Executive Summary

The fiscal year ending September 2009 (FY2009) concluded the second year of the third five-year renewal of Cooperative Agreement DE-FC52-08NA28302 with the U.S. Department of Energy (DOE). This annual report summarizes progress in inertial fusion research at the Laboratory for Laser Energetics (LLE) during the past fiscal year. It also reports on LLE's progress on laboratory basic science research; laser, optical materials, and advanced technology development; operation of OMEGA and OMEGA EP 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 Inertial Confinement Fusion (ICF) Research

The science research program at the University of Rochester's Laboratory for Laser Energetics (LLE) focuses on inertial confinement fusion (ICF) research supporting the goal of achieving ignition on the National Ignition Facility (NIF). This program includes the full use of the OMEGA 60-beam UV laser as well as the OMEGA EP high-energy, short-pulse laser system. During FY09, OMEGA EP was operated on target at an energy level of 2.1 kJ at 10 to 12 ps, making the laser the world's highest-energy short-pulse laser system. Within the National Ignition Campaign (NIC), LLE is the lead laboratory for the validation of the performance of cryogenic target implosions, essential to all forms of ICF ignition. LLE has taken responsibility for a number of critical elements within the Integrated Experimental Teams (IET's) supporting the demonstration of indirect-drive ignition on the NIF and is the lead laboratory for the validation of the polar-drive approach to ignition on the NIF. LLE is also developing, testing, and building a number of diagnostics that are being deployed on the NIF for the NIC. During this past year, progress in the inertial fusion research program was made in three principal areas: NIC experiments; development of diagnostics for experiments on OMEGA, OMEGA EP, and the NIF; and theoretical analysis and design efforts aimed at improving direct-drive-ignition capsule designs and advanced ignition concepts such as fast ignition and shock ignition.

1. National Ignition Campaign Experiments

In FY09, LLE, in collaboration with Lawrence Livermore National Laboratory (LLNL) and Sandia National Laboratories (SNL), demonstrated a key shock-timing technique for ignition targets at the NIF. The article beginning on p. 1 reports on this technique to measure the velocity and timing of shock waves in a capsule contained within hohlraum targets. This technique is critical for optimizing the drive profiles for high-performance ICF capsules, which are compressed by multiple precisely timed shock waves. The shock-timing technique was demonstrated on OMEGA using surrogate hohlraum targets heated to a radiation temperature of 180 eV and fitted with a re-entrant cone and quartz window to facilitate velocity measurements using velocity interferometry. Cryogenic experiments using targets filled with liquid deuterium further demonstrated the entire timing technique in a hohlraum environment. Direct-drive cryogenic targets with multiple spherical shocks were also used to validate this technique, including convergence effects at relevant pressures (velocities) and sizes. These results provide confidence that shock velocity and timing can be measured in NIF ignition targets, thereby optimizing these critical parameters.

Recent progress in high-density implosions of direct-drive cryogenic capsules based on a collaboration including scientists from LLE, NRC (Israel), and the Plasma Science and Fusion Center–MIT (PSFC–MIT) is reviewed beginning on p. 12. Ignition-relevant areal densities of ~200 mg/cm^2 in cryogenic D_2 implosions with peak laser-drive intensities of $\sim 5 \times 10^{14}$ W/cm^2 were previously reported. The laser intensity is being increased to $\sim 10^{15}$ W/cm^2 to demonstrate ignition-relevant implosion velocities of 3 to 4×10^7 cm/s, providing an understanding of the relevant target physics. Planar-target acceleration experiments show the importance of the nonlocal electron-thermal-transport effects for modeling the laser drive. Nonlocal, hot-electron preheat is observed to stabilize the Rayleigh–Taylor growth at the peak drive intensity of $\sim 10^{15}$ W/cm^2. The shell preheat caused by the hot electrons generated by two-plasmon-decay (TPD) instability was reduced by using Si-doped ablators. The measured compressibility of planar plastic targets driven with high-compression, shaped pulses agrees well with 1-D simulations at these intensities. Shock mistiming has contributed to compression degradation of recent cryogenic implosions driven with continuous pulses. Multiple-picket (shock-wave) target designs make it possible for a more robust tuning of the shock-wave arrival times. Cryogenic implosions driven with double-picket pulses demonstrate improved compression performance at a peak drive intensity of $\sim 10^{15}$ W/cm^2.

Experiments (p.178) on the OMEGA Laser System (in collaboration with LLNL and SNL) using laser-driven vacuum hohlraum targets show distinct differences between cryogenic (<20 K) and warm targets. Warm hohlraum targets coated with 2 μm of CH replicate the behavior of cryogenic targets. This indicates that cryogenic hohlraums are affected by the condensation of background gases on the cold hohlraum surface. The introduction of low-*Z* material into the hohlraums significantly reduces the x-ray conversion efficiency, resulting in lower hohlraum radiation temperature. The coatings (both CH and condensates) produce long-scale-length, low-*Z* plasmas that reduce the absorption of laser light in the hohlraums. This causes higher reflectivity and produces hot electrons that generate hard x rays ($h\nu > 20$ keV), both of which are detrimental to the performance of hohlraum-driven inertial confinement fusion targets. These finding are important to some non-ignition hohlraums that use low-*Z* liners (or layers) on the inside hohlraum walls to tamp or resist the expansion of the laser-ablated wall material. In contrast, ignition hohlraums will be filled with a low-*Z* gas to keep the laser entrance hole open. Windows are placed on the laser entrance holes to retain the gas; these windows also serve to protect the inside of the hohlraum from the deposition of condensates. Moreover, the NIF cryogenic targets are housed inside shrouds to minimize condensation until they open a few seconds before the shot. These OMEGA experiments confirm that eliminating condensation on cryogenic targets is crucial for optimal hohlraum performance.

Scientists from PSFC–MIT, LLE, and LLNL present recent experiments using proton backlighting of laser–foil interactions to provide a unique opportunity for studying magnetized plasma instabilities in laser-produced, high-energy-density plasmas (p. 74). Time-gated proton radiograph images indicate that the outer structure of a magnetic field entrained in a hemispherical plasma bubble becomes distinctly asymmetric after the laser turns off. It is shown that this asymmetry is a consequence of pressure-driven, resistive magnetohydrodynamic (MHD) interchange instabilities. In contrast to the predictions made by ideal MHD theory, the increasing plasma resistivity after the laser turns off allows for greater low-mode destabilization (mode number $m > 1$) from reduced stabilization by field-line bending. For laser-generated plasmas presented herein, a mode-number cutoff for stabilization of perturbations with $m > \sim\sqrt{8\pi\beta\left(1 + D_m k_\perp^2 \gamma_{\max}^{-1}\right)}$, is found in the linear growth regime. The growth is measured and is found to be in reasonable agreement with model predictions.

2. Cryogenic Target Fabrication

Scientists from the University of Rochester's (UR's) Department of Electrical Engineering and LLE present a method by which the ponderomotive force, exerted on all dielectric liquids by a nonuniform electric field, can be used for the remote, voltage-controlled manipulation of 10- to 100-nl volumes of cryogenic liquids (p. 101). This liquid dielectrophoretic (DEP) effect, imposed by specially designed electrodes, combines with capillarity to influence the hydrostatic equilibria of liquid deuterium. A simple, 1-D model accurately predicts the measured meniscus rise of D_2 against gravity for sufficiently wide, parallel electrodes. For narrow electrodes, where the sidewalls influence the equilibrium, a finite-element solution using the Surface Evolver software correctly predicts the behavior. A bifurcation phenomenon previously observed for room-temperature dielectrics is also observed in liquid deuterium. This effect could possibly be used in the future to meter cryogenic deuterium when fueling targets for laser fusion.

Scientists from LLE, the Power Photonic Corporation, and the State University of New York at Stony Brook describe the spectral and output-power stability of a 3-nm-wavelength, GaSb-based diode laser operated at room temperature (p. 111). More than 50 mW of output power has been achieved at 14°C with high spectral and output-power stability. This diode laser has a direct application for layering cryogenic targets for ICF implosions on the OMEGA laser.

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

Beginning on p. 20 we describe a new method (developed in collaboration with PSFC–MIT) for analyzing the spectrum of knock-on deuterons (KOd's) elastically scattered by primary DT neutrons, from which a fuel ρR can be inferred for values up to $\sim$200 mg/cm^2. This new analysis method, which used Monte Carlo modeling of a cryogenic DT implosion, significantly improves the previous analysis method in two fundamental ways: First, it is not affected by significant spatial-yield variations, which degrade the diagnosis of fuel ρR (spatial-yield variations of about ±20% are typically observed), and second, it does not break down when the fuel ρR exceeds 70 mg/cm^2.

Based on a joint effort involving LLE, PSFC–MIT, and the University of Nevada–Reno, we describe a method from which the cold fuel layer's density is inferred from framed x-ray radiographs of a laser-driven spherical implosion (p. 26). The density distribution is determined by using Abel inversion to compute the radial distribution of the opacity κ from the observed optical depth τ. With the additional assumption of the mass of the remaining cold fuel, the absolute density distribution can be determined. This is demonstrated at the Omega Laser Facility with two x-ray backlighters of different mean energies that lead to the same inferred density distribution independent of backlighter energy.

The article beginning on p. 55, co-authored by scientists from LLE, LLNL, the University of Nevada–Reno, and the University of California at San Diego, highlights the diagnosis of high-energy-density plasmas created in laser-fusion experiments with x-ray spectroscopy. Over the last three decades, x-ray spectroscopy has been used to record the remarkable progress made in ICF research. Four areas of x-ray spectroscopy for laser-fusion experiments are highlighted in this article: K_α emission spectroscopy to diagnose target preheat by suprathermal electrons, Stark-broadened K-shell emissions of mid-Z elements to diagnose compressed densities and temperatures of implosion cores, K- and L-shell absorption spectroscopy to diagnose the relatively cold imploding shell (the "piston") that does not emit x rays, and multispectral monochromatic imaging of implosions to diagnose core temperature and density profiles. A large portion of the seminal research in these areas has been carried out by LLE and is discussed in this report.

A report beginning on p. 68 authored by scientists from LLE and the UR's Institute of Optics discusses high-resolution coherent transition radiation (CTR) imaging for diagnosing electrons accelerated in laser–solid interactions with intensities of $\sim 10^{19}$ W/cm^2. The CTR images indicate electron-beam filamentation and annular propagation. The beam temperature and half-angle divergence are inferred to be ~1.4 MeV and ~16°, respectively. Three-dimensional hybrid-particle-in-cell code simulations reproduce the details of the CTR images, assuming an initial half-angle divergence of 56°. Self-generated resistive magnetic fields are responsible for the difference between the initial and the measured divergences.

A team from LLE and Ad-Value Photonics report (p. 51) on work that experimentally validates the concept of effective Verdet constant to describe the Faraday rotation characteristics of optical fiber. The effective Verdet constant of light propagation in fiber includes contributions from the materials in both the core and the cladding. This article presents a measured Verdet constant in 25-wt% terbium-doped–core phosphate fiber to be −6.2±0.4 rad/Tm at a wavelength of 1053 nm, which is 6× larger than in silica fiber. The result agrees well with the Faraday rotation theory for optical fiber.

This same team reports (p. 206) on an all-fiber optical magnetic field sensor. The sensor consists of a fiber Faraday rotator and a fiber polarizer. The fiber Faraday rotator uses a 2-cm-long section of 56-wt%-terbium-oxide–doped silica fiber, and the fiber polarizer is a Corning SP1060 single-polarization fiber. The all-fiber optical magnetic field sensor has a sensitivity of 0.45 rad/T and can measure a magnetic field up to 3.5 T.

4. Theoretical Analysis and Design

Beginning on p. 31 we report on integrated simulations of implosion, electron transport, and heating for direct-drive fast-ignition targets. A thorough understanding of future integrated fast-ignition experiments combining compression and heating for high-density thermonuclear fuel requires hybrid (fluid + particle) simulations of the implosion and ignition process. Different spatial and temporal scales need to be resolved to model the entire fast-ignition experiment. The 2-D axisymmetric hydrocode *DRACO* and the 2-D/3-D hybrid-PIC code *LSP* have been integrated to simulate the implosion and heating of direct-drive, fast-ignition targets. *DRACO* includes the physics required to simulate compression, ignition, and burn of fast-ignition targets. *LSP* simulates the transport of hot electrons from their generation site to the dense fuel core, where their energy is absorbed. The results from integrated simulations of cone-in-shell CD targets designed for fast-ignition experiments on the OMEGA/OMEGA EP Laser System are presented. Target heating and neutron yields are computed. The results from *LSP* simulations of electron transport in solid-density plastic targets are also presented. They confirm an increase in the electron-divergence angle with the laser intensity in the current experiments. The self-generated resistive magnetic field is found to collimate the hot-electron beam and increase the coupling efficiency of hot electrons with the target. Resistive filamentation of the hot-electron beam is also observed.

Lasers, Optical Materials, and Advanced Technology

A report co-authored by scientists from LLE and the UR's Department of Mechanical Engineering discusses *in-situ*, simultaneous measurements of both drag and normal forces in magnetorheological optical finishing (MRF) using a spot-taking machine (STM) as a test bed to take MRF spots on stationary optical parts (p. 42). The force measurements are carried out over the entire removal area, produced by the projected area of the MRF removal function/spot on the part surface, using a dual-force sensor. This approach experimentally addresses the mechanisms governing material removal in MRF for optical glasses in terms of the hydrodynamic pressure and shear stress, applied by the hydrodynamic flow of magnetorheological (MR) fluid at the gap between the part surface and the STM wheel. This work demonstrates that the volumetric removal rate shows a positive linear dependence on shear stress. Shear stress exhibits a positive linear dependence on a material figure of merit that depends on Young's modulus, fracture toughness, and hardness. A modified Preston's equation is proposed that will better estimate MRF material removal rate for optical glasses by incorporating mechanical properties, shear stress, and velocity.

A team from LLE and the UR's Departments of Mechanical Engineering and Chemical Engineering reports on MRF spotting experiments performed on glasses and ceramics using a zirconia-coated-carbonyl-iron-particle–based MR fluid (p. 190). The coating layer was ~50 to 100 nm thick, faceted in surface structure, and well adhered. Coated particles showed long-term stability against aqueous corrosion. A viable MR fluid was prepared simply by adding water. Spot-polishing tests were performed on a variety of optical glasses and ceramics over a period of nearly three weeks with no signs of MR fluid degradation or corrosion. Stable material-removal rates and smooth surfaces inside spots were obtained.

Scientists from the UR's Department of Mechanical Engineering discuss crack growth in brittle glass plates using known finite element modeling to determine the maximum allowable initial crack size in plates undergoing radiative cooling (p. 145). In these simulations both BK7 borosilicate crown and LHG8 phosphate glass were slowly cooled in vacuum from 200°C down to room temperature. The authors used finite elements and incorporated available experimental results on crack growth in BK7 and LHG8. Numerical simulation showed that the heaviest stressed locations were the midpoints of the plate's long edges, where any crack growth was likely to originate. This article outlines a procedure to estimate the deepest-allowable surface flaw to prevent fracture. Fracture is analyzed in terms of strength, fracture toughness, or slow crack growth. Merits of these approaches are discussed, and an extensive comparison of cracking in BK7 versus the laser glass LHG8 is presented.

Scientists from LLE; the UR's Department of Electrical Engineering; the Institute of Bio- and Nanosystems, Research Centre of Jülich; and the Institute of Electrical Engineering, Slovak Academy of Sciences applied finite element analysis to ultrafast photoconductive switches of the metal–semiconductor–metal (MSM) type to explain why MSM devices with alloyed electrodes show improved photoresponse efficiency compared to devices with surface contact electrodes (p. 154). The alloyed device, despite having a somewhat larger capacitance, has an active region of lower resistance with a more-uniform and deeper-penetrating electric field and carrier transport current. The authors use the latter to explain the experimentally observed faster response of the alloyed device in terms of the equivalent lumped parameters. They also use the model to predict improved responsivity, based on electrode spacing and antireflective coating.

Scientists from LLE and the UR's Department of Mechanical Engineering describe an extension of the theory governing motion of polymer cholesteric liquid crystal flakes in the presence of ac electric fields by introducing the effect of gravity acting on flakes, an important term when the flake density differs from the density of the suspending host fluid (p. 80). Gravity becomes the driving force for flake relaxation when the electric field is removed, and it is now possible to predict relaxation times. Experimental results are compared with predictions from the extended theoretical model.

Beginning on p. 86, an article by scientists from LLE and the UR's Department of Mechanical Engineering presents a method for modeling the effect of microencapsulation on the electro-optical behavior of polymer cholesteric liquid crystal (PCLC) flakes suspended in a host fluid. Several microencapsulation configurations in an applied ac electric field are investigated using Comsol Multiphysics software in combination with an analytical model. The field acting on the flakes is significantly altered as various encapsulant materials and boundary conditions are explored. The modeling predicts that a test cell with multiple materials in the electric-field path can have a wide range of electro-optic responses in ac electric fields. Both theoretical predictions and experimental evidence show that for PCLC flake reorientation to occur as a result of Maxwell–Wagner polarization, a reasonably strong electric field must be present along with at least moderately dissimilar PCLC flake and host fluid material dielectric constants and conductivities. For materials with low dielectric constants, electrophoretic behavior is observed under dc drive conditions at high field strengths for all evaluated microencapsulation configurations. The modeling method is shown to be a useful predictive tool for developing switchable particle devices that use microencapsulated dielectric particles in a host fluid medium.

A spatially resolved spectral interferometry technique, known as S^2 imaging, has been used for the first time to measure the higher-order-mode content of a large-mode-area amplifier at full power (p. 134). The technique was adapted for the short-fiber amplifier at full power and revealed a small amount of a co-polarized LP_{11} mode. This mode's power, relative to the fundamental LP_{01} mode, depended on the alignment of the input signal at injection to the rod amplifier, and ranged from –18 dB, for optimized alignment, to –13 dB when the injection alignment was offset along the LP_{11} axis by 15 μm (30% of the 55-μm mode-field diameter). The increase in LP_{11} contributed to the M^2 degradation that was measured when the injection was misaligned.

Optical differentiation in a regenerative amplifier (RA) with temperature-tuned volume Bragg grating (VBG) as an intracavity spectral filter has been demonstrated for the first time (p. 141). The VBG as a spectrally selective resonator mirror works as an optical differentiator when the VBG reflection peak is detuned from the central laser wavelength. A simple, reliable laser system that produces multimillijoule ~150-ps pulses without mode-locking, using an RA with VBG as an optical differentiator, is described.

Scientists from the UR's Department of Electrical and Computer Engineering and the Laboratory for Solid State Physics, ETH Zurich, report on their experimental studies on the time-resolved carrier dynamics in high-quality $Al_{0.86}Ga_{0.14}N$ single crystals, grown using a solution technique in a high-nitrogen-gas-pressure system (p. 210). Optical measurements were performed using two-color, femtosecond pump–probe spectroscopy. By studying the correlation signal amplitude's dependence on both the pump light's absorbed power and wavelength, they obtained a two-photon-absorption coefficient $b = 0.442 \pm 0.02$ cm/GW, as well as its spectral dependence, and confirmed that within the tuning range of the laser, the latter was in very good agreement with the Sheik–Bahae theory for wide, direct-bandgap semiconductors. The optical bandgap of the $Al_{0.86}Ga_{0.14}N$ crystal was determined to be 5.81±0.01 eV.

National Laser Users' Facility and External Users' Programs

Under the governance plan implemented in FY08 to formalize the scheduling of the Omega Laser Facility as a National Nuclear Security Agency (NNSA) facility, OMEGA shots are allocated by campaign. The majority of the FY09 target shots (~56.7%) were allocated to the National Ignition Campaign (NIC), and integrated experimental teams from LLNL, LANL, SNL, and LLE conducted a variety of NIC-related experiments on both the OMEGA and OMEGA EP Laser Systems. Twenty percent (20%) of the FY09 shots were allocated to high-energy-density stewardship experiments (HEDSE) from LLNL and LANL. Under this governance plan, 25% of the facility shots were allocated to basic science experiments. Roughly half of these were dedicated to university basic science, i.e., the National Laser Users' Facility (NLUF) Program, and the remaining shots were allotted to the Laboratory Basic Science (LBS) Program, comprising peer-reviewed basic science experiments conducted by the national laboratories and LLE/FSC. The Omega Facility is also being used for experiments by teams from the Commissariat à l'Énergie Atomique (CEA) of France and the Atomic Weapons Establishment (AWE) of the United Kingdom. These programs are conducted on the basis of special agreements put in place by DOE/NNSA and the participating institutions.

The external users during this year included a record 11 collaborative teams that participated in the NLUF Program as shown in Table I. Ten teams from LLNL, LANL, and LLE were allotted shots under the LBS Program (Table II). Integrated experimental teams from the national laboratories and LLE conducted 851 shots for the NIC, and investigators from LLNL, LANL, and LLE conducted over 232 shots for the HEDSE programs. A total of 56 shots were conducted by scientists from CEA and 35 shots were carried out by scientists from AWE.

1. NLUF Programs

FY09 was the first of a two-year period of performance for the NLUF projects approved for the FY09–FY10 funding and OMEGA shots. Eleven NLUF projects were allotted OMEGA and OMEGA EP shot time and received a total of 165 shots on OMEGA and 43 shots on OMEGA EP in FY09. Some of this work is summarized beginning on p. 218. A new solicitation will be issued by DOE in FY10 for NLUF grants for the period FY11–FY12.

A detailed article on Lorenz mapping of magnetic fields in hot, dense plasma, one of the NLUF experiments carried out by a collaborative team led by the Plasma Science and Fusion Center–MIT, is presented beginning on p. 129. The authors show that monoenergetic proton radiography combined with Lorentz mapping can be used to uniquely detect and discriminate magnetic and electric fields. Protons were used to image two identical expanding plasma bubbles, formed on opposite sides of a 5-μm-thick plastic (CH) foil by two 1-ns-long laser-interaction beams. The second bubble reversed the sign of any magnetic fields relative to the first bubble by the protons, while keeping the electric fields the same. Field-induced deflections of the monoenergetic, 14.9-MeV probe protons passing through

Table I: FY09–FY10 NLUF Projects.

Principal Investigator	Affiliation	Proposal Title
F. Beg	University of California, San Diego	Systematic Study of Fast-Electron Transport and Magnetic Collimation in Hot Plasmas
R. P. Drake	University of Michigan	Experimental Astrophysics on the OMEGA Laser
R. Falcone	University of California, Berkeley	Detailed *In-Situ* Diagnostics of Multiple Shocks
U. Feldman	ARTEP, Inc.	OMEGA EP–Generated X-Ray Source for High-Resolution 100- to 200-keV Point-Projection Radiography
Y. Gupta	Washington State University	Ramp Compression Experiments for Measuring Structural Phase Transformation Kinetics on OMEGA
P. Hartigan	Rice University	Dynamics of Shock Waves in Clumpy Media
R. Jeanloz	University of California, Berkeley	Recreating Planetary Core Conditions on OMEGA, Techniques to Produce Dense States of Matter
K. Krushelnick	University of Michigan	Intense Laser Interactions with Low-Density Plasmas Using OMEGA EP
R. Mancini	University of Nevada, Reno	Three-Dimensional Studies of Low-Adiabat Direct-Drive Implosions on OMEGA
M. Meyers	University of California, San Diego	Response of BCC Metals to Ultrahigh Strain Rate Compression
R. D. Petrasso	Massachusetts Institute of Technology	Monoenergetic Proton and Alpha Radiography of Laser-Plasma-Generated Fields and of ICF Implosions

Table II: Approved FY09 LBS Experiments.

Principal Investigator	Affiliation	Proposal Title	Facility Required
R. Betti	LLE/FSC	Ultra-Strong Shock and Shock-Ignition Experiments on OMEGA EP	OMEGA EP long pulse/short pulse
H. Chen	LLNL	Electron–Positron Jets	OMEGA EP short pulse/2 beams
J. H. Eggert	LLNL	Powder X-Ray Diffraction on OMEGA: Phase Transitions in Tin	OMEGA
M. B. Hegelich	LANL	Proton and Light Ion Production for Fast Ignition and Warm Dense Matter Applications	OMEGA EP short pulse
D. G. Hicks	LLNL	A New Technique for Efficient Shockless Compression to Several Mbar: Studies Using X-Ray Absorption Spectroscopy	OMEGA 40 beams
A. J. MacKinnon	LLNL	Fast Electron Transport in Hot Dense Matter	OMEGA EP long pulse
H.-S. Park	LLNL	Study of High-*Z* Material Properties Under Compression Using High Energy Backlighter Diffraction	OMEGA EP long pulse/short pulse
P. K. Patel	LLNL	Fundamental Benchmarking of Relativistic Laser–Matter Interaction Physics	OMEGA EP short pulse
S. P. Regan	LLE	Probing Hydrogen–Helium Warm Dense Matter (WDM) with Inelastic X-Ray Scattering: Toward the Equation of State of Jupiter's Core	OMEGA
W. Theobald	LLE	Integrated Core Heating for Fast Ignition	OMEGA and OMEGA EP

the two bubbles, measured quantitatively with proton radiography, were combined with Lorentz mapping to provide separate measurements of magnetic and electric fields. The authors' results provided absolute identification and measurement of a toroidal magnetic field around each bubble and determined that any electric field component parallel to the foil was below measurement uncertainties.

2. FY09 LLNL Omega Facility Programs

In FY09, LLNL led 238 target shots on the OMEGA Laser System. Approximately half of these shots supported the National Ignition Campaign (NIC). The remainder were dedicated to experiments for the high-energy-density stewardship experiments (HEDSE). Objectives of the LLNL-led NIC campaigns on OMEGA included

- *Laser–plasma interaction studies in physical conditions relevant for the National Ignition Facility (NIF) ignition targets*
- *Demonstration of* T_r = *100-eV foot-symmetry tuning using a re-emission sphere*
- *X-ray scattering in support of conductivity measurements of solid-density Be plasmas*
- *Experiments to study the physical properties (thermal conductivity) of shocked fusion fuels*
- *High-resolution measurements of velocity nonuniformities created by microscopic perturbations in NIF ablator materials*
- *Development of a novel Compton radiography diagnostic platform for ICF experiments*
- *Precision validation of the equation of state for quartz*

The LLNL HEDSE campaigns included the following:

- *Quasi-isentropic (ICE) drive used to study material properties such as strength, equation of state, phase, and phase-transition kinetics under high pressure*
- *Development of a high-energy backlighter for radiography in support of material strength experiments using OMEGA EP and the joint OMEGA/OMEGA EP configuration*
- *Debris characterization from long-duration, point-apertured, point-projection x-ray backlighters for NIF radiation transport experiments*
- *Demonstration of ultrafast temperature and density measurements with x-ray Thomson scattering from short-pulse-laser–heated matter*
- *Development of an experimental platform to study non-local thermodynamic equilibrium (NLTE) physics using direct-drive implosions*
- *Opacity studies of high-temperature plasmas under LTE conditions*
- *Characterization of copper (Cu) foams for HEDSE experiments*

A summary of experiments carried out by LLNL at the Omega Laser Facility in FY09 begins on p. 235.

3. FY09 LANL Omega Facility Programs

Los Alamos National Laboratory (LANL) successfully fielded a range of experiments on the OMEGA laser during FY09 in support of the national program. LANL conducted a total of 104 target shots: 93 on OMEGA and 11 on OMEGA EP. Collaborations with LLNL, LLE, LULI, NRL, MIT, NSTec, UCSD, and AWE remain an important component of LANL's program on OMEGA. The LANL programs executed on OMEGA in FY09 included the following:

- *NIF 5*
- *High* Z
- *OMEGA EP ions*
- *Gamma-reaction history diagnostic*
- *Defect implosion experiment (DIME)*
- *High-energy backlighting on OMEGA EP*
- *Neutron imaging*

The LANL experiments are summarized beginning on p. 246.

4. FY09 AWE Omega Facility Programs

The AWE conducted 35 OMEGA laser target shots and joined CEA on 5 shots on OMEGA EP. AWE-led experiments on OMEGA in FY09 continued to test radiation–hydrodynamic simulations of hohlraum drive and capsule implosion under conditions where a hohlraum target was driven in a deliberately asymmetric manner. The FY09 experiments are summarized beginning on p. 254.

5. FY09 CEA Omega Facility Programs

CEA conducted 56 OMEGA shots in FY09 (51 on OMEGA and 5 on OMEGA EP (jointly with AWE). The CEA efforts included the following:

- *CEA copper activation diagnostic for DT neutron-yield measurements*
- *MeV photon x-ray sources produced by OMEGA EP*
- *Two new neutron imaging systems on OMEGA*
- *Ablative Rayleigh–Taylor stabilization mechanism experiment*

A summary of the FY09 CEA programs on OMEGA begins on p. 256.

Laboratory Basic Science (LBS) Experiments

Ten proposals were approved and were allocated 25 shot days on OMEGA in FY09 under the Laboratory Basic Science Program (six proposals from LLNL, three from LLE, and one from LANL as shown on Table II).

Unfortunately, because of the DOE funding shortfall in FY09, only 17 days (109 shots) of LBS experiments were actually funded and carried out during this fiscal year. The FY10 solicitation for the LBS Program resulted in 25 proposals with shot requests totaling 63.5 shot days. After peer review by an independent committee, 13 LBS proposals have been recommended for 29 shot days in FY10. Three additional shot days were recommended and approved for FY09 make-up shots. The approved FY10 LBS proposals are listed in Table III.

Table III: Approved FY10 LBS Experiments.

Principal Investigator	Affiliation	Proposal Title	Facility Required
R. Betti	LLE/FSC	Integrated Shock-Ignition Experiments on OMEGA	OMEGA
P. M. Celliers	LLNL	Measurement of the Viscosity of Shock-Compressed Fluids: Studies of Water and Silica	OMEGA
H. Chen	LLNL	Producing Pair Plasma and Gamma-Ray Burst Using OMEGA EP	OMEGA EP
D. E. Fratanduono	LLE	Optical Properties of Compressed LiF	OMEGA and OMEGA EP
D. H. Froula/J. S. Ross	LLNL	First Observations of Relativistic Plasma Effects on Collective Thomson Scattering	OMEGA
S. H. Glenzer	LLNL	Capsules Adiabat Measurements with X-Ray Thomson Scattering	OMEGA
D. G. Hicks	LLNL	Ramp and Multi-Shock Compression of Iron to Several Megabars: Studies Using Extended and Near Edge X-Ray Absorption Spectroscopy	OMEGA
H.-S. Park	LLNL	Study of High-*Z* Material Properties under Compression Using High-Energy Backlighter Diffraction	OMEGA EP
P. K. Patel	LLNL	Benchmarking Laser-Electron Coupling at Fast Ignition–Relevant Conditions	OMEGA EP
S. P. Regan	LLE	Validating Inelastic X-Ray Scattering from H and H/He Warm Dense Matter with Shock Velocity Measurements: Toward the Equation of State of Jupiter's Core	OMEGA
R. Smith/J. H. Eggert/ S. M. Pollaine	LLNL	Phase Transformation Kinetics	OMEGA
C. Stoeckl/ W. Theobald/W. Seka	LLE	Channeling in Long-Scale-Length Plasmas	OMEGA EP
W. Theobald	LLE	Integrated Core Heating for Fast Ignition	OMEGA and OMEGA EP

One of the LBS experiments is focused on studies of shock ignition and is based on a collaboration including LLE, the Fusion Science Center for Extreme States of Matter and Fast Ignition Studies, and PSFC–MIT. An article beginning on p. 117 discusses shock-ignition experiments that have been performed on OMEGA with peak shock-generating laser intensities of ~1×10^{16} W/cm^2. Shock ignition is a two-step ICF concept in which a strong shock wave is launched at the end of the laser-drive pulse to ignite the compressed core, relaxing the driver requirements and promising high gains. In the experiments described in this article, room-temperature plastic shells filled with D_2 gas were compressed on a low adiabat by 40 beams of the 60-beam OMEGA Laser System. The remaining 20 beams were delayed and tightly focused onto the target to drive a strong shock into the compressed core. Good coupling of the shock-beam energy was observed in these experiments, leading up to an ~20× increase in neutron yield compared to a similar implosion without the high-intensity pulse. The authors observed significant stimulated Raman backscattering of laser energy; however, fast-electron measurements showed a relatively cold energy distribution. These fast electrons are actually beneficial for shock ignition since they have short mean free paths and are stopped in the thin outer layer of the imploding target, augmenting the strong hydrodynamic shock.

Laser-driven magnetic-flux compression in high-energy-density plasma experiments (p. 123) is an LBS program that is based on a collaboration involving LLE, FSC, MIT, and LLNL. During FY09, this team demonstrated for the first time magnetic-field compression to many tens of megagauss (MG) in cylindrical implosions of inertial confinement fusion targets. The very high magnetic-flux compression was achieved using the ablative pressure of the OMEGA laser to drive a cylindrical shell at high implosion velocity, trapping and compressing an embedded external field to tens of MG, high enough to magnetize the hot-spot plasma. The magnetic fields in the compressed core were probed via proton deflectrometry using the fusion products from an imploding D^3He target. Line-averaged magnetic fields between 30 and 40 MG were observed.

An LBS experiment based on a collaboration involving LLNL, LLE, and Rice University demonstrated the highest positron production rate ever achieved in the laboratory (Fig. 1).

FY09 Laser Facility Report

During FY09 the Omega Laser Facility conducted 1153 target shots on OMEGA and 349 target shots on OMEGA EP for a total of 1502 combined target shots (see Table IV). Twenty-four DT and 24 D_2 low-adiabat spherical cryogenic target implosions were conducted on OMEGA. Triple-picket pulse-shaping developments highlighted the ongoing development of

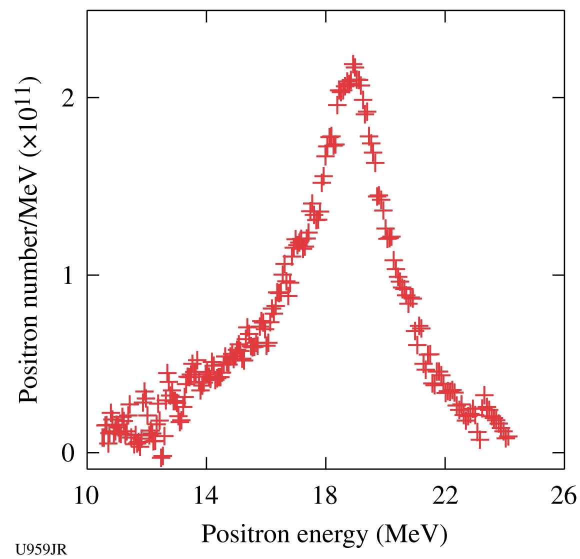

Figure 1
Positron spectrum measured on the OMEGA EP laser.

Table IV: OMEGA Facility target shot summary for FY09.

OMEGA Target Shot Summary					
Laboratory	Planned Number of Target Shots	Actual Number of Target Shots	NIC	Shots in Support of NIC	Non-NIC
LLE	476	488	68	420	0
LLNL	200	230	125	0	105
NLUF	145	165	0	0	165
LANL	85	93	3	0	90
LBS	70	73	0	0	73
CEA	45	51	0	0	51
AWE	30	35	0	0	35
U. Mich.	10	11	0	0	11
SNL	5	7	7	0	0
Total	1066	1153	203	420	530

OMEGA EP Target Shot Summary					
Laboratory	Planned Number of Target Shots	Actual Number of Target Shots	NIC	Shots in Support of NIC	Non-NIC
LLE	215	212	0	212	0
LLNL	40	42	16	0	26
NLUF	40	43	0	0	43
LBS	45	36	0	0	36
LANL	10	11	0	0	11
CEA/AWE	5	5	0	0	5
Total	355	349	16	212	121

direct-drive cryogenic implosion capability. A planar cryogenic platform to measure spherical shock timing was validated and used extensively to support spherical cryogenic experiments. A total of 31 planar cryogenic target shots were taken. The OMEGA Availability and Experimental Effectiveness averages for FY09 were 93% and 96%, respectively.

OMEGA EP was operated extensively in FY09 for a variety of internal and external users. A total of 298 short-pulse IR target shots were conducted. Of these, 212 target shots were taken on the OMEGA EP target chamber and 86 joint target shots were taken on the OMEGA target chamber. Beams 1 and 2 were activated to target in the UV, and the first four-beam UV target shots were conducted. A total of 76 OMEGA EP target shots included UV beams. OMEGA EP averaged 4.7 target shots per day with Availability and Experimental Effectiveness averages for FY09 of 90% and 97%, respectively.

Education

As the only major university participant in the National ICF Program, education continues to be an important mission for the Laboratory. Laboratory education programs span the range of high school (p. 214) to graduate education.

1. High School Student Program

During the summer of 2009, 16 students from Rochester-area high schools participated in the Laboratory for Laser Energetics' Summer High School Research Program. The goal of this program is to excite a group of high school students about careers in the areas of science and technology by exposing them to research in a state-of-the-art environment. Too often, students are exposed to "research" only through classroom laboratories, which have prescribed procedures and predictable results. In LLE's summer program, the students experience many of the trials, tribulations, and rewards of scientific research. By participating in research in a real environment, the students often become more excited about careers in science and technology. In addition, LLE gains from the contributions of the many highly talented students who are attracted to the program.

The program culminated on 26 August with the "High School Student Summer Research Symposium," at which the students presented the results of their research to an audience including parents, teachers, and LLE staff. The students' written reports will be made available on the LLE Web site.

Two hundred and forty-nine high school students have now participated in the program since it began in 1989.This year's students were selected from a record 80 applicants.

At the symposium LLE presented its 13th annual William D. Ryan Inspirational Teacher Award to Mr. Jeffrey Klus, a mathematics teacher at Fairport High School. This award is presented to a teacher who motivated one of the participants in LLE's Summer High School Research Program to study science, mathematics, or technology and includes a $1000 cash prize.

2. Undergraduate Student Programs

Approximately 60 undergraduate students participated in work or research projects at LLE this past year. Student projects include operational maintenance of the Omega Laser Facility; work in laser development, materials, and optical-thin-film–coating laboratories; computer programming; image processing; and diagnostics 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.

3. Graduate Student Programs

Graduate students are using the Omega Facility as well as other LLE facilities for fusion and high-energy-density physics research and technology development activities. These students are making significant contributions to LLE's research program. Twenty-five faculty from the five University academic departments collaborate with LLE scientists and engineers. Presently, 88 graduate students are involved in research projects at LLE, and LLE directly sponsors 37 students pursuing Ph.D. degrees via the NNSA-supported Frank Horton Fellowship Program in Laser Energetics. 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 fabrication technology, and target fabrication.

In addition, LLE directly funds research programs within PSFC–MIT, 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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