Executive Summary

The fiscal year ending in September 2005 concluded the third year of the second five-year renewal of Cooperative Agreement DE-FC52-92SF19460 with the U.S. Department of Energy. This report summarizes research at the Laboratory for Laser Energetics (LLE) conducted during the past fiscal year, operation of the National Laser Users' Facility (NLUF), a status report of the new OMEGA Extended Performance (EP) laser project, and programs concerning the education of high school, undergraduate, and graduate students during the year.

Progress in Laser Fusion Research

Progress in laser fusion this past year falls into five broad categories: (1) direct-drive results from OMEGA; (2) progress in the development of the cryogenic target system and experiments with cryogenic targets; (3) results for polar direct drive (the application of nonspherically disposed laser beams for direct-drive spherically symmetrically driven systems), which is of great interest for the National Ignition Facility (NIF); (4) fast ignition, which uses short-pulse (<100-ps), high-intensity (~10^{15}-W) laser beams to ignite a compressed thermonuclear fusion capsule; and (5) high-energy-density physics results that use inertial fusion facilities to produce matter in extreme states that are central to understanding and modeling nuclear weapons phenomena important to the National Stockpile Stewardship Program. The following sections furnish a guide to this year's results in each of these five areas.

1. Direct-Drive Results

Inertial confinement fusion (ICF) capsules with shaped adiabats are expected to exhibit hydrodynamic stability without compromising the one-dimensional (1-D) performances exhibited by flat-adiabat shells. While theoretical formulas for the adiabat profiles generated by the relaxation method of adiabat shaping have been previously derived in LLE Review 98 (pp. 106–121), the formulas presented in the article beginning on p. 1 present simplified power-law expressions to facilitate the use of the general formulas.

We have experimentally demonstrated (p. 13) that target stability improves when picket pulses are used to increase and shape the ablator adiabat. Hydrodynamic simulations show that a picket pulse preceding the main target drive pulse in a direct-drive ICF implosion can reduce both the ablation-interface Rayleigh–Taylor (RT) instability seed and the growth rate by increasing the adiabat while maintaining a low adiabat in the inner fuel layer for optimal target compression and a minimal drive energy for ignition. Experiments show that the RT growth of nonuniformities is suppressed in both planar and spherical targets with picket-pulse laser illumination. Two types of picket pulses—a "decaying shock-wave picket" and a "relaxation" picket—are used to shape the adiabat in spherical targets. Planar growth measurements using a wide, intense picket to raise the adiabat of a CH foil showed that the growth of short-wavelength perturbations was reduced, and even stabilized, by adjusting the intensity of the picket. Planar imprint experiments showed the expected reduction of imprinting when a picket pulse is used. The data show that the imprint level is reduced when a picket is added and, for short wavelengths, is as effective as 1-D, 1.5-Å smoothing by spectral dispersion (SSD). A series of implosion experiments with a 130-ps-wide picket pulse showed a clear improvement in the performance of direct-drive implosions when the picket pulse was added to the drive pulse. Results from relaxation-picket implosions show larger yields from fusion reactions when the picket drive is used. These adiabat-shaping concepts make the likelihood of achieving ignition with direct-drive implosions on the NIF significantly more probable.

Beginning on p. 92, we provide a multidimensional analysis of direct-drive, plastic-shell implosions on OMEGA. Direct-drive, plastic-shell targets were imploded on the OMEGA Laser System with a 1-ns square pulse using the multidimensional hydrodynamic code *DRACO*. Yield degradation in "thin" shells is primarily caused by shell breakup during the acceleration phase due to short-wavelength ($\ell > 50$, where ℓ is the Legendre mode number) perturbation growth, whereas "thick" shell performance is influenced primarily by long and intermediate modes ($\ell \leq 50$). Simulation yields, the temporal history of neutron production, areal densities, and x-ray images of the core compare well with experimental observations. In particular, the thin-shell neutron production history falls off less steeply than 1-D predictions due to shell breakup induced under compression and delayed stagnation. Thicker, more-stable shells show burn truncation due to instability-induced mass flow into the colder bubbles. Estimates of small-scale mix indicate that turbulent mixing does not influence primary neutron yields.

The effects of temporal density variations and convergent geometry on nonlinear bubble evolution in classical RT instability are discussed beginning on p. 104. Effects of temporal density variation and spherical convergence on the nonlinear bubble evolution of single-mode, classical RT instability are studied using an analytical model based on Layzer's theory. When a temporal density variation is included, the bubble amplitude in the planar geometry asymptotes to a fixed value that depends on the Layzer bubble velocity, the fluid density, and a factor to account for the two- and three-dimensional geometries. The model can be applied to spherical geometries to predict the nonlinear bubble amplitude.

Nonlinear growth measurements of 3-D broadband nonuniformities near saturation using x-ray radiography in planar foils accelerated by laser light are described on p. 137. The initial target modulations were seeded by laser nonuniformities and later amplified during acceleration by RT instability.

2. Cryogenic System and Experimental Results

We report the first measurements of electron preheat in direct-drive laser implosions of cryogenic deuterium targets (p. 54). Preheat due to fast electrons generated by nonlinear laser–plasma interactions can reduce the gain in laser-imploded fusion targets. The preheat level is derived directly from the measured hard x-ray spectrum. The fraction of the incident laser energy that preheats the deuterium fuel is found to be less than 0.1%, suggesting that preheat will have a negligible impact on target performance. These results are encouraging for the success of high-gain, direct-drive-ignition experiments on the NIF.

Direct-drive, spherical, cryogenic, D_2-filled capsules were illuminated using the 60-beam OMEGA Laser System (p. 78). The targets are energy scaled from the baseline ignition design developed for the NIF. Thin-walled (~4-μm), ~860-μm-diam deuterated (CD) polymer shells are permeation filled with D_2 gas and cooled to the triple point (~18.7 K). Cryogenic ice layers with a uniformity of ~2-μm rms are formed and maintained. The targets were imploded with high-contrast pulse shapes using full single-beam smoothing (1-THz bandwidth, 2-D SSD) to study the effects of the acceleration- and deceleration-phase RT growth on target performance. Two-dimensional simulations show good agreement with experimental observations. Scattered-light and neutron burn-history measurements are consistent with predicted absorption and hydrodynamic coupling calculations. Time-resolved and static x-ray images show the progress of the imploding shell and the shape and temperature of the stagnating core. Particle-based instruments measure the fusion yield and rate, the ion temperature in the core, and the fuel areal density at the time of neutron production. These experiments have produced fuel areal densities up to ~100 mg/cm^2, primary neutron yields of ~4×10^{10}, and secondary neutron yields 1% to 2% of the primary yield. These results validate the hydrocode predictions for the direct-drive ignition-point design, giving increasing confidence in the direct-drive approach to ICF ignition.

We have developed a high-performance "planar" cryogenic target handling system that has been added to LLE's OMEGA Laser Fusion Facility (p. 128). The system has demonstrated a shot-to-shot cycle interval of less than two hours and has fielded more than 125 experiments using several distinct target types. This article provides an overview of the cryogenic capabilities at LLE and then compares the operational requirements of LLE's spherical and planar cryogenic systems.

Three-dimensional characterization of cryogenic target ice layers is important in understanding experiments important to an ignition demonstration. We report (p. 169) on backlit optical shadowgraphy, the primary diagnostic for D_2 ice-layer characterization of cryogenic targets for the OMEGA Laser System. Measurement of the position of the most prominent rings, caused by the reflection and refraction of light in the ice layer, in conjunction with ray-trace model predictions, allows the construction of a 3-D ice-layer representation, an estimation of the global surface roughness, and a determination of a Legendre-mode spectrum suitable for implosion modeling.

3. Polar-Direct-Drive Results

The article beginning on p. 61 examines a design concept that is proposed for direct-drive implosions on the NIF while the facility is in its initial indirect-drive configuration. The concept differs from earlier polar-direct-drive designs by adding a low-*Z* ring around the capsule equator (Saturn target). Refraction in the plasma formed around this ring permits time-dependent tuning of the capsule drive uniformity. An optimized simulation shows an implosion-velocity nonuniformity at the end of the laser pulse of ~1% rms for a cryogenic

DT shell, enhancing the prospects for an early direct-drive ignition demonstration on the NIF.

In the second article on polar direct drive (p. 67), we report the results for proof-of-principle, polar-direct-drive (PDD) experiments on OMEGA and prospects for ignition on the NIF. Experiments have been carried out using 40 repointed beams of the 60-beam OMEGA Laser System to approximate the NIF PDD configuration. Backlit x-ray framing camera images of D_2-filled spherical CH capsules show a characteristic nonuniformity pattern that is in close agreement with predictions. Saturn targets increase the drive on the equator, suggesting that highly symmetric PDD implosions may be possible with appropriate tuning. Two-dimensional simulations reproduced the approximately threefold reduction in yield found for the non-Saturn PDD capsules. Preliminary simulations for a NIF Saturn design predict a high gain close to the 1-D prediction. These results increase the prospects of obtaining direct-drive ignition with the initial NIF configuration.

Designs with the objective of achieving direct-drive ignition on the NIF at 1 MJ using the x-ray-drive beam configuration are described on p. 186. The PDD approach achieves the required irradiation uniformity by repointing some of the beams toward the target equator and by increasing the laser intensity at the equator to compensate for the reduced laser coupling from oblique irradiation.

4. Fast-Ignition Progress and Results

In "High-Density and High ρR Fuel Assembly for Fast-Ignition Inertial Confinement Fusion" (p. 117), LLE authors optimize implosion parameters for fast-ignition inertial confinement fusion and design fast-ignition targets relevant to direct-drive inertial fusion energy. It is shown that a 750-kJ laser can assemble fuel with $V_I = 1.7 \times 10^7$ cm/s, $\alpha = 0.7$, $\rho =$ 400 g/cc, $\rho R = 3$ g/cm^2, and a hot-spot volume of less than 10% of the compressed core. If fully ignited, this fuel assembly can produce energy gains of 150.

A second article (p. 122) describes recent OMEGA experiments that have studied the fuel assembly of gas-filled, cone-in-shell, fast-ignition targets. Using both fusion products and backlit images, an areal density of ~60 to 70 mg/cm^2 was inferred for the dense core assembly. The results are promising for successful integrated fast-ignition experiments on the OMEGA EP Facility, scheduled to be completed in 2007.

We present observations of a hot, T_e ~ 2- to 3-keV surface plasma in the interaction of a 0.7-ps petawatt laser beam with solid copper-foil targets at intensities >10^{20} W/cm^2 (p. 208). These temperatures were inferred from Cu, He$_\alpha$, and Ly$_\alpha$ emission lines, which have not previously been observed with ultrafast laser pulses.

We are also developing new techniques to characterize future fast-ignition experiments and for use on the OMEGA EP Facility. The interaction of directed energetic electrons with hydrogenic plasmas was modeled analytically from fundamental principles (p. 87). The effects of stopping, straggling, and beam blooming are rigorously treated in a unified approach for the first time. Enhanced energy deposition, which occurs in the latter portion of beam penetration, is inextricably linked to straggling and beam blooming. Both effects asymptotically scale with the square root of the linear penetration. Eventually they dominate over all other sources of beam divergence; therefore, understanding their effects is critical for evaluating the requirements of fast ignition.

Simulations of integrated fast-ignition experiments on the combined OMEGA/OMEGA EP Laser Systems with the multidimensional hydrodynamic code *DRACO* are summarized beginning on p. 189. An OMEGA cryogenic DT target, designed to reach a 1-D fuel ρR of 0.5 g/cm^2, has been simulated in 2-D with and without nonuniformities. The neutron yield is predicted to be in excess of 10^{15} (compared to ~10^{14} without an ignitor beam) over a synchronization range of ~80 ps.

The article (p. 196) describes the development of a proton emission imaging system that has been used to measure the nuclear burn regions in the cores of ICF implosions. This imaging technique relies on the penumbral imaging of 14.7-MeV D^3He fusion protons. Experimental data, analysis, and error analysis are presented for a representative symmetric implosion of a fuel capsule with a 20-μm-thick plastic shell and 18 atm of D^3He gas fill.

5. High-Energy-Density Physics

In the first article in this category, we present extended x-ray absorption fine structure measurements (p. 161). These have been used to demonstrate the phase transformation from body-centered-cubic (bcc) to hexagonal-closely-packed (hcp) iron due to nanosecond, laser-generated shocks. This is a direct, atomic-level, and *in-situ* proof of shock-induced transformation in iron.

The second article (p. 178) describes velocity interferometry and optical self-emission measurements from shock waves in polystyrene targets driven by two 90-ps pulses separated by 1.5 to 2 ns. The velocity histories, coalescence times, and transit times are unambiguously observed and are in good agreement with 1-D code predictions. The timing of multiple shock waves is crucial to the performance of ICF ignition targets.

Lasers, Optical Materials, and Advanced Technology

Crater formation in SiO_2 thin films containing artificial defects by ultraviolet (UV) pulsed-laser irradiation depends on the lodging depth of the defects (p. 23). At laser fluences close to the crater-formation threshold and for lodging depths of a few particle diameters, the dominating material-removal mechanisms are melting and evaporation. For absorbing defects lodged deeper than ~10 particle diameters, however, a two-stage material-removal mechanism occurs. The process starts with the material melting within the narrow channel volume and, upon temperature and pressure buildup, film fracture takes place.

The polishing performance of magnetorheological (MR) fluids prepared with a variety of magnetic and nonmagnetic ingredients to minimize artifact formation on the surface of CVD ZnS flats is reported on p. 35. The results show that altering the fluid composition greatly improves smoothing performance of magnetorheological finishing. A nanoalumina abrasive used with soft carbonyl iron and altered MR fluid chemistry yields surface roughnesses that do not exceed 20 nm p–v and 2-nm rms after removing 2 μm of material. Significantly, the formation of an "orange peel" and the exposure of a "pebble-like" structure inherent in ZnS from the CVD process are suppressed.

A 63-channel, high-resolution, UV spectrometer that can be used to check the tuning state of the KDP triplers has been designed and tested (p. 43). The spectrometer accepts an input energy of 1 μJ per channel, has a dispersion at the detector plane of 8.6×10^{-2} pm/μm, and has a spectral window of 2.4 nm at $\lambda = 351$ nm. The wavelength resolution varies from 2.5 pm at the center of the field of view to 6 pm at the edge.

The quantum efficiency (QE) and the noise equivalent power (NEP) of the latest-generation, nanostructured NbN, superconducting, single-photon detectors (SSPD's) operated at temperatures in the 2.0- to 4.2-K range in the wavelength range from 0.5 to 5.6 μm is discussed (p. 49). The detectors are designed as 4-nm-thick, 100-nm-wide NbN meander-shaped stripes, patterned by electron-beam lithography. Their active area is $10 \times 10\ \mu m^2$. The best-achieved QE at 2.0 K for 1.55-μm photons is 17%, and the QE for 1.3-μm infrared photons reaches its saturation value of ~30%. The SSPD NEP at 2.0 K is as low as 5×10^{-21} W/Hz$^{-1/2}$. These SSPD's, operated at 2.0 K, significantly outperform their semiconducting counterparts. With their gigahertz counting rate and picosecond timing jitter, they are the devices of choice for practical quantum key distribution systems and quantum optical communications.

An all-solid-state, diode-pumped Nd:YLF laser system has been developed and tested (p. 155). It produces fiducial timing signals at three wavelengths (fundamental, second, and fourth harmonics) and will be used as a primary timing reference for the OMEGA facility diagnostics. Performance results of the new OMEGA fiducial laser are reported.

Significant developments in tritium-capture technology have occurred over the past two decades (p. 142). The merits and drawbacks of the various technologies that have been developed for both air and inert gas streams are discussed.

Status and Progress on OMEGA EP

The OMEGA EP (extended performance) project continued on a fast-track schedule to complete two short-pulse beams and the scope was increased in FY05 to include two additional beams. FY06 Congressional funding has allowed the full four-beam project to proceed. This added two long-pulse beams to the originally authorized two short-pulse beams with completion in April 2008. The full OMEGA EP total estimated cost is $89 million of which $87 million has been appropriated through FY06. The building constructed to house the OMEGA EP equipment was completed in February 2005 at a cost of $21 million. This building was funded by the University of Rochester and its completion enabled the start of the laser's assembly.

Prior to building completion, major assemblies were prepared for installation and work on laser technology development activities was completed. Technology development projects included optical parametric chirped-pulse amplification (OPCPA), multilayer-dielectric diffraction gratings, and coherent tiling of large-aperture gratings. These projects concluded with demonstrations of performance that meet or exceed OMEGA EP requirements. Additionally, LLE adopted plasma-electrode Pockels cell (PEPC) and adaptive optics (deformable mirrors) technology from LLNL's NIF project. The deformable mirror hardware was designed by LLNL but is operated with a LLE-developed wavefront sensor and control system. The PEPC, while similar to LLNL's, has design requirements and features specific to deployment at LLE. Both of these projects were concluded in FY05, which allowed the acquisition of prime hardware to commence.

Once the building was complete, the process of installing the infrastructure required to support the beamlines, compressors, and target chamber began. Support structure acquisitions were initiated upon completion of the beamline design and approval of the baseline change to enable four beams. Several of these structures arrived in FY05 and were placed in the OMEGA EP Laser Bay; the majority of the structures will be installed in the first quarter of FY06. The target area structure was installed and prepared for the insertion of the target chamber. The target chamber, a near replica of the OMEGA target chamber, was acquired with a grant from the New York State Energy Research and Development Authority and will be integrated at LLE in FY06. The 350,000-lb, 70-ft. × 15-ft × 15-ft, nine-segment grating compressor chamber (GCC) arrived from Los Angeles and was precision cleaned in the Laser Bay. Final GCC assembly and vacuum testing will be completed in FY06. Lastly, deployment of the controls system in concert with the laser hardware installation began. The control room installation is complete and operational testing for remote operation of OMEGA EP has commenced.

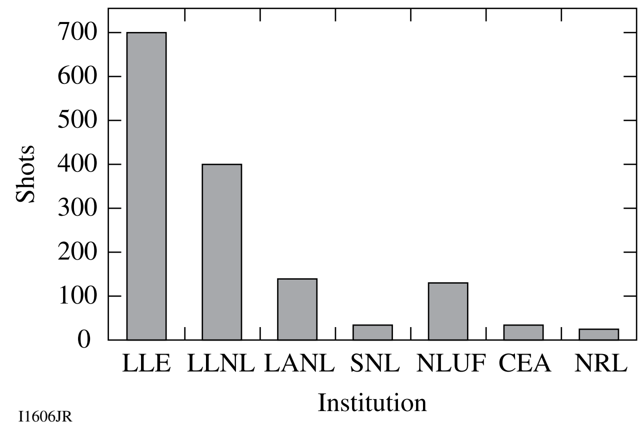

Figure 1
FY05 OMEGA usage.

National Laser Users' Facility and External Users' Programs

A detailed summary of the operation and use of the National Laser Users' Facility and External User's Programs is given on p. 225. A discussion of user experiments included

- *Isentropic Compression Experiments (ICE) for Measuring EOS on OMEGA*
- *Laser–Plasma Interactions in High-Energy-Density Plasmas*
- *Three-Dimensional Study of the Spatial Structure of Direct-Drive Implosion Cores on OMEGA*
- *NLUF Proton Radiography Experiments*
- *FY05 LANL OMEGA Experimental Programs*
- *FY05 Sandia National Laboratory's Experiments on OMEGA*
- *2005 CEA Experiments on OMEGA*

FY 2005 Laser Facility Report

The use of the OMEGA Facility is reported in the article that begins on p. 223. During the year, 1461 target shots were conducted for LLE, NLUF, and external users. LLE usage accounted for less than 50% of the total target shots. Figure 1 illustrates the shot allocations during the fiscal year.

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. 221. Fifteen students participated in this year's program. The William D. Ryan Inspirational Teacher Award was given to Mr. Stephen Locke, a chemistry teacher at Byron-Bergen High School.

Graduate students are using the world's most powerful UV laser for fusion research on OMEGA, making significant contributions to LLE's research activities. Twenty-one faculty from five departments collaborate with LLE's scientists and engineers. Presently, 102 graduate students are involved in research projects at LLE, and LLE directly sponsors 43 students pursuing Ph.D. degrees. Their research includes theoretical and experimental plasma physics, high-energy-density 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 seventy-seven University of Rochester students have earned Ph.D. degrees at LLE since its founding. An additional two undergraduate students, fourteen graduate students, two postdoctoral, and seven faculty positions from other universities were funded by NLUF grants. The most recent University of Rochester Ph.D. graduates and their thesis include the following:

Bigelow, Matthew S.	*"Ultra-Slow and Superluminal Light Propagation in Solids at Room Temperature"*
Erdmann, Reinard K.	*"Quantum Interference Engineered by Dispersive Parameter Design"*
Guazzotto, Luca	*"Equilibrium and Stability of Axisymmetric Plasmas with Arbitrary Flow"*
Kozlov, Maxim V.	*"Stimulated Brillouin Scattering in Multiple Species Plasmas"*
Rey-de-Castro, Robert C.	*"Ultrafast Optical Properties and Applications of* $Cd_{1-x}Mn_xTe$ *Semimagnetic Semiconductors"*
Striemer, Christopher C.	*"Applications of Silicon Nanostructures Compatible with Existing Manufacturing Technology"*
U'Ren, Alfred B.	*"Multi-Photon State Engineering for Quantum Information Processing Applications"*
Weiss, Sharon M.	*"Tunable Porous Silicon Photonic Bandgap Structures: Mirrors for Optical Interconnects and Optical Switching"*
Zheng, Lianqing	*"UV-Laser-Induced Densification of Fused Silica: A Molecular Dynamics Study"*

Approximately 45 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 Wisconsin, and the University of North Carolina at Chapel Hill. These programs involve a total of approximately six graduate students, twenty-seven undergraduate students, and four faculty from other universities.

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