysis, a *Draft Environmental Safety and Health* (*ES&H) Management Plan*, a *Draft Quality Assurance* (*QA*) *Project Plan*, a *Draft Project Execution Plan*, and a *Title I Design Plan.* The *QA Project Plan* and *ES&H Management Plan* were approved by DOE in November 1995. In addition, work has proceeded smoothly on the non–site-specific sections of the *Preliminary Safety Analysis Report*, which is required before construction begins.

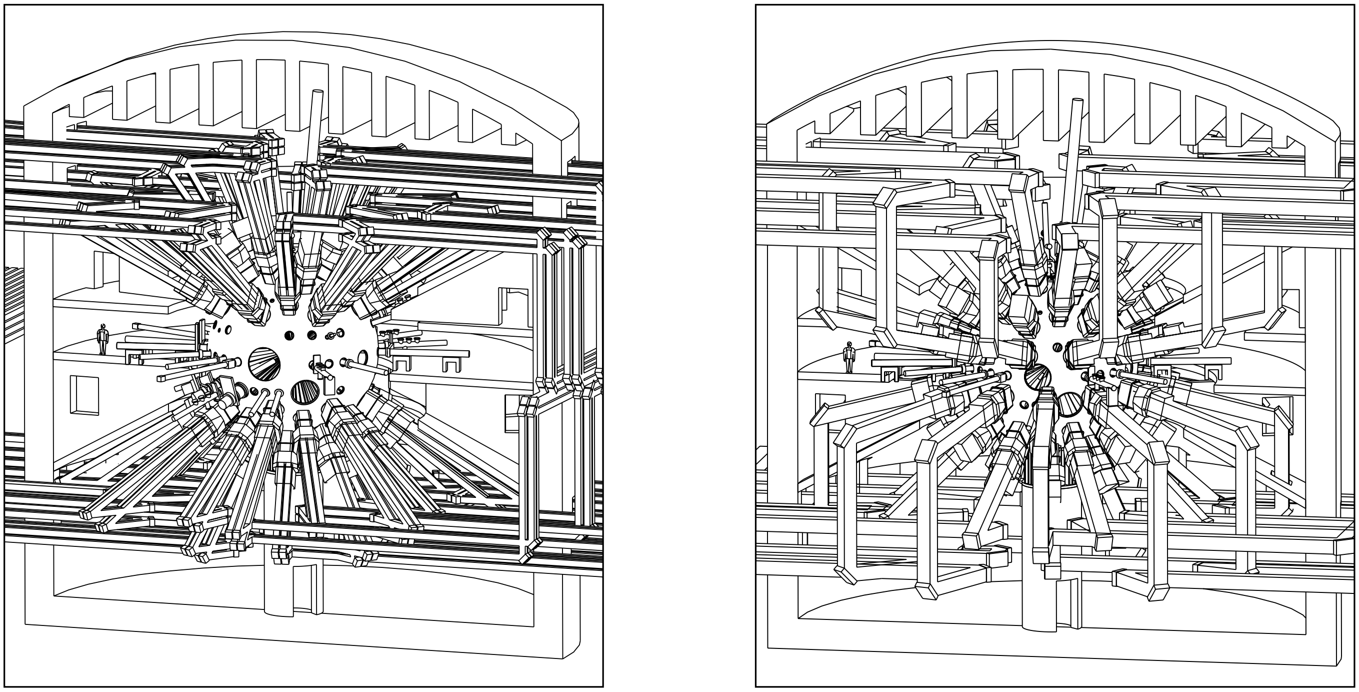
Laser Science and Technology

The mission of the Laser Science and Technology (LS&T) Program is to provide technical innovation and leadership for the Laser Programs Directorate and Laboratory in the core competencies of laser science and technology.

Our primary activity in FY 1995 was in support of ICF by providing for laser development for the NIF Project. This year we began a four-year effort to develop critical components for the NIF laser, including the pulse generation system, large multi-aperture amplifiers, and multi-aperture plasma electrode Pockels cells. We continued to use the Beamlet laser, a full-aperture scientific prototype of one NIF beamline, which serves as an invaluable tool for learning more about large multipass lasers. We developed many software design tools to optimize the NIF laser design. We also completed a study reviewing the status and projecting the laser requirement for direct-drive ignition on NIF and worked on associated laser technology development. For ICF experiments on Nova, in collaboration with Nova engineering staff, we completed the 100-TW laser and designed, ordered, and installed much of the hardware for the Petawatt (10^{15}W) laser beam. These ultrashort (<1 ps) pulse, high-energy lasers are used to study the fast ignitor approach to ICF, which could greatly reduce the laser energy required for fusion gain. In another advanced ICF project, we developed critical technology for a laser driver for high average power applications such as for an IFE plant. The LS&T Program continued to advance diode-laser and diode-pumped laser technology for NIF, advanced ICF systems, and other applications. Our proven expertise in building laser systems enabled us to become an important contributor for U.S. Air Force, Army, and Navy projects. We were also involved in several cooperative research and development agreements (CRADAs) with U.S. companies.

NIF Laser Components

The LS&T Program is responsible for developing the key components for the NIF laser on a schedule and at a cost that permits incorporation into the NIF design. Over a four-year period (1995–98), the following areas will be developed: optical pulse generation system (see Fig. 2), multisegment amplifiers, multipass laser components, frequency conversion, diffractive optics, pulsed power systems, laser diagnostics, lasers alignment and wavefront control, and wavefront control systems. A



Reposition 24 of the 48 4-beam clusters

Laser target
indirect drive

Laser target
direct drive

FIGURE 1. The current NIF indirect-drive design can be simply reconfigured for direct drive without the costly addition of a second target area and chamber by repositioning 24 of the 48 4-beam clusters. (40-00-0495-0976Apb02)

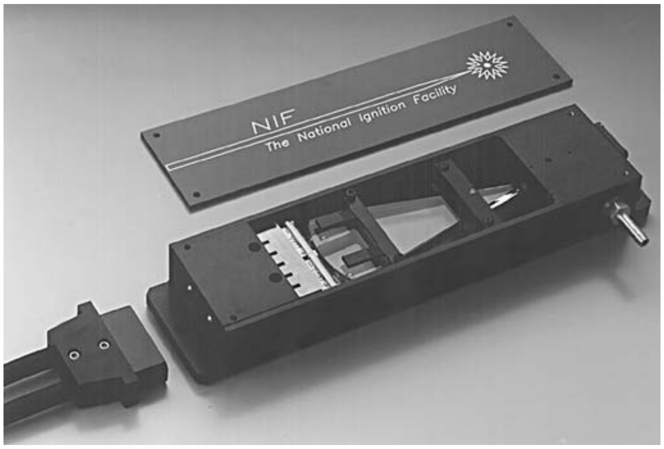


FIGURE 2. Prototype of the diode-pumped regenerative amplifier, which is part of the NIF optical pulse generation system. The prototype has shown ≤ 2% gain stability, operating at an overall gain of 10^6. (99-00-0595-1337pb01)

detailed plan, *Core Science and Technology (CS&T) Development Plan for Indirect-Drive Ignition*,[13] written in 1994 and updated in 1995, describes the activities necessary to develop these components and shows schedules for their completion. The plan includes input from LLNL; LANL; and SNL, Albuquerque; and covers the laser, optics, target chamber, and target science development. In most cases, laser technology prototypes are being built to test the design concept. For example, an effort is under way to build a 4 × 2 multisegment amplifier and a new laboratory to test it. This laboratory, located in the former Shiva target bay in the Nova building, will be used to prove the optical performance of the amplifier as well as to evaluate the new bottom-loading assembly procedures using a robotic transport cart. The 4 × 2 amplifier could be coupled to a Pockels cell array, deformable mirror, or large beam diagnostics to evaluate their combined performance.

Many NIF concepts have been tested on the Beamlet using components that are predecessors of those anticipated for NIF. The *ICF Quarterly Report* (95-1 issue, pp. 1–85) was devoted entirely to the Beamlet system and its components, which were developed over several years. The initial Beamlet performance demonstrations are discussed in this issue (see "System Description and Initial Performance Results for Beamlet," on p. 1 of this report). Beamlet has been remarkably successful in reaching its performance goals and has greatly increased our confidence in the NIF design. Also during the year, an alternative laser architecture (beam reverse architecture) was jointly tested with our French colleagues at Centre d'Etudes de Limeil–Valenton, discussed in the article "Testing a New Multipass Laser Architecture on Beamlet," on p. 142. This year we added a large vacuum chamber to Beamlet to evaluate focusing characteristics of the high-power output beam after conversion to the third harmonic and after passing through a phase plate, diagnostics, and debris shield similar to those planned in NIF. The vessel shown in Fig. 3 is 8 ft in diameter and 33 ft long and contains many large-aperture optics, including a front-surface reflecting mirror (1 m diam) to refocus a sample of the high power beam. Beamlet has provided invaluable information on operating a multipass laser; for example, the NIF spatial filter lenses were redesigned and a lens monitoring diagnostic developed, after an optically damaged lens imploded on Beamlet in May. We also performed smaller-scale experiments on the Optical Sciences Laser to resolve basic nonlinear optics issues and to evaluate NIF components.

Many of the computer modeling codes needed to optimize the NIF laser design were written in 1995, as discussed in the article "The National Ignition Facility Project" on p. 110. A network of 28 computer workstations was purchased and linked together to provide rapid laser design and optimization. Design modifications to correct one issue in particular are being investigated—nonlinear growth of beam modulation which, in an extreme case, can lead to beam filamentation and optical damage. Final design optimization of the NIF laser is scheduled for completion by February 1996 to provide many critical design parameters such as the most cost-effective number and thickness of amplifier slabs, beam dimensions, spatial filter lengths, etc.

A white paper study[6] on direct-drive capability for NIF was completed, detailing the additional hardware required for direct drive and predicted laser and target performance. Direct-drive requires a spherical layout of beams entering the chamber to symmetrically radiate the targets and also requires more uniform (smoother) beams in a time-averaged sense than indirect drive. To meet beam smoothness specifications for direct-drive on NIF, we analyzed the technique of two-dimensional smoothing by spectral dispersion (SSD), which was invented by the Laboratory for Laser Energetics at the University of Rochester. A demonstration of SSD on Beamlet is planned for 1996.

Figure 4 shows the 100-TW laser installed and operated on the 2-beam chamber of Nova. This laser is a predecessor to the Petawatt laser and is capable of producing 40 J pulses at 400 fs (400×10^{-15} s) in duration. The 100 TW of peak power is comparable to the peak power normally available for the entire 10-beam Nova system. The 100-TW beam can be operated simultaneously with the primary Nova beams in the 2-beam chamber, thus allowing flexible target studies. The Petawatt laser, expected to generate ten times the power of the 100-TW laser, is scheduled for completion in late 1996. However, because of the long-order times, most of the design work and planning had to be completed in 1995. The Petawatt pulse compression chamber is a vacuum vessel several times larger than the Nova

FIGURE 3. A vacuum test station added to Beamlet to evaluate the focusing properties of the beam after conversion to the third harmonic. (70-50-0496-0721pb01)

FIGURE 4. The 100-TW laser installed on the Nova 2-beam chamber. (70-60-0895-1969Apb01)

chamber and uses a pair of 1-m aperture, unsegmented gratings, the largest ever made. See the article entitled "High-Efficiency Multilayer-Dielectric Diffraction Gratings" on p. 187 for a discussion of advanced grating development. The power and energy available from the Petawatt laser allow us to test the fast-ignitor approach to ICF.

NIF Optics Development

The specifications for the large NIF optics are similar to those for the Beamlet laser (a scientific prototype of NIF) recently completed at LLNL. For all optics in transmission (except the crystals), the transmitted wavefront error specification (peak-valley) is $\lambda/6$ at 633 nm; for the crystals, the transmitted wavefront specification is $\lambda/4$. The reflected wavefront specifications (peak-valley) for the mirrors and polarizer are 0.4 λ and 0.8 λ, respectively, confined to low-power aberrations. The reflectivities of the mirrors and polarizer (*s*-polarization) must exceed 99%; the transmission of the polarizer must also be greater than 98% for *p*-polarized light. The damage threshold requirement for these optics is extremely demanding. For intracavity and transport optics (1 μm wavelength), the damage threshold requirement ranges from 15 J/cm^2 to 20 J/cm^2 for a 3 ns pulse, depending on location. The damage threshold of the harmonic conversion crystals, focus lens, and debris shield must exceed 12 J/cm^2 at 351 nm. For the NIF, we plan to use the ISO 10110 standard for optics drawings; we are in the process of converting the NIF optics drawings into this format.

Production of most of these optics will begin in late 1998 to early 1999, and continue into early 2002. Crystal production is expected to begin in early 1998. While the U.S. optics industry can manufacture optics meeting the technical specifications (and did so for Beamlet), it lacks the capacity to meet the production schedule. Furthermore, in some areas, such as laser glass, the present manufacturing technology is not cost effective for the quantity of optics needed for the NIF. LLNL has started a comprehensive multi-year development program with leading optics manufacturers to improve the U.S. optics industry's ability to meet the cost and schedule requirements for the NIF. This development program started in mid-1994, and will continue through late-1997. Toward the end of development, equipment will be purchased and installed at the optics manufacturing sites, production teams will be formed, and a pilot production campaign initiated to address any remaining issues prior to the start of production.

In laser glass manufacturing, both Schott Glass Technologies[14] and Hoya[15] had significant accomplishments in FY 1995. Hoya built and tested a sub-scale continuous melter for phosphate laser glass—the first time this glass has been melted continuously. Schott, taking a different development approach, demonstrated casting of continuously melted glass at the NIF-scale using BK-7 as an analog to phosphate glass. The BK-7 also met the NIF specification for homogeneity. In addition, Schott produced five slabs of LG-770 laser glass for testing on Beamlet; this glass composition has been engineered to improve the melting characteristics in Schott's melter design.

Progress was substantial in the KDP crystal growth and finishing activities. We demonstrated high supersaturation levels (greater than 50%) and long-term stability in NIF-size growth tanks as needed for fast growth. We also demonstrated NIF optical specifications on 15-cm boules grown in our small tanks. A continuous filtration system to raise the damage threshold of these crystals was also designed and built. To help understand damage in KDP crystals, we built a dedicated test system with an in-situ scatter diagnostic for characterizing internal features in these crystals.

In fused silica, the new Corning[16] material 7980, made from a non-polluting source material, was qualified for use on NIF. A requirement for low neutron/gamma induced damage from the NIF targets was also included in the qualification criteria.

Finishing and optics specification activities focused on initiation of the development work on deterministic figuring processes for flats and lenses, high-speed polishing, and the use of power spectral densities (PSDs) for specifying mid-spatial length-scale errors. We completed a draft specification package for NIF optics based on PSDs and made provisions for describing these specifications using the ISO 10110 international optics standard. In crystal finishing, we completed an extensive characterization of the existing diamond turning machine at Cleveland Crystals[17] to establish a baseline for planned improvements. The initial upgrades were completed, including building and installing an improved flexure coupling to better isolate the crystal surface from machine irregularities, and a NIF-size flywheel for mounting the diamond tool.

In coatings development, we started upgrading the coating chambers to improve diagnostic capabilities for the damage threshold improvement campaigns in FY 1996. We also found that ion-beam sputtered coatings which have superior spectral properties, have defects that lower damage threshold to levels unacceptable for NIF. Although the density of these defects is quite small, full-area testing readily locates their position. As a result of this problem, this technology probably will not be pursued further in FY 1996. Transport mirrors coated using traditional electron-beam technology were successfully laser conditioned to the NIF baseline level.

The NIF requires a full-aperture phase measuring interferometer. To accommodate this requirement, Zygo[18] and WYKO[19] began working on conceptual designs that will be completed in early FY 1996.

Diode-Pumped Solid-State Laser (DPSSL)

We are developing the technology for upgrading solid-state lasers to provide for an efficient (~10%), repetitively pulsed (~10 Hz) system, suitable for future dual-use ICF laser-fusion facilities for defense and energy research. The technology of this system has a strong connectivity with Nova and NIF laser technologies. Furthermore, the natural modularity and scaling laws of laser architectures reduce the physics risks and research costs associated with this effort.

Our leading candidate for a laser driver is based on a diode-pumped solid-state laser (DPSSL), for which the gain medium [Ytterbium-doped strontium fluorapatite (Yb:S-FAP)] is cooled by He gas, using the GCS or gas-cooled slab concept. We completed a conceptual study of a DPSSL in the power plant context in FY 1994 and wrote an extensive article on this topic.[20] The detailed laser physics is explicitly included in the model, while costs, target performance, and power plant phenomenology are handled using community-accepted paradigms.

In FY 1995, we pursued an experimental campaign to construct and test a small subscale DPSSL. Early experiments on this laser provide enhanced credibility for this type of novel cooling technology, which is scalable to high-repetition rates and average powers in the megawatt range. The GCS cooling technology is unique, as compared with more conventional transverse water-cooled rod or zig-zag slab designs (the cooling and optical extraction simultaneously occur across the two large faces of the slab). See the summary below for details of this technology and the graphic illustration shown in Fig. 5.

These experiments were also conducted at a thermal flux (out of each face of the slab) up to $3.5\ \text{W/cm}^2$. This is several times greater than that required for a large IFE driver operating at moderate rep-rates. The overall objective of this project was to convincingly show that the DPSSL driver offers adequate performance to serve in a fusion energy power plant.

Advanced Technologies and Enhancements

The LS&T Program also contributed to a DOE project supporting nuclear nonproliferation and delivered a 20 J/pulse laser to the U.S. Navy. For the Air Force, a 4-beam laser for integration into a land-based, space-imaging system is being built, which has an output of 60 J of green light at a pulse length of $600\ \mu s$—a unique regime for solid-state lasers. The laser is a flashlamp pumped Nd:glass zig-zag slab laser that uses a special technique of low-threshold phase conjugation.

The CRADAs with several U.S. companies included developing laser driven x-ray light sources for making sub-micron resolution computer chips with x-ray lithography, lasers to remove port-wine stain birthmarks, efficient high-power lasers for cutting and welding, and a very compact three-color laser for incorporation into a prototype of a laser video projector.

Heavy Ion Fusion (HIF) for IFE

LLNL made significant progress in FY 1995 to advance the development of IFE and to initiate new applications of ICF Program technology for U.S. industry and for government-sponsored programs in addition to the ICF Program. The funding for much of this work

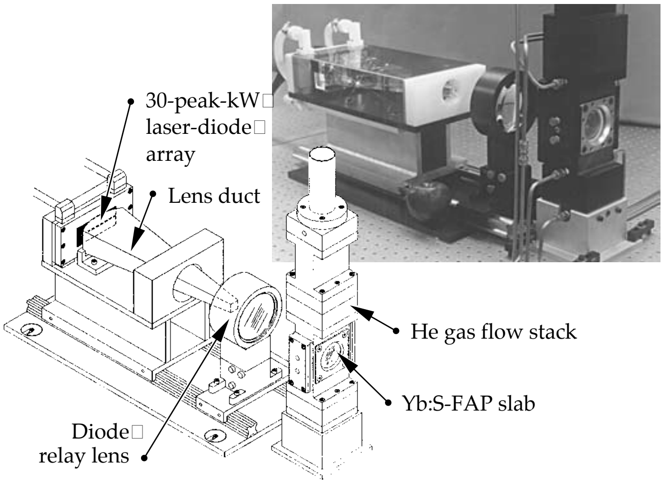


FIGURE 5. A diode-pumped Yb:S-FAP gas-cooled slab laser. (70-00-0795-1744Epb01)

Gas-Cooled Slab Laser

A gas-cooled slab (GCS) laser consists of the gain medium slab, over which gas flows across both faces through narrow (~1-mm-thick) channels, and the laser-diode array. The laser-diode array longitudinally pumps the slab through access windows on either side of the slab. (Figure 5 shows an earlier configuration of only one side of the slab.) The laser-diode array has 192 bars producing 20 kW (with an aperture of 3.5×10 cm, a 43% electrical efficiency at 900 nm, and a 5.5-nm full-width half maximum), including the thermal-induced spectral chirp within the millisecond pulse length. The output is ~20 J in 1 ms at a peak current of 140 A. A lensing duct concentrates the diode light down to a 2×2 cm aperture with an 85% efficiency. An f_2 relay lens transfers the diode energy from the lensing duct to the Yb:S-FAP laser slab in the gas flow channel.

The coolant gas is He, due to its uniquely low scatter properties (low index) and good thermal conductivity (for a gas). The He gas flow stack separates the gas flow into two broad channels at the bottom of the stack in a diffuser to homogenize the flow. The flow is then accelerated at 4 atm pressure to Mach 0.1 in a nozzle section specifically designed to prevent flow instabilities and is directed to flow across both slab faces in rectangular channels (1-mm-thick $\times$ 22-mm-wide). For our operating conditions of 80 std L of He/min, the flow is characterized as well into the turbulent rather than laminar or intermittent flow regime. Turbulent flow is critical because it minimizes the thermal impedance between the gas and the slab by minimizing the effects of the thermal boundary layer. Finally, the flow is gently decelerated in a tapered channel and exhausted through an additional diffuser.

The laser output efficiency is 51% with respect to the absorbed pump power. Using this configuration, we achieved up to 50 W of optical power at 25 Hz. The Yb:S-FAP slab fractures above 25 Hz, which is expected since the laser operates at a significant fraction of the thermal fracture limit. Note that the maximum repetition rate before fracture is two to five times higher than the requirements proposed for megawatt-scale ICF laser facilities.[21]

is independent of ICF Program funds. The work is included here because it demonstrates some of the possible applications and spinoffs of capabilities developed by the ICF Program. During FY 1995, a sequence of experiments in heavy-ion beam physics began with magnetically focused heavy-ion beam transport. This sequence will lead to later experiments in ion-beam bending, recirculation, and drift compression to be conducted during FY 1996.

The U.S. Heavy Ion Fusion (HIF) Program is developing the concept of using ion-induction accelerators as drivers for IFE and post-NIF ICF research. LLNL's HIF project made significant progress in FY 1995 on the accelerator physics and technology, target physics, and chamber propagation physics necessary to make HIF a reality. Our approach combines experiment, analytic theory, and computer simulation to gain the required level of understanding in all of those research areas. A major new thrust was the initiation of an experimental research program in high-current ion beam dynamics. During the year, the first in a sequence of experiments was conducted in magnetically focused beam transport, beam bending, and ultimately recirculation. If successful, this series of experiments will lead to a small prototype recirculating induction accelerator.

The recirculating induction accelerator is a promising approach to a reduced-cost heavy-ion driver. A small, scaled ring was designed to explore this approach and to facilitate studies in beam bending, beam transport over long path lengths, and precise beam sensing and handling. The design uses permanent-magnet quadrupoles for beam confining and electric dipoles for bending. To understand beam-bending effects, we first characterized magnetic beam transport in a linear channel. To achieve this, we installed an electrostatic-focusing "matching section," followed by a transport line, consisting of seven permanent-magnet quadrupole lenses at the output of the injector. Experiments in this beam line are ongoing; initial tests show a high-quality beam that has yet to be optimally "matched" to the line. Associated with this work has been the development of novel beam-sensing diagnostics. The prototype recirculator design, the linear transport experiments, and the associated theory and modeling effort are described in "Progress Toward a Prototype Recirculating Ion Induction Accelerator" on p. 179 of this report.

An important element of a recirculating induction accelerator, or of a multipulse linear accelerator, is an accelerating module capable of generating a series of pulses in rapid sequence, with a repetition frequency up to 100 kHz. We are developing an accelerator power source that is switched entirely by field-effect transistors (FETs). This approach is motivated by the need for an agile device that can afford pulse-to-pulse variability and excellent waveform control. The devices developed are made possible by recent advances in high-power FETs. This research is described in "Evolution of Solid-State Induction Modulators for a Heavy-Ion Recirculator" on p. 103 of this report. In another technology area, we made major strides in understanding how to synthesize a variety of multipole fields using iron-free assemblies of permanent magnets.[22]

LLNL played an important role in the support of the larger HIF experimental program at Lawrence Berkeley National Laboratory (LBNL), including the design of the first phase of the Induction Linac Systems Experiments Program, called Elise. The optimized design point for Elise was derived from a zero-dimensional Mathematica-based program. While the Elise project has not received approval for a construction start, the experience gained will enable the U.S. HIF Program to propose a far more capable machine for construction, beginning in the next few years.

LLNL 3-D, PIC modeling, using the WARP code, precipitated the successful fielding of LBNL's new driver-scale injector. This model uses a novel electrostatic-quadrupole approach to beam acceleration and confinement and also played a critical role in the recirculator physics effort (see Ref. 20 for more details). Other tools, including the Circe moment-equation code, played an important role in both the driver-scale injector and the recirculator physics effort as well. LLNL also provided support in control systems and diagnostic development to the LBNL program.

The HIF group has continued to make progress in the study of IFE heavy-ion beam chamber propagation, target design, and power plant studies. Electromagnetic PIC simulations are being used to better understand transport in the target chamber. Recent results examining near-ballistic focusing through a low-density preformed plasma channel are encouraging—they show that with only half-percent ionization of the background gas, lower-mass or higher-charge-state ions can be focused onto a small spot. In the area of target physics, detailed converter designs have been conducted and preliminary "integrated" simulations using LASNEX are well under way. We recently initiated a LASNEX study of ion beam heating of Au foils, whereby high-energy densities in matter are achieved using highly focused heavy-ion beams.

New Initiatives and Spin-Off Technologies

Spin-off laser program technology initiatives were pursued in medical technology and modeling, night-vision systems, plasma probing, laser pinhole closure, x-ray imaging for semiconductor defects, oil and gas exploration, enhanced surveillance, and Advance Design and Production Technology (ADaPT). A preliminary design was completed for an advanced radiography machine based on megahertz induction pulse rate technology, and work began on building a test facility for Relativistic Klystron Two-Beam Accelerator (RK–TBA) tests at LBNL as a joint effort with LLNL.

In FY 1995, we identified and initiated efforts to exploit ICF Program expertise and technology to capture a share of industrial and governmental markets in areas such as:

- **Health care technology—**Applications of our expertise/technology that are being applied to medicine include: (a) Modeled laser–tissue interactions, using a 3-D laser–tissue simulation code called LATIS to optimize benign prostate hyperplasia treatment, laser thrombolysis of cerebral and cardiovascular clots, and laser–tissue welding for laparoscopic and endovascular applications. (b) Set up a medical photonics laboratory for developing a host of new medical technologies (e.g., optical sensors for tissue identification and blood and tissue analyte monitoring, Optical Coherence Tomographic imaging, and ultrashort pulse-laser drilling of hard tissue). (c) Developed a user-defined diode and DPSSLs for medical procedures (e.g., port wine stain removal, tattoo removal, and laser surgery).
- **X-ray imaging and lithography—**Developed laser-based debriless x-ray sources for x-ray lithography under contract to the Advanced Research Project Agency and in collaboration with AT&T, Motorola, Silicon Valley Group, and IBM. We are engaged in the development of collimating x-ray optics for minimizing feature sizes printed while maximizing system throughput. Another important technology is the development of x-ray imaging technologies for defect inspection, which is a program we are currently initiating.
- **Military visualization systems—**Pulsed microchannel x-ray imaging technologies are now being applied to developing advanced night- and underwater-vision technologies for the Department of Defense. This work is being done in collaboration with key industrial partners such as Intevac and Litton.
- **Oil and gas exploration—**We have teamed with Shell Oil Co. to develop advanced imaging and image reconstruction algorithms for geostrata mapping.
- **Plasma probing—**X-ray laser technology has been applied to the probing of ICF plasmas, in particular large-scale plasmas necessary for producing ignition with the NIF. The first x-ray laser-based Mach–Zehnder interferometer was developed as part of this effort.
- **Enhanced surveillance—**Advanced x-ray imaging technologies are now being applied to the DOE's enhanced surveillance initiative. This technology, similar to that developed for measuring ICF capsule performance, will be used to nondestructively inspect nuclear weapons in our nation's stockpile to verify nuclear readiness. Modified medical technologies of endoscopic imaging and noninvasive sensors are also being developed to verify the status of nuclear weapons components in the national stockpile.
- **AdaPT—**We are developing advanced sensor technologies for monitoring laser materials processing associated with the ADaPT initiative (providing a means to manufacture nuclear weapons components when or if required in the future).
- **Advanced high-energy particle accelerators—**Three areas are being developed to support advanced accelerator technology. (1) A high-gradient dielectric-wall accelerator is being developed to demonstrate transport of electrons at 1 kA with a record gradient of 20 MeV/m using novel insulating materials. We demonstrated operation of novel pulse forming lines (Asymmetric Blumleins), which provides the accelerating voltage to the dielectric wall. Additionally, we invented and successfully tested a high-gradient laser-induced surface-flashover switch, providing a subnanosecond rise time to initiate the pulse from the Asymmetric Blumlein. Proposed future work will involve tests of a stack of pulse forming lines with laser switches, operating at high gradient. (2) We are supporting the development of a high-current electron-induction accelerator for B-Division's Advanced Hydro-Test Facility proposal (a National Radiographic Facility). We built and tested a 15-kV, 3-kA induction modulator cell that runs at an extremely high repetition rate (300 kHz), necessary for multiple images of a single high-explosive shot. We are completing a second generation modulator that will run at 15 kV, 4.8 kA, and at least 800 kHz. We are developing the beam switching and transport technology that will be required to produce multiple lines of sight to the radiographic object. (3) We began construction during FY 1995 of the RK–TBA Test Facility at LBNL as a joint effort with LLNL. The facility will study physics, engineering, and costing issues of using RK–TBA's as rf power sources for high-energy linear colliders. Important issues to be addressed by the test facility are efficiency, longitudinal beam dynamics, beam stability, emittance preservation, and rf amplitude and phase control. Testing will be performed on a 25-m-long RK–TBA accelerator prototype that includes eight high-power rf output structures. Each structure will produce a 180-MW, 250-ns rf pulse at 11.4 GHz.

Program Resources and Facilities

Resources

In FY 1995, financial resources for the LLNL ICF Program totaled $75.8M in DOE operating funds and $4.6M in DOE capital equipment allocations. Work-for-others funding increased slightly in FY 1995, with $30.8M coming from various sources within the DOE community, other federal sponsors, and international sources. At LLNL, the NIF Project received $4.1M in DOE operating funds for FY 1995. The average LLNL full-time employee equivalent count over the year was 353.1. Supplemental contract labor personnel were used in clerical, design, and engineering positions and as Nova operators. The ICF Program employed approximately 77.3 supplemental labor and other labor personnel in FY 1995.

Figure 6 shows the resources available to the ICF Program over the past 12 years and compares the operating funds provided by DOE in then-year-dollars vs the same funding discounted to reflect 1982 dollars. The figure illustrates that the real purchasing power for the DOE funding, as related to FY 1982, has remained fairly constant and is expected to remain so in FY 1996.

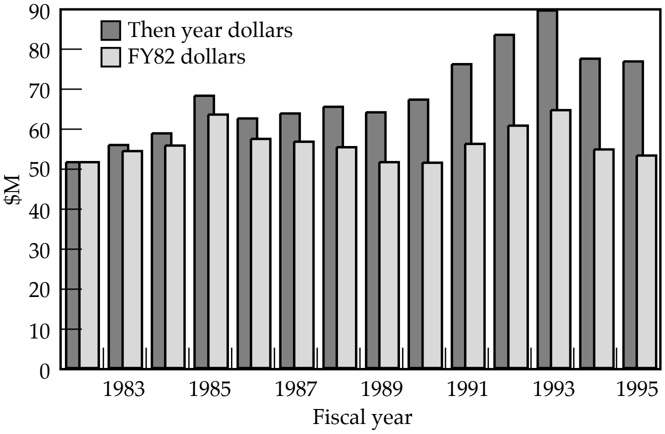


FIGURE 6. ICF program operating funds. (02-20-0396-0582pb01)

Figure 7 illustrates Work-for-Others funding, which is becoming a significant part of the total resources available to the ICF Program, but is expected to decrease slightly in FY 1996.

These resources enabled the ICF Program to continue its support of research and development of high-energy-density physics, laser component development, optics technology, and IFE. A few examples of major projects accomplished during FY 1995 are the completion of the 100-TW modification to the Nova laser system, the addition of the focusing vessel to Beamlet, and the facilitization of the Optics Processing facility in Bldg. 392. The ICF Program also purchased equipment for video teleconferencing, which will provide opportunities to maintain close collaboration with both national and international Program participants.

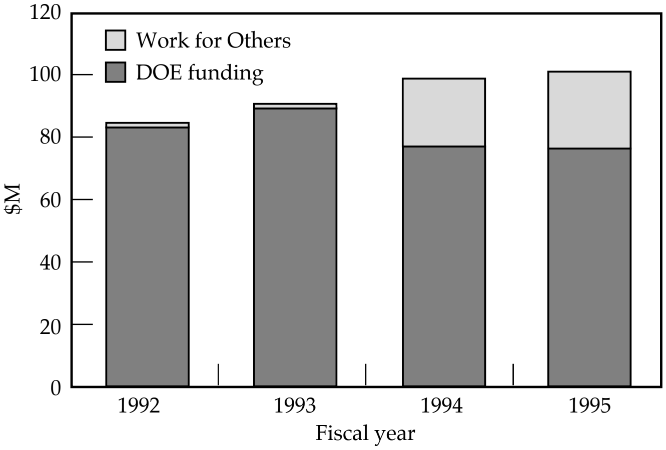


FIGURE 7. LLNL ICF program funding. (02-20-0396-0583pb01)

Facilities

In FY 1995, the ICF Program comprised 36 facilities—laboratories, offices, and specialized facilities in excess of 500,000 ft^2. Figure 8 shows the locations of ICF facilities within the Laser Programs.

The emphasis in facility upgrades during the year was in support of the core science and technology developments in lasers and optics. This included major modification upgrades, renovation, and special projects as summarized below. In addition, several facility maintenance projects were completed.

- Completed the $1.5M clean room installation and modifications to the Bldg. 392 Optics Processing facility to support the development of Nova, Beamlet, and the NIF.
- Completed the $200K Bldg. 165 facility upgrade to grow rapid-growth KDP crystals in support of the NIF.
- Completed a $150K *Conceptual Design Report* for a proposed Advanced Optical Technical Center.
- Completed the detail design for a $1.3M Bldg. 391 basement upgrade for the new NIF amplifier development, flash-lamp development laboratories, capacitor bank, and control room.
- Finished planning and designing the major Bldg. 298 $430K upgrade to house phase-plate development in support of the NIF.

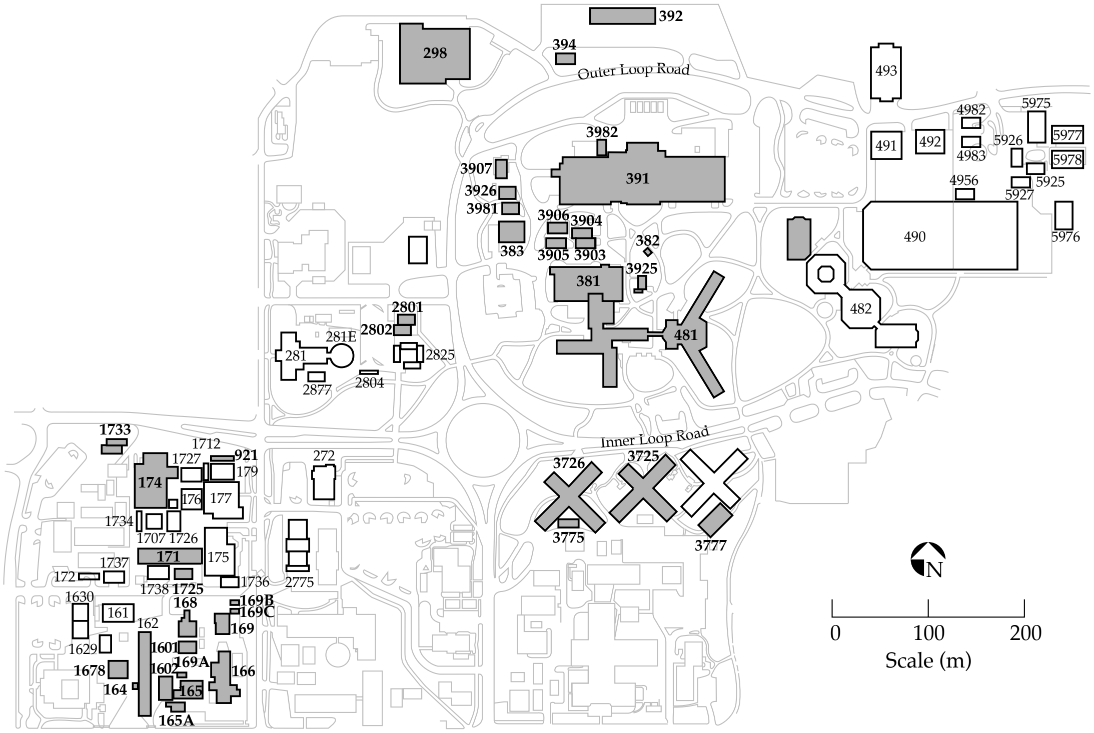


FIGURE 8. A map of the Laser Programs' area with facilities used by ICF shaded.
(40-00-0794-2902Apb01)

- Completed the Laser Programs' first teleconferencing facility in Trailer 3725.
- Installed two new 350-ton chillers in Bldg. 381 to support a major $700K AC upgrade to one of our key facilities. This installation accommodates 136 offices, several experimental laboratories, and the Beamlet system.
- Allocated $140K to refurbish and paint the Iron Cross triplex—Trailers 3724, 3725, and 3726.
- Finished the design for the Bldg. 481 transformer upgrade.

For FY 1995, the ICF Program continued a proactive management approach to environment, safety, and health (ES&H) issues. To support FY 1994's ICF management reorganization, the Assurances and ES&H managerial position (formerly the Building Superintendent) is now part of the ICF Program Operations office. Examples of the ES&H accomplishments are as follows:

- Completed the required documentation, according to the NEPA, for the Amplifier Development Laboratory to be built in Bldg. 391 in FY 1996.
- Replaced the Personal Protective Equipment (PPE) with reusable nylon suits, resulting in a considerable savings to the Program. PPE was worn during the Nova Target Chamber clean out and was disposed of as low-level hazardous waste.
- Began two NIF-related experiments in Bldg. 298 based on authorization under safety procedures coordinated by the ICF ES&H office.
- Received approval from the Environmental Protection Department (EPD) to allow discharge of Nova sol-gel rinse water to the sanitary sewer. Prior to this petition, all rinse water was sampled before discharge, requiring the sol-gel technical staff to collect rinse water instead of cleaning the Nova optics.
- Secured funding from EPD's Waste Minimization group to purchase and evaluate an ethanol distillation unit to reduce the ethanol waste from Nova's sol gel.
- Coordinated the Preliminary Hazards Analysis performed for Bldgs. 381 and 391 in accordance with DOE Order 5480.23 to reduce their classification from low hazard to radiological/excluded.
- Set up the ICF Emergency Preparedness Plan, participated in the Laboratory-wide earthquake evacuation drill, and located and treated pre-arranged "victims."
- Completed the Self Assessment inspections, covering 230 laboratories with 318 noted deficiencies, and their subsequent repair.
- Secured Air Permits from the Bay Area Air Quality Management District for wipe-cleaning operations in Bldgs. 174 and 381.
- Corrected 177 items from the ICF Def Track—the Laboratory-wide Deficiency Tracking System.

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FACILITY REPORT
OCTOBER–DECEMBER 1994

G. Hermes
Nova Operations Group
Nova Experiments Group
Laser Science Group

During this quarter, Nova Operations fired a total of 252 system shots resulting in 308 experiments. These experiments were distributed among ICF experiments, Defense Sciences experiments, X-Ray Laser experiments, Laser Sciences, and facility maintenance shots. Only four of these experiments were classified.

The fail-safe chirp system was successfully demonstrated. The system produces a small frequency "chirp" on the laser pulse that spoils stimulated Brillouin scattering (SBS) induced in the large-aperture chamber optics when operating with long pulses of high energy at 3ω. High levels of SBS can damage the final focus lenses and therefore limit the amount of energy we can direct into the chamber for use in target experiments. The fail-safe chirp system will allow us to increase the current energy limit by about 33% at a 3-ns pulse length.

Effort continued in support of the Petawatt Laser Project, which involves the modification of a Nova beamline and development of the necessary technology to produce a short-pulse beam on-target in the 10-beam chamber of ~1000 J at 1 ps. Beam transport experiments to the 2-beam target area were performed using the Petawatt laser front end as the pulse source with amplification through the Nova laser chain. The purpose of these experiments was to measure the spectral, temporal, and spatial modification of a broadband, linearly chirped pulse as a function of laser energy. Beamline 6 (BL-6) of Nova was configured according to the Petawatt design to produce a high-spatial-quality 40-cm-diam beam at the output of the laser chain. This included removal of the 46-cm amplifiers and spatial filter #6 on this beamline.

The Petawatt configuration of BL-6 significantly improved the beam quality relative to conventional Nova operation. Preliminary analysis indicates a far-field spatial distribution at the 2-beam chamber of approximately three times diffraction limited for the first shot of the day. Convection currents induced by temperature gradients in the disk amplifiers severely degraded the beam quality on subsequent laser shots.

Significant spectral and temporal reduction of the pulse was observed on propagation through Nova. This bandwidth limitation arises due to passive components in the Nova chain. Gain narrowing of the spectrum was also observed with increasing pulse energy at the predicted level. The impact of convective currents on the Petawatt beam quality should be minimized in an alternative configuration of Nova with spatial filter #6 left in place. This concept will be tested on an upcoming Nova/Petawatt shot series.

Engineering effort continued on the Petawatt project. A component design review was held on the vacuum compressor vessel, an aluminum chamber ~2.7 m across × ~12.8 m long. This vessel will house large-diam (94-cm) gratings for use in pulse compression. We plan to have the chamber installed in the 10-beam bay and demonstrate Petawatt capability by the end of FY 1995. Modifications to the 10-beam chamber to use the Petawatt beam in target experiments will be done in FY 1996.

A final design review was held on the 100-TW system for use on the 2-beam target chamber. This system will use a pulse from the Petawatt master oscillator with some non-Nova amplification to produce a beam on-target of ~36 J at 400 fs (or ~30 J at 300 fs using mixed glass in the amplifiers). The system will be used for investigation of ignitor concepts and compressed-pulse issues prior to installation of the Petawatt system on the 10-beam chamber. Fabrication of the large vacuum vessel began, all the major optics were ordered or bid, and many other off-the-shelf items were ordered. Completion is scheduled for the 3rd quarter of FY 1996.

Effort continued on converting x-ray pinhole cameras from film to charge-coupled-device data recording. One system has been installed on the Nova target chamber and has recorded many images on a variety of target shots. Software has also been developed to process the raw data and more quickly determine beam offsets for use in precision pointing. The system lacks only a communication link to the open lab net to become a routine instrument on Nova. A second camera is planned to be installed on the chamber in the 3rd quarter of FY 1996 and will have the ability to change filtering as well as magnification without venting the target chamber. The first camera will then be retrofitted to incorporate this same capability.

We are working on improving the resolution of our gated microchannel plate detectors used in many of our x-ray diagnostics. The armed forces have shown an interest in this technology, as it is also applicable to night vision goggle detectors.

Most of the Nova operations personnel attended Total Quality Leadership classes sponsored by Allied Signal Corporation (the Nova facility contractor). These classes are intended to aid in team interactions, help understand performance measures, and improve overall Nova productivity.

FACILITY REPORT JANUARY–MARCH 1995

G. Hermes
Nova Operations Group
Nova Experiments Group
Laser Science Group

During this quarter, Nova Operations fired a total of 242 system shots resulting in 299 experiments. These experiments were distributed among ICF experiments, Defense Sciences experiments, X-Ray Laser experiments, Laser Sciences, and facility maintenance shots.

To support continued experiments in FY 1995, the Nova target chamber, Master Oscillator Room (MOR), and beamline 7 (BL7) were reconfigured to conduct *f*/8 and four-color operations. Several scattered light diagnostics were also installed and activated in the target chamber. At the completion of these experiments, the system was again reconfigured for normal *f*/4 single-color operations.

Work began to convert the old Nova safety interlock system to a new Programmable Logic Controller (PLC) system with expanded capability to support the 100 TW project: Phase I supports the 100 TW project and is scheduled for completion in early May; Phase II completes the system conversion in FY 1995.

A digital oscilloscope (SCD 5000) and a fast diode replaced the MOR Fidu Diagnostic (MFD) streak camera. After the system is validated by the MOR personnel, it will be integrated into the Laser Diagnostics controls software.

All major optics procurements have been awarded for the 100 TW project, with delivery expected by mid-April. We completed the installation of the 100 TW capacitor bank, and high-voltage cabling between the bank and the 9.4-cm amplifier will be installed early in the third quarter FY 1995. We received the 100 TW compressor chamber from EG&G, Inc. on March 21, 1995 and installed it in the two-beam area the following week.

In support of precision alignment operations, we performed two 2ω alignment shots to determine the consistency between the 2ω and 3ω transverse offsets. The data show that it is probably reasonable to use the 3ω offsets for the 2ω precision pointing series. However, the z (focus) offsets were quite different, as expected. Therefore, it might be necessary to perform 2ω alignment shots periodically to update the z offsets.

A series of shots verified beam timing—nine of the ten beams were within the Precision Nova specification of ±10 ps (BL7 was approximately 30 ps early). As a result, five timing adjustments were made and confirmed using the 1ω streak camera data.

The BL7 potassium dihydrogen phosphate array was replaced with a refurbished unit, increasing the conversion efficiency by ~20%.

FACILITY REPORT APRIL–JUNE 1995

G. Hermes
Nova Operations Group
Nova Experiments Group
Laser Science Group

During this quarter, Nova Operations fired a total of 313 system shots resulting in 337 experiments. These experiments were distributed among ICF experiments, Defense Sciences experiments, X-Ray Laser (XRL) experiments, Laser Sciences, and facility maintenance shots.

Work has begun in support of a series of XRL experiments planned for mid-August on Nova's 10-beam chamber. This effort includes planning and preparation to install cylinder lenses on beamline 3, the XRL assembly, the imaging diagnostics, and the alignment system.

The gated x-ray imager 4 was also completed, installed, and activated on Nova's 10-beam chamber.

We implemented a new "precision pulse shape" capability on Nova**.** This enables us to produce a power balance report immediately after each shot. Data from the 3ω streak camera and Incident Beam Diagnostic energy diodes are used to show plots of power vs time for the 10 beams and the power balance error vs time.

We began installation and activation of the 100-TW system with full-system activation planned for early fourth quarter. The compressor chamber was delivered and installed, and the 10-cm amplifier, spatial filters, other beamline components, and optical components for the compressor and diagnostics systems were installed and aligned. The vacuum system for the compressor chamber was completed. The control systems and interlock systems were installed and tested, including firing the 10-cm amplifier.

Two Total Quality Management working groups were formed—one to focus on shot quality and the other on shot quantity. We have also made significant progress in cross training personnel among the operations groups.

FACILITY REPORT
JULY–SEPTEMBER 1995

G. Hermes
Nova Operations Group
Nova Experiments Group
Laser Science Group

During this quarter, Nova Operations fired a total of 279 system shots resulting in 301 experiments. These experiments were distributed among ICF experiments, Defense Sciences experiments, X-Ray Laser experiments, Laser Sciences, and facility maintenance shots.

This is the final report for FY 1995. During the past year, Nova fired a total of 1101 system shots resulting in a total of 1228 experiments. There were 856 target experiments done in the 10-beam chamber and 128 experiments done in the 2-beam chamber. As a result of the declassification of ICF, there were only six target shots that were classified. There were 92 experiments conducted in support of laser science work, including precision pointing, failsafe chirp activation, and miscellaneous beam propagation experiments. We fired 150 calibration shots in support of routine and precision operations.

The first 8× CCD camera was installed and activated on the 10-beam chamber. This camera, plus one more, will eventually replace the film-based pinhole cameras currently being used to acquire x-ray images from precision pointing shots. Using the CCD cameras will greatly reduce the time required to analyze data from the pointing shots.

A set of cylinder lenses was removed from the 2-beam chamber and installed on beamline 3 of the 10-beam chamber in support of a series of x-ray laser experiments. This lens set was removed after several days of experiments and reinstalled on the 2-beam chamber. These lenses will be reinstalled next quarter with an additional spacer to allow for a longer line focus on the x-ray laser targets.

The 100-TW system was activated this quarter. We fired a shot at ~129 TW with a pulse width of 395 fs and an energy of 51 J. Work will continue to complete the target system activation to support target shots with the 100-TW system next quarter.

Work continues in support of the Petawatt system. The support frames for the compressor vacuum chamber and turning mirrors have been installed in the 10-beam target bay. The fabrication of the three major sections of the compressor tank is well under way. We are planning to install the compressor chamber in mid-November.

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ICF Program
Lawrence Livermore National Laboratory
P.O. Box 808, L-475
Livermore, California 94551