Executive Summary

The fiscal year ending in September 2006 concluded the fourth year of the five-year renewal of Cooperative Agreement DE-FC52-92F19460 with the U.S. Department of Energy. This report summarizes progress in laser-fusion research at the Laboratory for Laser Energetics (LLE) during the past fiscal year; LLE progress on laser, optical materials, and advanced technology development; work on the OMEGA Extended Performance (EP) laser project, operation of OMEGA for the National Laser Users' Facility (NLUF) and other external users; and programs focusing on the education of high school, undergraduate, and graduate students during the year.

Progress in Laser Fusion Research

The laser-fusion research program at the University of Rochester's Laboratory for Laser Energetics (LLE) is focused on Campaign-10 inertial confinement fusion (ICF) ignition and experimental support technology, operation of facilities (OMEGA), and the construction of OMEGA EP—a high-energy petawatt laser system. LLE is the lead laboratory for research into the direct-drive approach to ICF ignition and is taking a lead role in some indirect-drive tasks within the National Ignition Campaign.

Progress in the laser-fusion research program during this past year was made in three principal areas: OMEGA direct-drive and indirect-drive experiments and targets; development of diagnostics for experiments on OMEGA, OMEGA EP, and the National Ignition Facility (NIF); and theoretical analysis and design efforts aimed at improved direct-drive-ignition capsule design.

1. OMEGA Direct-Drive Targets and Experiments

Virtually all ignition target designs for the NIF are based on a spherical low-*Z* ablator containing a solid, cryogenic-fuel layer of deuterium and tritium. Techniques refined at LLE have produced targets with an inner D_2- or DT-ice surface that meets the surface-smoothness requirements for ignition (≤ 1-μm rms in all modes meeting an FY07 Level-2 milestone). The first of a series of direct-drive, ignition-scaled cryogenic capsule implosions containing tritium occured in 2006. A DOE milestone was achieved in March by imploding two β-layered capsules containing tritium. The first high-yield, direct-drive, ignition-scaled β-layered 50:50 DT cryogenic implosion was carried out in June 2006—the first time such a target has been imploded in an ICF facility. We report (p. 167) on the historical development and the significant progress made recently in cryogenic D_2 and DT capsule fabrication and characterization technology and present results from the most recent cryogenic-capsule implosions. Simulations of these experiments suggest that values for peak areal density (ρR_{peak}) as high as 190 ± 20 mg/cm^2 may have been achieved.

The results of OMEGA direct-drive implosions of capsules filled with different mixtures of D_2 and ^{3}He gas are reported (p. 90). At temperatures above a few electron volts, D_2 and ^{3}He gases are fully ionized, and hydrodynamically equivalent fuels with different ratios of D_2 and ^{3}He can be chosen to have the same mass density, total particle density, and equation of state. Implosions with a 50:50 mixture of D^3He by atom consistently result in measured nuclear yields half of that anticipated by scaling from measured yields of implosions with pure D_2 and nearly pure ^{3}He. This observation is seen over a wide range of experimental configurations, including targets with a variety of shell thicknesses and fill pressures, simultaneously for two different nuclear yields (D-D and D^3He), as well as for shock and compression yields. A number of possible mechanisms that may cause this scaling are considered, but no dominant mechanism has yet been identified.

In a collaborative effort with the Massachussetts Institute of Technology (MIT) Plasma Science and Fusion Center (PSFC), measurements of the dependence of the nuclear burn region size on implosion parameters in OMEGA experiments were carried out (p. 1). Radial profiles of nuclear burn in directly driven implosions were systematically studied for the first time using a proton emission imaging system on OMEGA. The system is sensitive to energetic 14.7-MeV protons from the D^3He fusion reaction. Clear relationships were identified between variations in the size of the burn region and variations in such experimental parameters as capsule size, shell composition and thickness, gas-fill pressure, and laser energy.

Measurements of the Rayleigh–Taylor hydrodynamic instability growth rate in the nonlinear regime are presented on p. 17. The measured modulation Fourier spectra and nonlinear growth velocities are in excellent agreement with Haan's model. In real-space analysis, the bubble merger was quantified by a self-similar evolution of bubble-size distributions, in agreement with the Alon–Oron–Shvarts theoretical predictions.

Detailed studies of the displacement of cryogenic targets from their optimum position [at target chamber center (TCC)] are presented (p. 179). While beam smoothing and power balancing can ensure highly uniform illumination of capsules, target displacement greater than 5 μm or more from TCC can lead to significant drive nonuniformity and reduce the capsule performance. Correlation between target vibration at TCC and the response characteristics obtained in this study indicate that the modes of spider silk are the primary cause of the displacement.

Results of studies of isotopic fractionation during solidification of H_2-HD-D_2 mixtures are reported on p. 26. Isotopic fractionation could reduce the efficiency of the fusion reaction in future crogenic D-T targets. It is found that frozen H–D mixtures have spatial concentration gradients of the order of 0.02 to 0.05 molecular fraction per millimeter, well below the level that would compromise cryogenic target performance (p. 35).

The development of methods and techniques for the decontamination of metals and alloys from tritium is presented (p. 70). The efficacy of tritium removal from stainless steel using two different approaches was studied: thermal desorption in an inert gas purge containing hydrogen peroxide, and radio-frequency–driven argon plasma irradiation. This study indicates that reducing the activity in metals below 0.5 μCi/g is feasible without generating secondary active waste by-products other than water.

2. Target Diagnostics for OMEGA, OMEGA EP, and the NIF

The time interval from the beginning of the laser pulse to the peak of neutron emission (bang time) is an important parameter in inertial confinement fusion experiments. The NTD streak camera previously deployed on OMEGA was saturated by neutron yields in excess of 3×10^{13}, whereas the latest OMEGA experiments and the planned fast-ignition experiments using OMEGA EP are expected to produce neutron yields above 10^{14}. The new detector described on p. 147 will support these experiments plus high-yield experiments on the NIF.

A collaboration including MIT-PSFC, LLE, and LLNL led to a novel imaging technology for measuring *E* and *B* fields in laser-produced plasmas using monoenergetic proton radiography (p. 189). The generation of electromagnetic fields by the interaction of laser light with matter is a process of fundamental interest in high-energy-density physics. This article presents high-resolution, time-gated radiographic images of a plastic foil driven by a 10^{14}-W/cm^2 laser that imply *B* fields of ~0.5 MG and *E* fields ~1.5×10^8 V/m. Furthermore, these measurements demonstrate the beneficial focal-smoothing effects produced by distributed phase plates for substantially reducing medium-scale chaotic field structures.

Sensitive electronic detectors are difficult to operate in petawatt laser–target interaction experiments. The laser–plasma interaction at relativistic intensitites (>10^{18} W/cm^2) creates large amounts of relativistic electrons ($E > 1$ MeV), hard x rays, and charged particles. The article starting on p. 153 presents strategies to minimize the impact of electromagnetic pulses on diagnostics inside the OMEGA EP target chamber.

X-ray film is still commonly used for recording the absolute x-ray fluence in high-temperature plasma experiments. Absolute calibration of Kodak Biomax-MS film response to x rays in the 1.5- to 8-keV range has been carried out at LLE and is presented starting on p. 138. This calibration was performed using an e-beam–generated x-ray source, a crystal/multilayer monochrometer, a film pack, and an absolutely calibrated x-ray photon detector. The results agree with predictions from a theoretical model presented in a companion article beginning on p. 142. The response model starts with simple mathematical models and extends them to T-grain–type film such as Biomax-MS.

3. Theoretical Analysis and Design

A review of the basic concepts of laser-driven ICF ignition is presented (p. 83) with emphasis on the direct-drive-ignition target designs, requirements for the temporal shape of the laser pulse, and considerations of stability issues.

Polar-direct-drive (PDD) simulations and experiments on the OMEGA Laser System are discussed beginning on p. 41. Forty OMEGA beams were arranged in six rings to emulate the NIF x-ray-drive configuration and used to perform direct-drive implosions of CH shells filled with D_2 gas. Simulations performed with the *DRACO* code are in good agreement with the experimental x-ray radiographs. Simulations of NIF-scale capsules achieve ignition with a gain of ~20 and show the development of a 40-μm-radius, 10-keV region with a neutron-averaged ρR ~ 1.27 g/cm^2 near stagnation.

Implication of hydrogen fractionation in ICF ignition designs is discussed beginning on p. 35. A numerical investigation of the effects of fractionation on hot-spot formation, ignition, and burn in ICF target designs indicates that small levels of fractionation (~10%) are acceptable for ignition performance on the NIF.

Lasers, Optical Materials, and Advanced Technology

The design and analysis of binary beam shapers for high-power laser systems are described (p. 202). In a manner similar to NIF, OMEGA EP uses square beams with high-order super-Gaussian spatial profiles to maximize the fill factor of the power amplifiers without exceeding the damage fluence of the laser components. The spatially dependent gain of the amplifiers can be, to a large extent, precompensated by attenuating regions of the input beam inversely with the gain they receive in the amplifiers. An error diffusion algorithm is applied to the design of binary beam shapers consisting of a uniform array of 10-mm-sq pixels that can be produced using standard lithographic techniques on high damage threshold, metal-on-glass substrates. Simulations show that this technique can produce beam shapers with the correct profile to precompensate the spatially dependent gain of the OMEGA EP's amplifiers with low rms error.

The characteristics and performance of the high-contrast plasma-electrode Pockels cell (PEPC) are discussed beginning on p. 129. This device was developed as a prototype for OMEGA EP and demonstrated high-switching contrasts exceeding 500:1 throughout the clear aperture. The key to producing this level of performance was the reduction of stress birefringence by using circular windows. In addition to the usual function of holding the pulse in the amplifier cavity for four passes, the OMEGA EP PEPC will be used to provide isolation from target retroreflections. Most existing multipass high-energy laser systems use frequency conversion to direct second- or third-harmonic light onto the target. This is not the case for the short-pulse part of OMEGA EP; therefore, any light reflected by the target can experience gain in the unsaturated amplifiers as it propagates back up the system, posing a significant damage threat to the system.

A description of the characteristics and performance of a high-gain, polarization-preserving, Yb-doped fiber amplifier for low-duty-cycle pulse amplification begins on p. 63. A high-gain, low-noise, double-pass, ytterbium-doped amplifier for which amplified spontaneous emission (ASE)–suppression techniques were used to fabricate a double-pass amplifier with the noise properties of a single-pass amplifier has been demonstrated. A double-pass configuration allows for significantly higher gains to be obtained in a fiber amplifier than can be achieved in a single-pass configuration. Simulations based on a rate-equation model were used to analyze the ASE and the impact of the suppression techniques. These techniques were implemented in an alignment-free, double-pass fiber amplifier with 26-dB gain at a wavelength 23 nm off the gain peak and a –48-dB noise floor, while amplifying linearly polarized optical pulses with a low duty cycle.

In single-photon sources (SPS's) based on single-emitter fluorescence, a laser beam is focused into an area containing a low concentration of single emitters so that only one emitter becomes excited. A report on p. 102 shows the advantages of using liquid crystals as the hosts for SPS's. Deterministically polarized fluorescence from single emitters (dye molecules) was demonstrated for the first time at room temperature. In this experiment, a planar-aligned, nematic liquid crystal host provides uniaxial alignment of single-dye molecules in a preferred direction. As a result, fluorescence of these single emitters is deterministically polarized, which allows one to consider such systems for applications in photonic quantum information.

The performance of the fiber-coupled single-photon detectors based on NbN superconducting nanostructures for practical quantum cryptography and photon-correlation studies is described beginning on p. 108. Several two-channel, single-photon detector systems based on two fiber-coupled, superconducting, single-photon detectors were built and characterized. The best device reached the system quantum efficiency of 0.3% in the 1540-nm telecommunication wavelength with a fiber-to-detector coupling factor of about 30%.

Results from the design and synthesis of transition-metal dithiolene near-IR dyes are presented on p. 112. Transition-metal complexes based on nickel, palladium, or platinum dithiolene cores show substantial promise for guest–host liquid crystal (LC) devices operating in the near- to mid-IR region. Some specific application examples for these materials in LC electro-optical devices are presented and the most recent results in the computational modeling of physical and optical properties of this interesting class of organometallic optical materials are discussed.

Surface features of tungsten carbide composites processed by bound-abrasive microgrinding and magnetorheological finishing (MRF) were analyzed (p. 51). It was found that the peak-to-valley microroughness of the surface gives a measure of the deformed-layer depth. MRF spots revealed the true depth of the grinding-induced deformed surface layer.

Results of simulation for gain apodization in highly doped distributed-feedback (DFB) fiber lasers are presented on p. 160. DFB lasers can be designed with an internal grating structure to provide high output power (up to 60 mW), single frequency, single polarization, and high optical signal-to-noise ratio. The effects of gain apodization on threshold behavior along with the impact on output power and mode discrimination are investigated. Apodization of the longitudinal gain profile is found to lower the laser threshold by 21% without degrading mode discrimination.

Status and Progress of OMEGA EP

The OMEGA EP (extended performance) project was in its fourth year in FY06. In FY06 congressional funding allowed the project to move forward with the full four-beam project. In February 2006 a baseline change was adopted that includes two additional long-pulse beams that were in the original project conceptual design and UV conversion for all four beams. With these additions, the OMEGA EP total estimated cost increased from $67 million to $89 million. A total of $87 million was appropriated through FY06. The project will be complete in April 2008.

The first quarter of FY06 was highlighted by the installation of the major structural assemblies. The largest of the structure installations was the grating compressor chamber. This 350,000-lb vacuum vessel was assembled and tested at vacuum, completing one of the largest single acquisition items for the project. Adjacent to this structure, the target-area structure took form and in November the target chamber was delivered and installed. By the end of December 2005, the entire Laser Bay structure installation was complete, marking the end of heavy construction.

In the second quarter of FY06 the OMEGA EP bay was re-certified at class-1000 cleanliness and optical assembly deployment began. Beam equipment such as spatial-filter tubes and alignment tables were installed, and laser light began to traverse the optical path of the beamline. After one diffraction-grating vendor failed to perform, a second vendor demonstrated the ability to manufacture all gratings and deliver them by the end of 2006. During this quarter, acquisition of the grating compressor's internal structure became the controlling critical path item on the short-pulse-laser project path. Contamination issues drove a design revision that delayed the start of manufacturing and made the fabrication task substantially more complex.

During the third and fourth quarters of FY06, the Beam-1 laser source, amplifier, and power conditioning subsystems completed major assembly phases. The first beam assembly was completed to the output of the transport spatial filter, and four-pass alignment was accomplished. The completion of integration and alignment of the first beam included firing all of the amplifiers at full operational charge voltages. The successful activation of the amplifiers completed preparations for propagating beam tests to be carried out in FY07. Continued incremental delay in the manufacture of the grating compressor chamber's internal structures stimulated a change in schedule that advanced the UV activation of all four beams ahead of short-pulse activation.

Overall, the project achieved all objectives for FY06 and continued to make excellent progress toward project completion. With the baseline change to the full four-beam OMEGA EP system, the project scope, budget, and schedule are fixed. The initial highest-risk element of the project was overcome: diffraction gratings of large aperture, high efficiency, and high damage threshold. Other technically challenging elements such as adaptive optics, plasma-electrode Pockels cells, and optical parametric chirped-pulse amplification were completed through production and subsystem tests. At the end of the fiscal year the completion of these systems allowed the integrated operational testing phase to begin.

National Laser Users' Facility (NLUF) and External Users' Programs

Nearly half of the OMEGA shots in FY06 were dedicated to external users including the NLUF programs, LLNL, LANL, SNL, and CEA.

FY06 NLUF Experiments

Fiscal year 2006 was the second of a two-year period of performance for the NLUF projects approved for FY05–FY06 funding and OMEGA shots. A total of 122 OMEGA shots were dedicated to seven NLUF projects. Beginning on p. 215, their progress is detailed in the following reports:

- *Isentropic Compression Experiments (ICE) for Measuring EOS on OMEGA*
  (J. R. Asay, Washington State University)

- *Laser–Plasma Interactions in High-Energy-Density Plasmas*
  (H. Baldis, University of California, Davis)

- *Experimental Astrophysics on the OMEGA Laser*
  (R. P. Drake, University of Michigan)

- *Astrophysical Jets and HED Laboratory Astrophysics*
  (P. Hartigan, Rice University)

- *Recreating Planetary Core Conditions on OMEGA*
  (R. Jeanloz, University of California, Berkeley)

- *Three-Dimensional Study of the Spatial Structure of Direct-Drive Implosion Cores on OMEGA*
  (R. Mancini, University of Nevada, Reno)

- *Implosion Dynamics and Symmetry from Proton Imaging, Spectrometry, and Temporal Measurements*
  (R. D. Petrasso and C. K. Li, MIT)

FY07–FY08 NLUF Experiments

During this past year, DOE issued a solicitation for NLUF grants for the period FY07–FY08. Twelve proposals were submitted in response to this solicitation and an independent DOE Technical Evaluation Panel was convened to review the proposals. The following six proposals were approved for DOE funding and OMEGA shots:

- *Experimental Astrophysics on the OMEGA Laser*
  (R. P. Drake, University of Michigan)

- *X-Ray Compton Scattering on Compressed Matter*
  (R. Falcone, University of California, Berkeley)

- *Laboratory Experiments on Supersonic Astrophysical Flows Interacting with Clumpy Environments*
  (P. Hartigan, Rice University)

- *Recreating Planetary Core Conditions on OMEGA: Techniques to Produce Dense States of Matter*
  (R. Jeanloz, University of California, Berkeley)

- *Multiview Tomographic Study of OMEGA Direct-Drive Implosions*
  (R. Mancini, University of Nevada, Reno)

- *Monoergetic Proton Radiography of Laser/Plasma-Generated Fields and ICF Implosions*
  (R. D. Petrasso and C. K. Li, Massachusetts Institute of Technology)

FY06 LLNL–OMEGA Experimental Programs

In FY06, LLNL led 354 shots on the OMEGA Laser System for the National Ignition Campaign (NIC), for high-energy-density sciences (HEDS) experiments, and for the NWET program. The LLNL-led experiments included the following:

- *Foam-ball hohlraum symmetry studies*

- *Collective x-ray scattering from plasmons in warm dense matter*

- *Laser–plasma interaction studies*

- *"Cocktail" hohlraum albedo studies*

- *X-ray conversion measurements on spherical targets* (with CEA)

- *Rayleigh–Taylor experimental platform development*

- *Hohlraum window x-ray preheat studies*

- *NIF fill-tube simulations*

- *NIF x-ray backlighter development*

- *Hot hohlraum radiation sources*

- *Double-shell experiments*

- *Study of the radiative effects of high-Z dopants on implosions*

- *Opacity platform development*

- *Dynamic hohlraum experiments (double shell driven by radiative shock wave)*

- *Isentropic compression equation-of-state experiments*

- *Shock–sphere interaction experiment*

- *Jet generation and propagation into low-density background material*

FY06 LANL–OMEGA Experimental Programs

LANL teams led 125 OMEGA shots in FY06 for the following NIC and HEDS experiments:

- *Off-Hugoniot heated hydrodynamics*

- *Inhomogeneous radiation flow*

- *Beryllium fill-tube defect studies*

- *High-Z shell implosions*

- *High-Z dopant impact in stimulated Raman scattering (SRS)*

- *Gas Cherenkov detector development*

FY06 SNL OMEGA Experimental Programs

SNL carried out 30 shots on OMEGA in FY06 including the following experiments:

- *Beryllium ablation-rate measurements in planar geometry*

- *Beryllium x-ray burnthrough and ablation-rate measurements in convergent geometry*

- *VISAR determination of hohlraum radiation temperature*

- *Development of a NIF shock-timing diagnostic*

FY06 CEA OMEGA Experimental Programs

In FY06, CEA carried out 49 target shots on OMEGA including the following experiments:

- *Rayleigh–Taylor instabilities in indirect-drive, mode-coupling experiments*

- *Implementation of a high-resolution x-ray imaging diagnostic (HXRI)*

FY06 Laser Facility Report

During FY06 the OMEGA Laser Facility conducted 1394 target shots for a variety of users as illustrated in Fig. 1. During this period, the system availability and experimental effectiveness averaged 93.3% and 95.3%, respectively. Major highlights of the facility operations in FY06 were as follows:

- *First implosions of beta-layered ignition-scaled DT capsules*

- *A full set (42) of new indirect-drive distributed phase plates designed and fabricated*

- *Low-adiabat, high-contrast pulse shapes developed and implemented for the OMEGA ignition-scaled cryogenic DT implosion experiments*

- *Upgrade of the active-shock-breakout (ASBO) diagnostic completed*

- *OMEGA EP short-pulse beam-transport tube installed*

The detailed facility report may be found on p. 213.

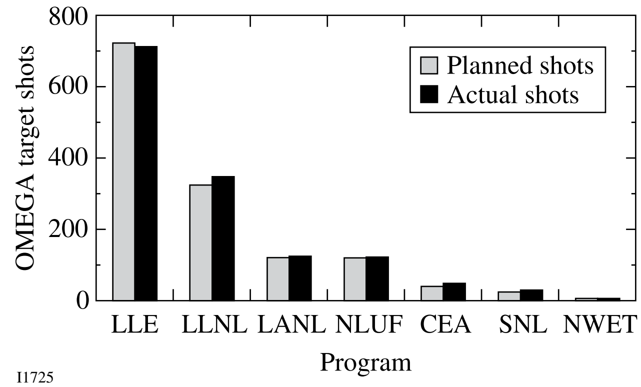

Figure 1
FY06 OMEGA usage.

Education at LLE

As the only major university participant in the National ICF Program, education continues to be an important mission for the Laboratory. A report on this year's summer high school research program is described in detail on p. 211. Thirteen students participated in this year's program. The William D. Ryan Inspirational Teacher Award was given to Mr. Thomas Lewis, a former Earth Science teacher (currently retired) at Greece Arcadia High School.

Graduate students are using the OMEGA laser for fusion research and other facilities for HED research and technology development. They are making significant contributions to LLE's research activities. Thirty faculty from five departments collaborate with LLE's scientists and engineers. Presently, 93 graduate students are involved in research projects at LLE, and LLE directly sponsors 48 students pursuing Ph.D. degrees. Their research includes theoretical and experimental plasma physics, high-energy-density physics, x-ray and atomic physics, nuclear fusion, ultrafast optoelectronics, high-power-laser development and applications, nonlinear optics, optical materials and optical fabrications technology, and target fabrication.

A total of 183 University of Rochester students have earned Ph.D. degrees at LLE since its founding. An additional 90 graduate students and 25 postdoctoral fellows from other universities have been funded by NLUF grants. The most-recent University of Rochester Ph.D. graduates and their thesis titles include the following:

Anderson, K. *"Adiabat Shaping in Direct-Drive Inertial Confinement Fusion Implosions"*

Culligan, S.	*"Organic Blue Light–Emitting Diodes and Field-Effect Transistors Based on Monodisperse Conjugated Oligomers"*
Gotchev, O.	*"Experiments on Dynamic Overpressure Stabilization of the Ablative Richtmyer–Meshkov Instability in ICF Targets"*
Guazzotto, L.	*"Equilibrium and Stability of Tokamak Plasmas with Arbitrary Flow"*
Park, J.-R.	*"Time-Resolved Imaging Using Non-Collinear Parametric Down-Conversion"*
Pearlman, A.	*"Ultrafast NbN Single-Photon Optical Detectors for Quantum Communications"*
Teng, X.	*"Synthesis of Metal, Metal Oxide, and Alloy Nanostructures for Magnetic and Catalytic Implications"*
Trajkovska, A.	*"Chiroptical Properties and Photoalignment of Monodisperse Glassy Liquid Crystalling Oligofluorences"*
Zheng, L.	*"UV-Laser–Induced Densification of Fused Silica: A Molecular Dynamics Study"*

Approximately 42 University of Rochester undergraduate students participated in work or research projects at LLE this past year. Student projects include operational maintenance of the OMEGA Laser System; work in laser development, materials, and optical-thin-film–coating laboratories; and programming, image processing, and diagnostic development. This is a unique opportunity for students, many of whom will go on to pursue a higher degree in the area in which they gained experience at the Laboratory.

In addition, LLE directly funds research programs within the MIT Plasma Science and Fusion Center, the State University of New York (SUNY) at Geneseo, the University of Nevada, Reno, and the University of Wisconsin. These programs involve a total of approximately 16 graduate students, 27 undergraduate students, and 7 faculty members.

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