Executive Summary

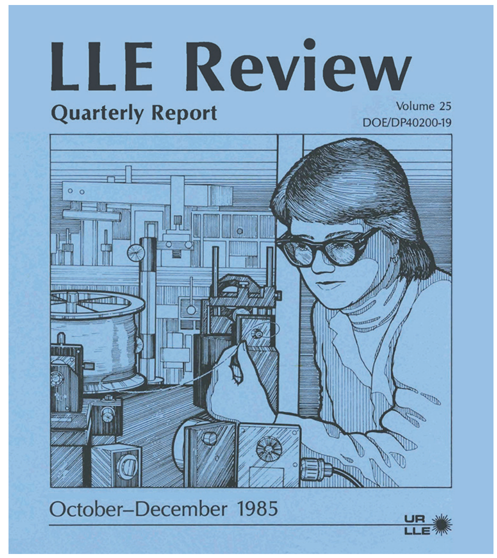

Figure 1
The cover illustration from 1985 depicts Donna Strickland, a graduate student at LLE, aligning a fiber optic in her laboratory while developing the chirped-pulsed–amplification technique to achieve high-peak-power pulses.

The federal fiscal year ending September 2018 (FY18) concluded the Cooperative Agreement DE-NA0001944 with the U.S. Department of Energy (DOE). This annual report summarizes work carried out under the Cooperative Agreement at the Laboratory for Laser Energetics (LLE) during the past fiscal year (FY18) including work on the Inertial Confinement Fusion (ICF) and High-Energy-Density (HED) science campaigns; laser, optical materials, and advanced technology development; operation of the Omega Laser Facility for the ICF and HED Campaigns, the National Laser Users' Facility (NLUF), the Laboratory Basic Science (LBS) Program, and other external users; and programs focusing on the education of high school, undergraduate, and graduate students. Of particular note during this past year was the award of the 2018 Nobel Prize in Physics to Donna Strickland and Gérard Mourou for their invention of chirped-pulse amplification (CPA) while working at LLE in the 1980s. CPA revolutionized laser science enabling amplification of ultrashort pulses by more than five orders of magnitude. This breakthrough is the basis of all modern ultrahigh-power laser systems including OMEGA EP, Lawrence Livermore National Laboratory's (LLNL) National Ignition Facility (NIF) Advanced Radiographic Capability (ARC) laser, the Extreme Light Infrastructure in Europe as well as thousands of small-scale pulse-compressed lasers in industrial and other applications. Donna Strickland was a graduate student at the University of Rochester's Institute of Optics at that time and Gérard Mourou had a joint appointment as Senior Scientist at LLE and a member of the faculty at The Institute of Optics. Strickland is only the third woman in history to receive the Noble Prize in Physics, joining Marie Curie (1903) and Maria Goeppert-Mayer (1963) and the only one educated in the United States. The Strickland and Mourou work of the 1980s was principally funded by the Cooperative Agreement with the DOE Office of Inertial Fusion active at that time. Figure 1 is a sketch of Donna Strickland working in her laboratory on the CPA technique that appeared on the cover of LLE Review 25, which reported on this discovery for the first time.

Inertial Confinement Fusion Research

One of LLE's principal missions is to conduct research in ICF with particular emphasis on supporting the goal of achieving ignition on the NIF. This program uses the Omega and NIF Laser Facilities and the full experimental, theoretical, computational, and engineering resources of the Laboratory. During FY18, 2319 target shots were taken at the Omega Laser Facility (comprised of the 60-beam OMEGA UV laser and the four-beam, high-energy petawatt OMEGA EP laser). Of the facility's 2319 target shots, 71.1% were designated for the ICF and HED Campaigns. LLE is the lead laboratory worldwide for the laser-direct-drive approach with research focused on cryogenic implosions on the 60-beam OMEGA laser and on laser–plasma interaction physics of importance to all laser-driven concepts at both the Omega and NIF facilities. LLE has also developed, tested, and constructed a number of diagnostics currently being used at both the Omega Laser Facility and on the NIF. During this past year, progress in the Inertial Fusion Research Program continued in three principal areas: ICF experiments and experiments in support of ICF; theoretical analysis and design efforts aimed at improving direct-drive–ignition capsule designs and advanced ignition concepts; and development of diagnostics for experiments on the NIF, OMEGA, and OMEGA EP Laser Systems.

1. Inertial Confinement Fusion Experimental Highlights in FY18

In a paper published just as this report was going to print [V. Gopalaswamy *et al.*, Nature **565**, 581 (2019)], we reported on a statistical approach that was used to design and quantitatively predict the results of implosions of solid deuterium–tritium targets carried out on the 30-kJ OMEGA Laser System, leading to tripling of the fusion yield to its highest value so far for direct-drive laser fusion. When hydrodynamically scaled to the laser energies of the NIF (1.9 MJ), these targets are predicted to produce a fusion energy output of ~500 kJ (see Fig. 2). This approach exploits the large database of OMEGA, and "machine learning" will guide the exploration of the vast parameter space of thermonuclear ignition conditions and enhance our understanding of laser-fusion physics.

In addition to the statistical model, it is important to understand the physics that limit the performance of laser-direct-drive implosions. A technique to identify trends in performance degradation based on reconstruction of the implosion core with a combination of low- and mid-mode asymmetries is described (p. 59). This technique was applied to the ensemble of hydro-equivalent deuterium–tritium implosions on OMEGA that achieved inferred hot-spot pressures of 56±7 Gbar.

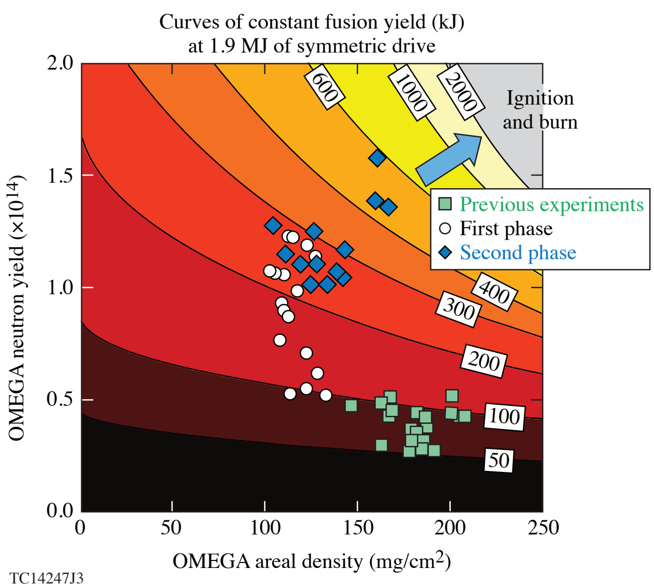

Figure 2
The results of the first (white circles) and second (blue diamonds) phases of the Optimization Campaign are compared with those of previous experiments (green squares) [S. P. Regan *et al.*, Phys. Rev. Lett. **117**, 025001 (2016); **117**, 059903(E) (2016)]. The black lines represent curves of constant extrapolated fusion yield for the symmetric laser drive of 1.9 MJ. The blue arrow shows the direction of future experiments. The increase in areal density and yield achieved using the framework presented in this paper results in implosions that would produce about 2×10^{17} fusion reactions, or 500 kJ of fusion energy, at NIF energies of ~1.9 MJ.

Recent results of experiments carried out on the Janus laser at the Jupiter Facility at LLNL on cross-beam energy transfer (CBET) are presented (p. 24). Wavelength tuning was used to vary the amount of energy transfer between two beams in a quasi-stationary plasma with carefully controlled conditions. The amount of transfer agreed well with calculations assuming linear ion-acoustic waves with amplitudes up to $\delta n/n \sim 0.015$. Increasing the initial probe intensity to access larger ion-acoustic wave amplitudes for otherwise fixed conditions yields evidence of saturation beyond this level. The ability to manipulate a beam's polarization, which results from the anisotropic nature of the interaction was also explored; an example is provided to demonstrate how polarization effects in a multibeam situation can dramatically enhance the expected amount of energy transfer.

The first direct measurement of nonlocal heat flux in laser-produced coronal plasma using Thomson scattering is reported (p. 125). Aluminum coronal plasma produced by six OMEGA beams was probed using Thomson scattering in regions of low- and high-temperature gradients. The measured Thomson-scattering spectra from electron plasma waves were fit with spectra calculated using non-Maxwellian electron distribution functions from Vlasov–Fokker–Planck simulations. The distribution functions are used to calculate the heat flux corresponding to the measurement points in the corona. The heat-flux calculations from both classical and nonlocal distributions agree well far from the target, where the temperature gradient and the ratio of electron–ion mean-free path to the temperature gradient length are small. The measured heat flux in the high-gradient region is reduced, however, from classical theory by as much as a factor of 2, indicating nonlocal effects.

To expand the physics opportunities with high-power lasers, a series of nuclear science experiments (p. 1) was conducted on OMEGA. The experiments used yields and energy spectra of neutrons from the D(n,2n)p reaction to study the breakup reaction measured at a forward angle of $\theta_{lab} = 3.5° \pm 3.5°$ using a sensitive, high-dynamic-range neutron time-of-flight spectrometer to infer the double-differential breakup cross section $d^2\sigma/dE d\Omega$ for 14-MeV D–T fusion neutrons.

A nuclear experiment platform was developed on the OMEGA EP short-pulse laser system. Energetic ions generated in the "converter" target via the target normal sheath acceleration process are sent through a secondary "physics" target in which nuclear reactions occur to produce neutrons and other charged particles (p. 182). First experiments to validate the performance of this setup studied the d(d,n)^{3}He and ^{9}Be(d,n)^{10}B reactions. This experimental platform is especially suitable for survey-type studies of nuclear reactions and for reactions involving rare or radioactive ions like tritium.

We also report on the measurement of rapid evolution of electron density and temperature in laser-produced underdense plasmas using collective Thomson scattering (p. 193). A pulse-front–tilt compensated streaked spectrometer enables one to measure picosecond time resolution with adequate spectral resolution of plasma-wave dynamics. The Thomson-scattering spectra were compared with theoretical calculations (BGK model) of the fluctuation spectrum. The measurements showed that the BGK model overestimates the spectral width of the electron plasma wave features, leading to an overestimate of the electron temperature by up to +50% at the most-collisional conditions. This overestimation of collisions by the BGK model has implications that extend well beyond Thomson scattering since this is an often-used collisional model in plasma physics, including modeling of thermal transport.

In FY18 the need to validate CBET modeling motivated the development of the tunable OMEGA P9 (TOP9) beam—an upgrade to the OMEGA EP laser that leverages the existing optical parametric amplification system in the short-pulse front end of Beamline 1 for spectrally broad amplification of a new, tunable, narrowband fiber front end. After amplification and frequency tripling, a new transport system image relays the beam to the P9 port of the OMEGA target chamber for joint operations with the OMEGA 60-beam laser (see Fig. 3). The beamline can deliver up to 0.5 TW in 1-ns-duration pulses with a wavelength that is tunable from 350.2 to 353.4 nm. Combined with the new gas-jet platform, TOP9 enables CBET experiments in large, uniform, quasi-stationary plasmas with open access to Thomson scattering for robust plasma characterization.

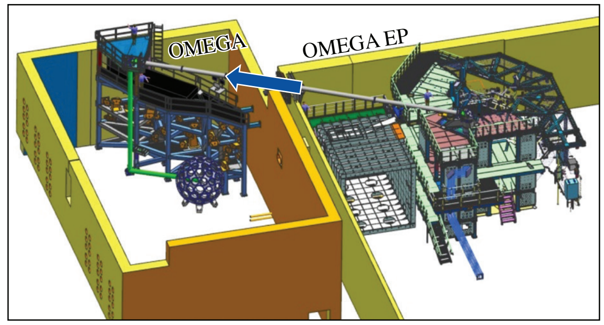

Figure 3
OMEGA EP Beamline 1, with a new wavelength-tunable front end, is transported to the P9 port of the OMEGA target chamber for joint operations.

Early experiments with this platform have tested the hypothesis that lead to non-Maxwellian electron distribution function required for CBET modeling, particularly for indirect-drive ICF. The idea that laser-plasma heating can distort the electron distribution function (EDF) away from the usual thermal Maxwellian (i.e., Gaussian) distribution and toward a higher-order super-Gaussian has been discussed for decades; however, no experimental validation existed in ICF-relevant conditions. Recent OMEGA experiments have found that when plasmas are heated in a manner that is similar to a hohlraum laser entrance hole, simultaneous electron- and ion-feature Thomson probing provides clear evidence for the presence of a super-Gaussian EDF of the order of $m = 3$ (see Fig. 4). In such plasmas, the ion-acoustic waves that mediate CBET oscillate at higher frequencies than they would in a Maxwellian plasma with equivalent thermal energy, which directly affects the coupled laser interactions. Preliminary TOP9 experiments have verified the impact of the non-Maxwellian distribution function on CBET. The expectation is that accounting for this effect will improve CBET modeling in both direct- and indirect-drive ICF, and that evidence of non-Maxwellian EDF's in ICF-relevant plasmas will spark interest in other potentially affected areas such as laser absorption and heat transport [R. K. Kirkwood *et al.*, Phys. Rev. Lett. **76**, 2065 (1996)].

In a joint experiment with Sandia National Laboratories (SNL), we studied scaling laser-driven magnetized liner inertial fusion (MagLIF) on OMEGA (p. 91). Considerable progress was made on the development of a laser-driven MagLIF platform for OMEGA during FY18. The predicted absence of window mix into the core was confirmed by placing a thin titanium layer on the back of the window and using MSPEC, an imaging spectrometer connected to a framing camera, to look for titanium line emission around peak compression, which was absent. Argon line emission, from a dopant in the gas and from dissolved air in the plastic shell, was measured and will be used to infer electron temperature. Dual magneto-inertial fusion electrical discharge systems (MIFEDS) were used for the first time, achieving an initial axial magnetic field up to 27 T, approaching the predicted optimal value. A magnetic field of 27 T increased yield in integrated shots by 26% compared to

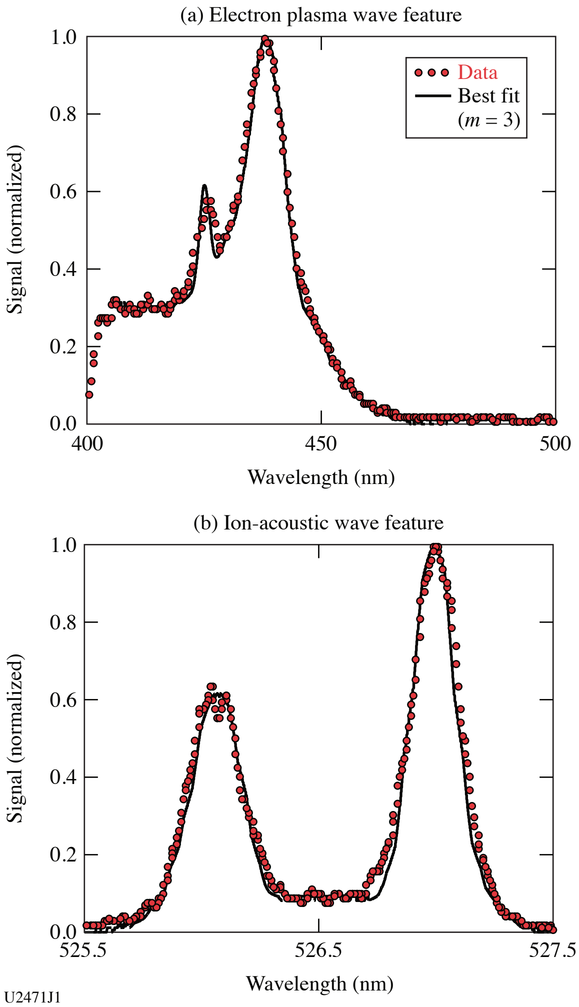

Figure 4
Fitting electron and ion-plasma wave features simultaneously requires a super-Gaussian electron distribution function of the order of $m = 3$, providing clear evidence of the non-Maxwellian electrons.

previous shots at 9 T. A preheat energy scan was carried out on integrated shots at 27 T, and the optimum preheat energy was found to be lower than expected; reducing the preheat laser energy from 170 J to 70 J doubled the yield. The best integrated shot now has a yield 5× higher than a typical compression-only shot. Without preheat, a magnetic field of 20 T or higher was found to reduce yield, indicating that there is an optimum magnetic field for yield enhancement, without preheat, of around 10 T. These results clearly confirm the benefit of combining preheat and magnetization, and show that higher magnetic field and lower preheat temperatures should be explored in the future.

2. Theoretical Design and Analysis

Computer simulations using a 3-D laser–plasma interaction code *LPSE* were carried out that indicate that laser frequency detuning can potentially be used to suppress the two-plasmon–decay (TPD) instability simulations (p. 35). For the plasma conditions and laser configuration in a direct-drive ICF implosion on the OMEGA laser, the simulations show that ~0.5% laser frequency detuning is sufficient to eliminate TPD-driven hot-electron generation in current experiments. This may allow for higher laser intensities in future implosion designs.

An improved ray-based modeling technique of CBET at caustics is presented (p. 131). The improvement, caustic gain truncation, is based on truncating the interaction length of incident rays in each cell using the geometrical caustic boundary information. This allows caustics to be treated more accurately and improves energy conservation. The new ray-based CBET calculations show excellent agreement with laser absorption from 2-D wave-based calculations (0.3% difference) and a 3-D 60-beam OMEGA implosion (2.4% difference) without artificial multipliers.

We also report on the reduction of resonance absorption of an incoherent infrared broadband pulse compared with a monochromatic pulse (p. 167). In the linear regime where the ponderomotive response of ions is neglected, bandwidth has little effect on resonance absorption; in the nonlinear regime, however, bandwidth suppresses enhanced absorption resulting from the electromagnetic decay instability. These simulations show that, regardless of bandwidth, an ICF implosion will confront at least linear levels of resonance absorption.

Direct-drive double-shell designs for ICF have been performed with the 2-D hydro code *DRACO* using the best physics models currently available. These simulations show that gradient-density inner shells are essential for igniting a double-shell target in which the outer shell can be driven at a very high adiabat ($\alpha \sim 8$ to 10). Furthermore, the simulations show that such designs could survive both laser-imprint and classical Rayleigh–Taylor (RT) instability growth, leading to the production of >3-MJ neutron yields with NIF energy of 1.9 MJ [S. X. Hu *et al.*, presented at the 60th Annual Meeting of the APS Division of Plasma Physics, Portland, OR, 5–9 November 2018].

A paper by Collins and Marozas [Phys. Plasma **25**, 072706 (2018)] presented two novel target designs for using direct drive on the NIF to ignite cryogenic fuel using the existing indirect-drive beam configuration. These are the first ignition-relevant "polar"-direct-drive target designs to include the physical effects of CBET between laser beams and nonlocal electron heat transport. One design is a moderate-adiabat, sub-ignition, alpha-burning design with a D–T neutron yield of 1.2×10^{17} while a second lower-adiabat design achieves a gain of 27.

3. Diagnostics

The design of an ultrafast x-ray streak camera for time-resolved studies of HED experiments is described beginning on p. 17. The streak camera's electro-optical imaging system features a polarity-reversible quadrupole doublet, allowing two imaging modes depending on the scientific mission needs. The streak camera's temporal impulse, detector efficiency, and linear dynamic range were qualified using a synchronized subpicosecond, 263-nm probe laser incident upon a gold photocathode. Dynamic testing shows a <2-ps impulse response in the fastest operating mode and a measured 400:1 dynamic range per resolution element in the high-dynamic-range mode.

A single-line-of-sight, time-resolved x-ray imager (SLOS-TRXI) has been developed and installed on OMEGA by a joint team including General Atomics, Kentech Instruments, LLNL, SNL, and LLE (p. 80). SLOS-TRXI is one of a new generation of fast-gated x-ray cameras comprising an electron pulse-dilation imager and a nanosecond-gated, burst-mode, hybrid complementary metal-oxide semiconductor (CMOS) sensor. SLOS-TRXI images the core of imploded cryogenic deuterium–tritium fuels in ICF experiments in the 4- to 9-keV photon energy range with a pinhole imager onto a photocathode. The diagnostic is mounted on a fixed port almost perpendicular to a 16-channel, framing-camera–based, time-resolved Kirkpatrick–Baez microscope, providing a second time-gated line of sight for hot-spot imaging on OMEGA. SLOS-TRXI achieves ~40-ps temporal resolution and ~10-μm spatial resolution. Shots with neutron yields of up to 1×10^{14} were taken without any hint of a neutron-induced background signal. The implosion images from SLOS-TRXI show the evolution of the stagnating core.

A Wollaston interferometer is now being used to measure the density of plasma plumes created in experiments on the OMEGA EP laser (p. 107). The diagnostic is installed as an additional arm on the 4ω probe system, a suite of diagnostics that share a 10-ps pulse of 263-nm laser light captured by an imaging system at *f*/4. The interferometer utilizes a Wollaston prism to create two angularly separated beams from a single input probe beam. Preliminary analysis has indicated that the interferometer allows the characterization of plasma density over a range of 3×10^{18} to 1×10^{20} cm^{-3} with a phase noise of approximately ± 0.4 rad. The unique advantages of this system over standard interferometric means are also discussed.

X-ray imaging using shaped crystals in Bragg reflection is shown to be a powerful technique that can be used in HED physics experiments (p. 113). The characterization of these crystal assemblies with conventional x-ray sources is very difficult because of the required angular resolution of the order of ~10 μrad and the narrow bandwidth of the crystal. The 10-J, 1-ps Multi-Terawatt (MTW) laser was used to characterize a set of Bragg crystal assemblies.

A new neutron time-of-flight diagnostic with an ultrafast instrument response function has been developed and fielded on the OMEGA laser in a highly collimated line of sight (p. 119). By using a small plastic scintillator volume, the detector provides a narrow instrument response of 1.7-ns FWHM while maintaining a large signal-to-noise ratio for neutron yields between 10^{10} to 10^{14}. The OMEGA Hardware Timing System is used with an optical fiducial to provide an absolute neutron time-of-flight measurement with a total neutron time-of-flight uncertainty of 84 ps. The fast instrument response enables one to accurately measure a primary-DT neutron peak shape, while the optical fiducial allows for an absolute neutron energy measurement.

4. Target Science and Technology

Conditions for forming defect-free deuterium-tritium ice layers in OMEGA-size fill tube targets were identified. Up to three days is required to form an ice layer with a root-mean roughness that is <0.7 μm, which is an upper bound defined by the resolution of the optical and x-ray cameras.

Design and construction of a new target delivery system for providing fill-tube targets for experiments on OMEGA is in progress. The system for housing and transporting the cryostat, and the configuration for characterizing the target (using optical and x-ray techniques) was assembled and is being tested. The design of the cryostat is complete and the components are being manufactured. Multiple concepts for the shroud retraction system subsystems were tested; the best-performing design demonstrated an impulse of 0.02 g to the base of the target support when the shroud was retracted at a constant acceleration of 0.33 g. The system is illustrated in Fig. 5 from a paper by Harding *et al.* [Fusion Sci. Technol. **73**, 324 (2018)].

Polystyrene shells being developed by General Atomics for use on OMEGA are substantially smoother than the current shells (glow-discharge polymer shells) used by the program. Work continues to address the one limitation with the target, which is the presence of submicrometer-size voids in the wall of the shell—an artifact of the manufacturing process.

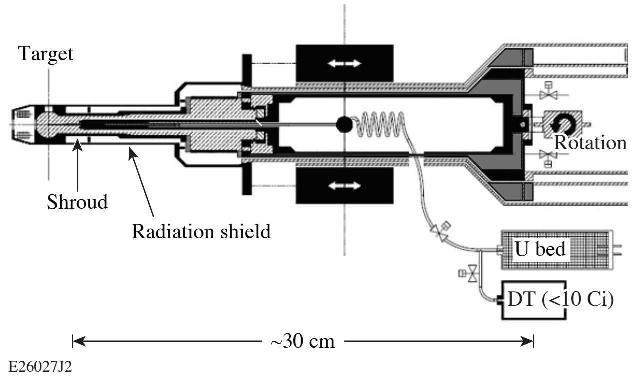

Figure 5
Schematic showing the target and DT gas supply positioned inside the cryostat. The thermal shroud (highlighted in black) protects the target from accumulating debris and provides the isothermal environment that is needed for forming the DT ice layer. The surrounding gray region represents the cryostat and linear induction motor.

New equipment that expands the characterization and fabrication infrastructure at LLE was commissioned this past year. These include: an electron microscope, a white light and laser interferometry and confocal microscope, an e-beam evaporator, and the ability to laser cut, 3-D print, and assemble targets using an optical coordinate measuring machine.

Understanding the interaction of tritium with native oxides on the surface of stainless steel is necessary for the development of surfaces that minimize tritium absorption and permeation through piping materials in tritium-handling systems. The distribution of tritium between the near surface and the bulk in 316 stainless steel has been investigated using two independent techniques: pulsed-plasma exposures and a zinc-chloride wash (p. 41). It was discovered that 17% to 20% of the total inventory absorbed into a stainless-steel sample after a 24-h exposure to DT gas at room temperature resides in the water layers present on the metal surface. Redistribution of tritium between the surface and the bulk of stainless steel, if it occurs, is very slow. Tritium does not appear to enter into the bulk at a rate defined by lattice diffusivity.

The increased tritium retention in a hexavalent chromate-conversion–coated (CCC) aluminum alloy is discussed beginning on p. 138. Both CCC and unmodified aluminum samples were exposed to DT gas for 24 h at room temperature to diagnose how these films interact with a tritium environment. After this exposure, samples were treated with either thermal desorption or a surface-stripping technique to measure the quantity of retained tritium. The results show that chromic-acid anodizing of aluminum dramatically increases the total quantity of tritium retained compared to unmodified aluminum. Because of the physical and chemical properties of CCC, these coatings are not suitable for use in tritium environments.

High-Energy-Density Science

During FY18, several HED science campaigns were conducted at the Omega Laser Facility. Most of these were carried out by LLNL, Los Alamos National Laboratory (LANL), SNL, and LLE scientists working under the HED Campaign and summaries are reported in **National Laser Users' Facility and the External Users' Programs** (p. 211). Some of the fundamental science HED physics experiments are carried out under the NLUF and LBS programs and are reported in high-impact journals such as Nature and Science (see **Publications**, p. 289).

The Thomas–Fermi model is used to describe the limiting pressure behavior of materials at extreme pressures. One of the predictions of this model is that at high enough pressure all materials become a metal and take on a simple dense packed structure. Several diffraction campaigns were carried out to explore the high-pressure structure of several important classes of materials (some for the Stockpile Stewardship Program and others for benchmarking theory) as well as their phase-transition mechanisms. New structural phases were discovered in several materials [D. N. Polsin *et al.*, Phys. Plasmas **25**, 082709 (2018) (invited)], some revealing a tremendous structural complexity. Moreover, this evolution of structure from simple to complex was able to happen in subnanosecond time scales—an observation not predicted by simple theory.

A technique to measure the sound speed of materials developed by Fratanduono *et al.* [Phys. Plasmas **26**, 012710 (2019)] was used to measure the sound speed in Fe to 20 Mbar, providing the highest-pressure sound-speed data yet taken.

A new x-ray spectrometer was developed and fielded [P. M. Nilson *et al.*, Bull. Am. Phys. Soc. **63**, BAPS.2018.DPP.GO4.5 (2018)], and used to measure the evolution of the He_α and He_β lines in Cu upon laser heating. High-pressure windows are integral to accurate equation-of-state and transport measurements in the HED regime. We extended refractive index measurements to several Mbar for key window materials (e.g., MgO).

Si is used as a dopant for ICF ablators but no data existed in the HED regime. We measured the Si Hugoniot to the TPa regime and it is being used to benchmark models in ICF design codes.

We present experimental data and simulation results of a study of direct laser acceleration (DLA) of electrons in a laser wakefield accelerator (LWFA) operating in the forced or quasi-blowout regimes (p. 46). When a significant overlap exists between the trapped electrons and the drive laser in a LWFA cavity, the resulting electrons can gain energy from both the LWFA and DLA mechanisms. Experimental work investigates the properties of the electron beams produced in a LWFA with ionization injection by dispersing those beams in the direction perpendicular to the laser polarization. These electron beams show certain spectral features that are characteristic of DLA. These characteristic spectral features are reproduced in particle-in-cell simulations, where particle tracking is used to elucidate the roles of LWFA and DLA to the energy gain of the electrons in this experimental regime and to demonstrate that such spectral features are definitive signatures of the presence of DLA in LWFA.

We have demonstrated the successful use of the flying focus technique that uses a chirped laser beam focused by a highly chromatic lens to produce an extended focal region within which the laser intensity can propagate at any velocity (p. 75). When that intensity is high enough to ionize a background gas, an ionization wave will track the intensity isosurface corresponding to the ionization threshold. We report on the demonstration of such ionization waves of arbitrary velocity. Subluminal and superluminal ionization fronts were produced that propagated both forward and backward relative to the ionizing laser. All backward and all superluminal cases mitigated the issue of ionization-induced refraction that typically inhibits the formation of long, contiguous plasma channels.

Lasers, Optical Materials, and Advanced Technology

High-energy UV sources are now required to probe hot dense plasmas, where deep UV probes provide a better penetration of the plasma [LLE Review Quarterly Report **153**, 12, Laboratory for Laser Energetics, University of Rochester, Rochester, NY, LLE Document No. DOE/NA/1944-1370 (2017)]. For fusion experiments, measuring Thomson scattering of 5ω pulses as a diagnostic technique is promising because there is less generated background from the plasma in the spectral regions of interest.

In collaboration with LLNL, the fifth-harmonic generation of a pulsed Nd:YLF laser in a cascade of nonlinear crystals with a 30% record efficiency has been demonstrated (p. 12). Cesium lithium borate is used in a Type-I configuration for sum–frequency mixing of 1053 nm and 266 nm, producing 211-nm pulses. Flattopped beam profiles and pulse shapes optimize efficiency. Energies up to 335 mJ in 2.4-ns pulses were demonstrated.

The effect of grating compressor misalignment in a CPA laser system is discussed (p. 143). The degradation of pulse duration and focal spot size is studied by increasing the grating tip/tilt and in-plane-rotation error. The tolerance analysis was calculated using a *FRED–MATLAB* optical compressor model. The grating-alignment tolerances are investigated for varying beam size, bandwidth, grating geometry, and groove density. Mitigation strategies for the misalignment effects are discussed.

A new rate-doubled, 10-GHz fiducial comb generator for precision optical timing calibration applications is described (p. 154). Solid-state optical comb-pulse generators provide a convenient and accurate method to include timing fiducials. A commercially available vertical-cavity surface-emitting laser (VCSEL) at 680 nm is modulated to 5 GHz and is optically interleaved with itself to generate a 10-GHz comb. The output pulse-to-pulse jitter ratio is <0.1-ps rms. This self-contained and portable unit will be useful for many optical timing calibration needs, especially for ultrafast streak-camera temporal calibration. Both internal reference frequency generation and external syncing options are available.

Three different types of damage-site morphology that capture thermomechanical signatures of the energy-release mechanism of laser-heated material under different damage-initiation conditions are identified (p. 160). These are related to whether the damage is defect driven or intrinsic, the location of the maximum electric-field intensity in the medium, and the laser pulse length. Mechanical or heat-diffusion models are adopted to describe the features of these damage sites. The test was performed on a high-reflecting dielectric coating comprised of SiO_2 and HfO_2 layers by varying the pulse width from 0.6 to 100 ps. Nano- to microscale features and the depth of the damaged sites were analyzed using various imaging modalities including atomic force microscopy. A high-spatial-resolution imaging system based on pump–probe and photon-counting techniques for detecting nanoparticles in a thin-film coating made of HfO_2 and SiO_2 layers is presented (p. 177). The system confirmed submicrometer spatial resolution in both absorption and luminescence imaging modes.

Omega Laser Facility Users Group

The Tenth Omega Laser Facility Users Group (OLUG) Workshop was held at LLE on 25–27 April 2018. It was attended by 130 researchers, including scientists, postdoctoral fellows (postdocs), and students (Fig. 156.38, p. 199). The attendees represented institutions from five countries, including the U.S., Canada, U.K., France, and Israel. As has been the case for previous workshops, postdocs and students received travel support to attend the workshop from DOE's National Nuclear Security Administration (NNSA). The Workshop included the presentations of invited talks highlighting four recent science experiments conducted at the Omega Laser Facility, a talk via web conferencing on the NNSA perspective by Acting ICF Program Director Dr. Njema Frazier, facility update and progress on OLUG Recommendations, facility tutorials on Optical Diagnostics at OMEGA, panel discussions on OLUG Findings and Recommendations, young researcher panel discussions, and three poster sessions comprising a total of 81 posters of which 63 were presented by graduate students, postdocs, and undergraduate students. Two additional posters were presented by high school students who had participated in LLE's 2017 Summer High School Research Program (p. 207). A summary of the OLUG Workshop is presented in an article starting on p. 199.

Education

As the only major university participant in the National ICF Program, education continues to be an important mission for LLE. The Laboratory's education programs cover the range from high school (p. 207) to graduate education.

1. High School Program

During the summer of 2018, 13 students from Rochester-area high schools participated in the LLE's Summer High School Research Program. This marks the 30th year of the program, which started in 1989. The goal of the program is to motivate 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 students spent most of their time working on their individual research projects with members of LLE's technical staff. The projects are related to current research activities at LLE and covered a broad range of areas of interest including computer modeling of implosion physics, experimental diagnostic modeling, cryogenic target characterization, physical chemistry, computational chemistry, laser beam modeling, laser flash-lamp diagnostics, web-based data analysis, and the adaptation of a technique developed to visualize laser damage to high-school life-science education (see Table 156.IV, p. 208).

The program culminated on 29 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 are available on the LLE website and bound into a permanent record of their work that can be cited in scientific publications.

Three hundred and seventy-seven high school students have now participated in the program. Two of this year's program participants, Maia Raynor and Anirudh Sharma, were named Scholars in the prestigious Regeneron Science Talent Search for research projects they carried out at LLE. Raynor investigated the use of a copper–zinc alloy to remove elemental hydrogen from air, providing a simplified method of reducing tritium emissions to the environment. Sharma carried out hydrodynamic simulations of a new "double cone-in-shell" target concept for an improved x-ray source on the NIF. A total of 38 students from the LLE program have now become Scholars since the program's inception in 1989. This year's students were selected from approximately 50 applicants.

2. Undergraduate Student Program

Approximately 40 undergraduate students participated in work or research projects at LLE this past year. Student projects included 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 go on to pursue a higher degree in the area in which they gained experience at LLE.

3. Graduate Student Program

Graduate students are using the Omega Laser Facility as well as other LLE facilities for fusion and HED physics research and technology development activities (see Table I). These students are making significant contributions to LLE's research program. Twenty-six faculty members from five University of Rochester academic departments collaborate with LLE scientists and engineers. In FY18, a total of 72 graduate students were involved in research projects at LLE. LLE directly sponsored 39 students pursuing Ph.D. degrees via the NNSA-supported Frank Horton Fellowship Program (Table I). Their research includes theoretical and experimental plasma physics, HED physics, x-ray and atomic physics, nuclear fusion,

Table I: University of Rochester Frank Horton Fellowship Program at LLE in FY18.

Student Name	Dept.	Faculty Advisor	LLE Advisor	Research Area	Status
M. B. Adams	PAS	P.-A. Gourdain		Numerical studies of ablation of DT fibers inside pulsed-power–driven imploding liners	
D. H. Barnak	PAS	R. Betti		Applications of magnetic fields in high-energy-density physics	Graduated (Postdoc researcher at LANL)
S. Bucht	PAS	D. H. Froula		Novel 1200-nm high-power laser beams for laser-plasma amplification	M.S. graduated (Sr. Lab. Engineer at LLE)
Z. Chen	PAS	A. Frank		Evolution of binary stars	
A. R. Christopherson	ME	R. Betti		Theory of alpha heating, burning plasmas, and ignition in inertially confined plasmas	Defending in 2019
L. Crandall	PAS	J. R. Rygg and G. W. Collins	T. R. Boehly	Equation of state of planetary fluids	
A. Davies	PAS	D. H. Froula	D. Haberberger	Investigation of collisional electron plasma waves and picosecond thermodynamics in a laser-produced plasma using Thomson-scattering spectroscopy	Defending in 2019
Y. Ding	ME	R. Betti	S. X. Hu	First-principles investigations on transport and optical properties of high-energy-density plasmas	
T. Eckert	PAS	P.-A. Gourdain	C. Forrest	Experimental nuclear physics	
M. Evans	PAS	P.-A. Gourdain		Experimental studies of ablation in magnetic anvil cells	
P. Franke	PAS	D. H. Froula		Control of ionization wave propagation with a flying focus	
J. M. Garcia-Figuero	CE	D. R. Harding		Manufacture of low-atomic-number nonpolymeric materials	
X. Gong	ME	G. W. Collins and J. R. Rygg		Structure and optical changes in ramp-compressed alkalais	
V. Gopalaswamy	ME	R. Betti		Applications of statistics and data science to direct-drive ICF design	
A. Hansen	PAS	D. H. Froula		Nonlinear cross-beam energy transfer physics	
R. J. Henchen	ME	D. H. Froula		Hydrodynamic gradients in under-dense plasmas	Graduated (Scientist at Harris Corp.)
B. J. Henderson	PAS	G. W. Collins and R. Rygg	T. R. Boehly	Optical properties of compressed matter deduced from reflectivity measurements	
G. W. Jenkins	OPT	J. Bromage		Broadband seed generation and amplification at high-average power	
A. Lees	ME	H. Aluie		High-performance code development	

Table I: University of Rochester Frank Horton Fellowship Program at LLE in FY18 (continued).

Student Name	Dept.	Faculty Advisor	LLE Advisor	Research Area	Status
W. Liu	ME	C. Ren		Magnetic fields and their effects on laser–plasma instabilities	Defending in 2019
O. M. Mannion	PAS	S. Y. BenZvi	C. J. Forrest and J. P Knauer	Moment analysis of neutron spectra	
A. L. Milder	PAS	D. H. Froula		Measurement of electron distribution function using collective Thomson scattering	
S. C. Miller	ME	V. N. Goncharov	P. B. Radha	Hydrodynamics of ICF implosions	
Z. L. Mohamed	PAS	D. H. Froula	J. P. Knauer	Gamma emission from fusion reactions	
D. Patel	ME	R. Betti	V. N. Goncharov	Hybrid direct–indirect drive for ICF	
R. Paul	ME	C. Ren	S. X. Hu	*Ab-initio* construction of high-pressure phase diagrams of materials	
D. N. Polsin	PAS	G. W. Collins	T. R. Boehly	Observation of a new high-pressure solid phase in dynamically compressed aluminum	Graduated (Scientist at LLE)
J. J. Ruby IV	PAS	G. W. Collins	J. R. Rygg	Equation-of-state measurements using convergent shocks	
R. Saha	PAS	J. R. Rygg and G. W. Collins	T. R. Boehly	Structure and transport of warm dense matter	
E. M. Schiesser	OPT	J. Rolland	S.-W. Bahk	Applying freeform optics to scalable, compact beamlines	Defending in 2019
A. Schwemmlein	PAS	W. U. Schroeder	J. P. Knauer	Thermonuclear fusion and breakup reaction between light nuclei	
K. A. Sharma	OPT	R. Brown and M. A. Alonso	J. D. Zuegel	351-nm characterization of scatter from distributed polarization rotator concepts for polar direct drive at the National Ignition Facility (NIF)	Graduated (Optical Engineer at LLE)
G. Tabak	PAS	G. W. Collins and J. R. Rygg	M. Zaghoo	Study of precompressed materials using shock compression	
N. D. Viza	CE	D. R. Harding		Integrated "lab-on-chip" micro-fluidic device for manufacturing foam targets	Graduated (Scientist at Merkel)
M. Wang	CE	D. R. Harding		Use of two-photon polymerization to "write" millimeter-size structures with micron resolution	
K. M. Woo	PAS	R. Betti		Three-dimensional ablative Rayleigh–Taylor instability	Defending in 2019
J.-C. Yang	CE	M. Anthamatten		Crystallization in shape-memory polymer networks	
D. Zhao	ME	H. Aluie		Analyzing multiscale physics of multimode and turbulent Rayleigh–Taylor hydrodynamics	
Y. Zhao	MS	W. R. Donaldson		Fabrication and testing of AgGaN photodiodes	Graduated (Engineer at SLD Laser)

ultrafast optoelectronics, high-power laser development and applications, nonlinear optics, optical materials and optical fabrication technology, and target fabrication. Many of LLE's alumni now fill responsible positions at the national laboratories, industry, academia, and government.

LLE also directly funds research programs within the Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center, the University of Michigan, the University of Nevada at Reno, and the State University of New York (SUNY) at Geneseo. These programs involve a total of approximately 9 graduate students, 29 undergraduate students, and 8 faculty members. A total of 362 graduate students have now conducted their research work at LLE since the program began.

In addition, 182 graduate students and post-graduate fellows from other universities have conducted research at the Omega Laser Facility as part of the NLUF and LBS programs. Thirty-four graduate students (Table 156.VIII, p. 213) were involved in NLUF research programs in FY18.

FY18 Omega Laser Facility Operations

During FY18, the Omega Laser Facility conducted 1441 target shots on OMEGA and 878 target shots on OMEGA EP for a total of 2319 target shots (see Tables 156.V and 156.VI, p. 209). OMEGA averaged 12 target shots per operating day with 95.0% Experimental Availability (EA) and 96.5% Experimental Effectiveness (EE).

OMEGA EP was operated extensively in FY18 for a variety of user experiments. A total of 833 target shots were taken into the OMEGA EP target chamber and 45 joint target shots were taken into the OMEGA target chamber. OMEGA EP averaged 8.3 target shots per operating day with 95.8% EA and 96.3% EE.

Per the guidance provided by DOE/NNSA, the facility provided target shots for the ICF, HED, NLUF, and LBS programs. The facility also provided a small number of shots for Commissariat à l'énergie atomique et aux energies (CEA), Centre Lasers Intenses et Applications (CELIA)/University of Bordeaux, Rutherford Appleton Laboratory/York University (RAL/York), and ARPA-E (Advanced Research Projects Agency–Energy) programs (see Figs. 6 and 7). The ICF and HED programs received 71.15% of the facility shots in FY18.

Details of this work are contained in an article beginning on p. 209.

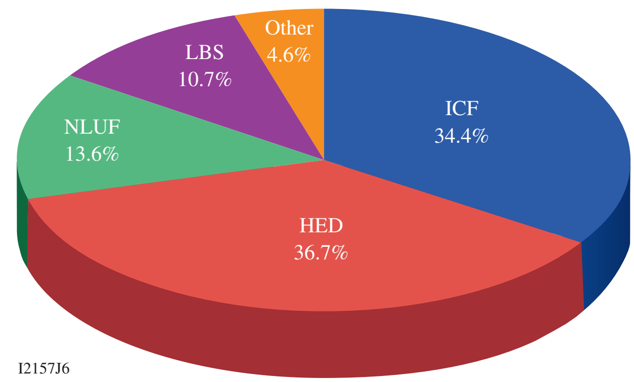

Figure 6
Omega Facility Users by program in FY18.

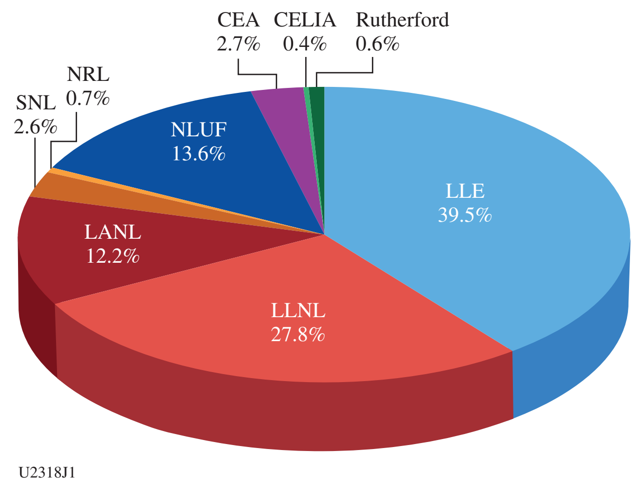

Figure 7
Institutional distribution of Omega Facility use in FY18.

National Laser Users' Facility and External Users' Programs

Under the facility governance plan implemented in FY08 to formalize the scheduling of the Omega Laser Facility as an NNSA User Facility, Omega Laser Facility shots are allocated by campaign. The majority (71.1%) of the FY18 target shots were allocated to the ICF Campaigns conducted by integrated teams from LLNL, LANL, Naval Research Laboratory (NRL), SNL, and LLE, as well as the HED Campaigns conducted by teams led by scientists from the national laboratories, some with support from LLE.

The Fundamental Science Campaigns accounted for 24.3% of the Omega Laser Facility target shots taken in FY18. Nearly 60% of these shots were dedicated experiments led by U.S.

academia and businesses under the NLUF Program, and the remaining shots were allotted to the LBS Program, comprising peer-reviewed fundamental science experiments conducted by the national laboratories and LLE.

The Omega Laser Facility was also used for several campaigns led by teams from CEA of France, the University of Bordeaux of France, and the joint RAL/York of the United Kingdom. These externally funded experiments are conducted at the facility on the basis of special agreements put in place by UR/LLE and participating institutions with the endorsement of DOE/NNSA.

The facility users during this year included 13 collaborative teams participating in the NLUF Program; 15 teams led by LLNL, LANL, and LLE scientists participating in the LBS Program; many collaborative teams from the national laboratories and LLE conducting ICF experiments; investigators from LLNL, LANL, and LLE conducting experiments for HED physics programs; and scientists and engineers from CEA, the University of Bordeaux, and RAL/York.

1. FY18 NLUF Program

FY18 was the second of a two-year period of performance for the 13 NLUF projects (Table 156.VII, p. 212) approved for FY17–FY18 funding and Omega Laser Facility shot allocation. A total of 293 target shots were taken for NLUF projects during FY18. Summaries of the FY18 NLUF experiments are presented beginning on p. 211.

A critical part of the NLUF Program is the education and training of graduate students in HED and plasma physics. During the year, 34 graduate students from ten universities participated in experiments conducted under the NLUF Program at the Omega Laser Facility (Table 156.VIII, p. 213). Ten graduate students trained under the Omega Science Program (NLUF and LBS) successfully defended their Ph.D. theses in 2017/2018 (Table 156.IX, p. 214).

2. FY18 LBS Program

Fifteen LBS projects previously approved were allocated Omega Laser Facility shot time and conducted a total of 231 target shots in FY18 (see Table 156.X, p. 231). Summaries of the FY18 LBS experiments are presented beginning on p. 231.

During FY18, LLE issued a solicitation for LBS proposals for beam time in FY19. A total of 39 proposals were submitted, 40% more than the previous year, showing strong interest and high demand of Omega Laser Facility time for Fundamental Science experiments from both NNSA ICF laboratories (LLNL, LANL, SNL, NRL, and LLE) and the Office of Science–funded national laboratories such as SLAC and Princeton Plasma Physics Laboratory (PPPL). An independent committee reviewed and ranked the proposals; on the basis of these scores, 20 proposals were selected in the first round and allocated 21.5 shot days at the Omega Laser Facility in FY19. With the FY19–FY20 NLUF solicitation being delayed (no DOE solicitation in FY18), six additional LBS proposals (based on their scores) were allocated six shot days to partially replace the eight shot days in Q3FY19 that were originally reserved for new NLUF experiments. One of those six LBS proposals was also recategorized as an ICF experiment following the LBS Review Committee's recommendation. Table 156.XI (p. 232) lists the approved FY19 LBS projects with a total allocation of 26.5 shot days at the Omega Laser Facility.

3. FY18 LLNL Omega Experimental Programs

In FY18, LLNL's HED Physics and Indirect-Drive ICF (ICF-ID) Programs conducted numerous campaigns on the OMEGA and OMEGA EP Laser Systems. This was the 20th year of national laboratory collaborative experiments at Omega since the Nova Laser at LLNL shut down in 1999, building upon prior collaborations. Overall, these LLNL programs led 465 target shots, with 283 shots using only the OMEGA laser, 172 shots using only the OMEGA EP laser, and 10 shots using both lasers jointly. Approximately 28% of the total number of shots (60 OMEGA shots and 71 OMEGA EP shots) supported the ICF-ID Campaign. The remaining 72% (223 OMEGA-only shots, 101 OMEGA EP-only shots, and 10 joint shots) were dedicated to experiments for HED physics. Highlights of the various HED and ICF-ID Campaigns are summarized beginning on p. 246. In addition to these experiments, LLNL Principal Investigators led a variety of LBS program experiments. In total, LLNL scientists led 603 target shots at the Omega facility in FY18. Summaries of the LLNL experiments begin on p. 246.

4. FY18 LANL Experimental Campaigns

In FY18, Los Alamos National Laboratory carried out 21 shot days with a total of 239 target shots on the OMEGA and OMEGA EP Laser Systems in the areas of HED science and ICF. The focus areas were on radiation flow, hydrodynamic turbulent mix and burn, and coupled Kelvin–Helmholtz (KH)/Richtmyer–Meshkov (RM) instability growth including convergent geometry. Several shot days also focused on transport properties in the kinetic regime as neutron imaging and performed tests of a new imaging concept to be installed on the NIF. Experiments were executed in support of the double-shell campaign, and initial experiments were started using the new *Revolver* triple-shell design platform. Summaries of the LANL experiments begin on p. 275.

5. FY18 NRL Experiments

During FY18, NRL in collaboration with LLE executed two shot days on OMEGA EP. Using an x-ray prepulse, the OMEGA EP experiments determined the minimum high-*Z* coating thickness (300 Å Pd) as well as the minimum expansion time (6 ns) needed for imprint reduction (Fig. 156.167, p. 285). This information is being used to design OMEGA spherical target experiments. The OMEGA EP experiments also investigated whether an unsmoothed laser prepulse could be used to pre-expand the high-*Z* coating for imprint suppression. These shots showed persistent laser imprint despite a range of coatings and prepulse parameters tested. This result indicates that smoothing by spectral dispersion will be necessary for the OMEGA experiments utilizing a laser prepulse.

6. FY18 RAL/York Experiments at Omega

The goal of this work was to characterize laser–plasma interactions and the resulting hot electrons at intensities relevant to shock ignition (1×10^{15} to 10^{16} W/cm^2) in the ablation plasma conditions anticipated to occur in NIF direct-drive implosions (500-μm density scale length, ~4-keV electron temperature). Simulations indicated this was not possible with a planar target with resulting density scale lengths of the order of 250 μm; however, by using a new experimental platform (Fig. 156.168, p. 285) that employs a novel open-cone geometry target in combination with beam repointings, ablation plasma conditions of 500-μm density scale length and 2.8-keV electron temperature were established at the point when the high-intensity beams switched on. Simulations indicate the high-intensity beams reached a peak incident intensity of 8.5×10^{15} W/cm^2, with the intensity at a quarter critical of 6×10^{15} W/cm^2. This raised the electron temperature to 3.5 keV. A brief report on this work appears on p. 285.

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