Executive Summary

The fiscal year ending September 2001 (FY01) was the fourth year of the cooperative agreement (DE-FC03-92SF19460) five-year renewal with the U.S. Department of Energy (DOE). This report summarizes progress and research at the Laboratory for Laser Energetics (LLE), operation of the National Laser Users' Facility (NLUF), and programs involving education of high school, undergraduate, and graduate students during the year.

Inertial Confinement Fusion Research

LLE is the principal laboratory investigating the direct-drive approach to inertial fusion for an ignition and gain demonstration on the National Ignition Facility (NIF) currently under construction at the Lawrence Livermore National Laboratory (LLNL). This requires precision laser diagnostics and controls, a cryogenic target handling system, sophisticated experimental diagnostics, robust theoretical and computational modeling, and the development of new laser and optical technologies.

The minimum drive energy needed to achieve ignition in inertial confinement fusion implosions is an important consideration to determine how much margin there will be on the NIF. Beginning on p. 153, we present a new model that consistently incorporates two competitive scaling approaches. The model includes a discussion of hot-spot dynamics, two approaches to model shell dynamics, derivations of ignition scaling, and verification of the initial assumptions of the model. Agreement with other published results from scaling laws derived from numerical simulations is also presented. In related work (p. 1), a model for the deceleration phase of an imploding inertial fusion capsule shows that the ablative flow off the inner shell surface plays a critical role in reducing the growth rate and suppressing short-wavelength modes in the deceleration-phase Raleigh–Taylor instability. This increased stability means that with proper care in drive symmetry and the use of techniques to reduce laser imprinting, the results of the model calculations (one-dimensional) may be achievable in the laboratory.

Experimental results this year include measurements to assess the effects of shock heating on the stability of direct-drive inertial fusion capsules. Pulses that rise rapidly to 10^{14} W/cm^2 produce shock-induced temperatures near 25 eV, whereas more slowly rising pulses show less heating (p. 11). We see a correlation between greater hydrodynamic stability for square-pulse drive (which has more shock heating) compared to the ramp-pulse drive that exhibits less shock heating and reduced stability.

Additional understanding of moderate-convergence-ratio (~10 to 20) direct-drive implosions was achieved using a consistent measurement-based static model of the stagnated core and fuel–pusher mix. The model (p. 68) assumes that the imploded core is comprised of a clean fuel region and a mix region where the shell material is mixed into the fuel. Excellent agreement with a suite of neutron and particle diagnostics is obtained through the use of this model. Results indicate that approximately 1 μm of shell material is mixed into the fuel during the thermonuclear burn in the experiments. It suggests that the fuel areal density is distributed equally between the clean core and fuel–shell mix region. In related experimental work for the same moderate radial convergence for DT-gas-filled polymer capsules, nuclear diagnostics (p. 54) employed a comprehensive array of knock-on deuteron, triton, and proton spectra in addition to traditional neutron measurements to compare the performance of capsules irradiated with full beam smoothing on OMEGA [1-THz, 2-D smoothing by spectral dispersion (SSD) and polarization smoothing (PS)] versus implosions of similar targets carried out with reduced beam smoothing (0.35-THz, 2-D SSD without PS). With full beam smoothing, the implosions show neutron yields, fuel areal densities, and shell areal densities approximately 80%, 60%, and 35% higher, respectively, than those with the reduced level of beam smoothing. Modeling and shot data showing the evolution of shell modulations near the point of peak compression in spherical direct-drive implosions for two different levels of beam smoothing show that modulations in the shell areal density decrease during compression and increase during decompression.

Our collaborative research [led by scientists from the Commissariat à L'Énergie Atomique (CEA) of France and scientists from Los Alamos National Laboratory (LANL)] on high-resolution neutron imaging of capsules using penumbral images with a biconical aperture demonstrated the highest spatial resolution yet achieved on ICF implosions (45 to 60 μm) using the CEA-designed diagnostic on direct-drive implosions carried out on the OMEGA facility (p. 74). Modifications that are expected to improve the resolution to 13 μm for OMEGA implosions have recently been carried out on this diagnostic.

Characterization of direct-drive implosion core conditions using time-resolved Ar *K*-shell spectroscopy in collaborative work with research scientists from the University of Wisconsin and the University of Florida using polymer shells filled with Ar-doped deuterium gas driven with up to 24-kJ, 1-ns square laser pulses smoothed with 1-THz, 2-D SSD and PS allowed us to infer the emissivity-averaged core electron temperature and density from the time-dependent Ar *K*-shell spectral line shapes (p. 47). We infer electron densities in excess of 2.5×10^{24} cm^{-3} and electron temperatures ~2.5 keV. This represents the highest combination of electron temperature and density measured for these types of implosions in laser-driven inertial fusion experiments.

A test of the feasibility of using extended x-ray absorption fine structure (EXAFS) to characterize the properties of solid materials shocked at moderately high pressures (up to a few Mbar) shows very-high-contrast EXAFS modulations when a thick, undriven Ti foil is backlighted by the x-ray radiation from an imploded CH shell (p. 92). This research is part of LLE's participation in the Department of Energy's Stewardship Science Program (SSP).

We report on the first multibeam laser–plasma interaction experiments with a critical density surface present at all times (p. 128). The plasma conditions are tailored to resemble future direct-drive laser fusion implosions on the NIF. The results show strong evidence of electromagnetic (EM) wave seeding of stimulated Brillouin scattering (SBS) backscatter as well as evidence of strongly driven, common, symmetrically located ion waves. The expected SBS scattering levels for NIF direct-drive ignition experiments are well below 1%. This gives increased confidence that good direct-drive target performance will be achieved on the NIF.

FY01 has seen significant progress in the development of new diagnostic capabilities for laser fusion. A selectable-streak-rate streak-camera deflection ramp generator produces streak-camera deflection voltage ramps with a 50-Ω composite MOSFET/avalanche transistor step generator and a relay-selectable low-pass filter network (p. 21). The design allows the remote selection of four different sweep rates and provides a 50-Ω interface to the streak camera's deflection plates. In other diagnostic development work, we highlight a low-cost, wide-dynamic-range, neutron bang time (NBT) detector (p. 171). The instrument complements the capabilities of the streak-camera-based neutron temporal diagnostic, which is also installed on OMEGA. It measures the neutron bang time of D_2- and DT-filled ICF implosion capsules at neutron yields between 10^7 and 10^{11} with an absolute timing accuracy of better than 100 ps. This level of accuracy allows the modeling of the implosions to be effectively guided using hydrocode calculations.

The self-calibrating, multichannel streak camera used on OMEGA is described beginning on p. 109. The article describes the system and focuses on the hardware and software calibration techniques that maximize the camera's utility. The system can diagnose each of the beams on every target shot and can measure beam energies with 8% accuracy and timing at 7 ps rms. Beam-to-beam power variations of less than 5% can be detected.

Laser and Optical Materials Research

We report on a new model for material behavior under compression (p. 15). The model was motivated by the fact that fused silica densifies permanently under sufficiently large compressive stresses. It is observed that the appearance of shear will facilitate densification. The model is based on a new constitutive law used to study spherical cavity expansion in material with densification.

We have developed a UV fiber-optic beam delivery system (p. 29) for OMEGA. The new fiber-optic system uses 15-m-long fibers with attenuation less than 220 dB/km at a wavelength of 351 nm to deliver optical pulses to the multibeam, streak-camera-based pulse characterization system. The modal dispersion of the fibers is low enough to allow an overall bandwidth of the streak camera's diagnostic system to be less than or equal to 30 GHz.

Preliminary design work for the NIF's 2-D SSD beam-smoothing system is presented beginning on p. 39. Broad-bandwidth-beam-smoothing techniques are critical to high-performance, direct-drive implosions on the NIF. As a partner in the ICF program, LLE has the lead role in defining direct-drive requirements for the NIF and preparing a preliminary 2-D SSD system design. A prototype NIF 2-D SSD preamplifier module (PAM) will be built and tested at LLE. The article describes the base-line system design for the NIF's direct-drive beam-smoothing system, which will be capable of 1-THz bandwidth in the ultraviolet, 50×100-μrad divergence, and 2×1 color cycles.

Ultrafast picket-fence pulses have been proposed by LLNL as a means to maximize the frequency-conversion efficiency and minimize beam-power imbalance on the NIF. We report on the results (p. 79) of the beam-smoothing performance of ultrafast picket-fence pulses for direct-dirve targets on the NIF. The beam smoothing achieved with ultrafast picket-fence pulses is equivalent to the smoothing attained with the NIF base-line 2-D SSD design if the applied bandwidth and divergence used for the picket-fence-configuration SSD is close to that of the base-line-design SSD system. Furthermore, the diffraction-limited far-field pattern produced by chirped picket-fence pulses can reduce the pinhole loading, potentially leading to a larger permissible beam divergence for the NIF with 2-D SSD.

Potassium dihydrogen phosphate (KDP) is an important electro-optic tetragonal crystal used widely in high-power laser systems. We report (p. 101) on studies of the microhardness and indentation fracture of KDP, together with an approximate model for analyzing crack-load microindentation data in tetragonal crystals. The model uses the minimum elastic modulus of the material.

Current substrate cleaning and handling methods used in the application of high-reflectance optical coatings are so effective that is necessary to test large parts in order to achieve statistically meaningful assessments. This has led LLE's Optical Manufacturing Group to use equipment designed by LLNL to condition coatings on large NIF optics to test new coating designs. The equipment facilitates testing of full-sized NIF substrates by automatically scanning the optic relative to an optical system that simultaneously subjects a small area to representative laser pulses and detects any resulting damage. Repeated scans at increasing fluence were used to quantify the performance of three candidate coating designs (p. 177).

Devices that could lead to revolutionary progress in areas ranging from multicast free-space satellite communications through quantum computing and quantum cryptography to semiconductor integrated circuit testing led us to fabricate and investigate the properties of a simple-to-manufacture and simple-to-operate NbN hot-electron photodetector with a picosecond response time, high intrinsic quantum efficiency, negligible dark counts, and the capability to detect single photons from the ultraviolet to the infrared wavelength range (p. 34).

We survey the main aspects of nonequilibrium hot-electron phenomena in superconducting films beginning on p. 134. Various theoretical models developed to describe the hot-electron effect are presented. The article describes a number of radiation-sensing devices that have been fabricated and tested and demonstrate significantly improved performance over conventional implementations.

Laser Facility Report

OMEGA operations during FY01 (p. 208) yielded a total of 1283 target shots (up from 1153 last year), including 311 shots for LLNL, 124 for LANL, 10 for Sandia National Laboratory (SNL), 11 for the French Commissariat à L'Énergie Atomique (CEA), and 125 for the National Laser Users' Facility (NLUF). The report summarizes highlights and other achievements during the year. All investigators have benefited from the improvements that have increased the reliability and repeatability of the OMEGA system.

National Laser Users' Facility and External Users of OMEGA

During FY01, external use of OMEGA increased by over 5% over the prior fiscal year, accounting for nearly 47% of the total target shots. Eight NLUF experiments were carried out in FY01 and are summarized beginning on p. 210. Target experiments conducted during the year for the national laboratories, nuclear weapons effects testing (NWET), and the CEA programs are summarized beginning on p. 217. LLNL carried out experiments on laser–plasma interactions; investigations of the potential of "cocktail" hohlraums to increase the energy coupling to NIF targets; high-convergence HEP-5 implosions; NIF-relevant hohlraum symmetry; planar Rayleigh–Taylor experiments; development of ignition diagnostics; tests of a new laser-driven, high-pressure source (IDrive); high-*Z* and low-*Z* equation-of-state measurements; direct-drive Richtmyer–Meshkov instability; supersonic jets; nonideal backlit implosions; slit closure measurements; and gas-filled x-ray sources for NWET applications. Along with LLNL scientists, SNL performed shock-timing and ablator burnthrough measurements.

The LANL campaigns examined double-shell capsule designs, the development of x-ray backlighting sources, several classified experiments, direct-drive cylindrical implosions, and the development of NIF diagnostics. CEA carried out work on neutron imaging and gamma-ray measurements.

Education at LLE

As the only major university participant in the National ICF Program, education continues to be an important mission for the Laboratory. Graduate students are using the world's most powerful ultraviolet laser for fusion research on OMEGA, making significant contributions to LLE's research activities. Twenty-three faculty from five departments collaborate with LLE's scientists and engineers. Presently 60 graduate students are pursuing Ph.D. degrees at the Laboratory. The research includes theoretical and experimental plasma physics, high-energy-density plasma physics, x-rays and atomic physics, nuclear fusion, ultrafast optoelectronics, high-power-laser development and applications, nonlinear optics, optical materials and optical fabrications technology, and target fabrication. Technological developments from ongoing Ph.D. research will continue to play an important role on OMEGA.

One hundred fifty-one University of Rochester students have earned Ph.D. degrees at LLE since its founding. An additional 81 graduate students and 23 postdoctoral positions from other universities were funded by NLUF grants. The most recent University of Rochester Ph.D. graduates and their thesis titles are

Roman Adam	*Fabrication and Characterization of Ultrafast Superconducting Optoelectronic Devices*
Luis de Araujo	*Quantum Control of Atoms and Molecules*
Guy Delmarter	*Hydrodynamic Models of Outflows from Young and Evolved Stars*
Galina Grom	*Nanocrystalline Silicon/Silicon Oxide Superlattices: Fabrication, Characterization, and Applications in Nano-Flash Memories*
Viktor Lobatchev	*Hydrodynamics of Inertial Fusion Implosions: Feedout and Deceleration-Phase Instability*
Herman Lopez	*Porous Silicon Nanocomposites for Optoelectronic and Telecommunication Applications*
Eduard Startsev	*Ponderomotive Particle Acceleration in a Plasma*
Carlo Williams	*Ultrafast Photodetectors Based on the Hot-Electron Effect in Superconductors*
Hong Ye	*Hot Carrier Dynamics in GaN*
York Young	*Cold Collisions of Laser-Cooled Na and Rb Atoms*

Approximately 40 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; 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, and the University of Wisconsin. These programs involve additional graduate and undergraduate students in the LLE ICF Program. The joint work with SUNY Geneseo, for example, currently involves approximately 15 undergraduates.

For the past 11 years LLE has run a Summer High School Student Research Program (p. 206) in which this year 13 high school juniors spent eight weeks performing individual research projects. Each student is individually supervised by a staff scientist or an engineer. At the conclusion of the program, the students make final oral and written presentations on their work. The reports are published as an LLE report.

In 2001, LLE presented its fifth William D. Ryan Inspirational Teacher Award to Mr. David Dussault, a mathematics and computer science teacher at Livonia High School. Alumni of our Summer High School Student Research Program were asked to nominate teachers who had a major role in sparking their interest in science, mathematics, and/or technology. This award, which includes a $1000 cash prize, was presented at the Summer High School Student Research Symposium. Mr. Dussault was nominated by Mr. Michael Harvey, a 1999 participant in the program.

Robert L. McCrory
Director