Executive Summary

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The Laboratory for Laser Energetics (LLE) is funded primarily by the U.S. Department of Energy (DOE) National Nuclear Security Administration's (NNSA's) Office of Experimental Sciences Inertial Confinement Fusion (ICF) Program through a five-year Cooperative Agreement. The fiscal year ending September 2021 (FY21) comprised the third year of LLE work under DOE/NNSA Cooperative Agreement No. DE-NA0003856. The New York State Energy Research Development Authority (NYSERDA) and other federal agencies including the DOE Office of Science (Fusion Energy Sciences), Advanced Research Projects Agency–Energy (ARPA-E), and the National Science Foundation (NSF) also sponsor work at the Laboratory.

In all cases, high-quality science and technology advances were delivered while maximizing impact to our sponsors. This annual report summarizes work conducted at LLE during FY21 and includes research on the 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 including the newly established LaserNetUS supported by the DOE Office of Fusion Energy Sciences (FES); and programs focusing on the education of high school, undergraduate, and graduate students. Most of this work has been submitted to and accepted by scientific journals and is also therefore covered in the 128 peer reviewed journal papers in 2021.

Inertial Confinement Fusion Research

ICF is one of the principal missions of the Laboratory. ICF research supports the NNSA goal of achieving fusion ignition and determining what capabilities are needed to achieve ignition and then be ready for future capabilities to achieve 100-MJ fusion outputs. The NNSA program uses the Omega Laser Facility, the National Ignition Facility (NIF), and the full experimental, theoretical, computational and engineering resources of the Laboratory. By taking advantage of remote operations throughout FY21, the Omega Laser Facility (comprised of the 60-beam OMEGA UV laser and the four-beam, high-energy petawatt OMEGA EP laser) performed 2098 individual target experiments. The ICF and HED campaigns accounted for 67% of the facility shots.

LLE is the lead laboratory worldwide for the laser-direct-drive approach to fusion ignition with research focused on cryogenic DT implosions on the 60-beam OMEGA laser and on laser–plasma interaction physics of importance to all laser-driven ignition concepts at both the Omega and the 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 the past year, progress in the ICF Program continued in three principal areas: (1) ICF cryogenic DT implosion experiments on OMEGA and focused physics experiments in support of ICF on OMEGA, OMEGA EP, and the NIF; (2) design efforts aimed at improving direct-drive implosion performance and the development of advanced ignition concepts such as magnetized implosions; and (3) the development of diagnostics for experiments on the NIF, OMEGA, and OMEGA EP Laser Systems. This annual report includes the summaries published in the LLE Review (Quarterly Reports) on LLE research performed during FY21 in these areas. Twenty-seven of the summaries highlighted in the report concern research on various aspects of ICF by LLE scientists and external Omega users including:

- polar-direct-drive (PDD) exploding-pusher experiments on the NIF;

- unabsorbed light measurements on OMEGA using the gated optical imagers;

- mode-one drive asymmetries in OMEGA implosions due to beam mispointing;
- the Bayesian inference technique to infer hot-spot plasma conditions and uncertainties;
- density functional theory to calculate more-accurate values for the ionization state and index of refraction in the partially ionized material that is released after shock breakout;
- progress enabled by the collaboration between LLE and General Atomics;
- pentagonal prism hohlraums as a test bed for high-symmetry ICF experiments;
- the impact of 3-D ρR asymmetries on the generalized Lawson criterion;
- hydrodynamic modeling to infer the degree of fuel–shell mixing near stagnation;
- extended-magnetohydrodynamic models that include both nonlocal suppression of Biermann battery field generation and radiation transport;
- the suppression of self-generated magnetic fields in a cylindrical implosion;
- the comparison of the laser model *IFRIIT* to direct-drive implosion experiments;
- scaling laws for higher adiabat fusion yields on OMEGA;
- a comparison of shock release in radiation-hydrodynamic models to laser-driven CH shell data;
- hot-electron source characterization and shock dynamics relevant to shock ignition;
- a comparison of plasma-jet interactions at 11.7 and 116 GPa;
- a demonstration of species separation during CH shock release;
- a correlation of scattered-light nonuniformity with polarization smoothing on OMEGA;
- quantification of shell decompression from the imprint-seeded Rayleigh–Taylor instability;
- a demonstration that the dominant instability in NIF-scale ablation plasmas relevant for shock ignition is convective stimulated Raman scattering (SRS);
- a demonstration of SRS and preheat mitigation using mid-Z layers in an ablator;
- a description of thermal decoupling in deuterium and tritium in OMEGA and NIF implosions;
- a demonstration of increased energy coupling using the SG-650 distributed phase plates;
- a proposal of using spin-polarized fuels for fusion-based spacecraft propulsion systems;
- a demonstration that electron-temperature profile measurements are in good agreement with *HYADES* predictions;

- a demonstration of increasing convergence ratio in simulations of dynamic in-flight shell formation using an extended series of picket pulses; and
- performance predictions of a new cryogenic DT target design using thin-ice DT liners.

Plasma and Ultrafast Science

Theoretical and experimental plasma physics and ultrafast science including the generation of more powerful, efficient, and compact radiation sources (high-energy photons and directed particle beams) for use as advanced probes underlies much of the ICF and HED mission science supported by NNSA, LLE, and the National Laboratories. In addition, understanding the interaction of intense laser fields with plasmas can significantly enhance ICF designs and experiments. Fifteen of the summaries highlighted in this report concern research on various aspects of plasma physics and ultrafast science by researchers at LLE including:

- measurements of cross-beam energy transfer (CBET) saturation;
- calculations of absolute thresholds for SRS and two-plasmon–decay instabilities;
- the development of an analytic approach to the reflection and transmission of light at a temporal boundary inside of a dispersive medium;
- a description of a laser-plasma accelerator with an electron charge exceeding 700 nC and conversion efficiencies up to 11%;
- the nonlinear saturation of CBET using vector particle-in-cell (VPIC) simulations;
- the collimation of a relativistic charge neutral electron–positron beam using the MIFEDS (magneto-inertial fusion electrical discharge system);
- the use of Thomson scattering to measure plasma conditions and distribution functions;
- a description of magnetized plasma experiments on the Zebra pulsed-power machine;
- the use of shaped space–time and transverse intensity profiles to drive optical shocks for self-photon acceleration;
- a description of nonlinear Thomson scattering with ponderomotive control;
- a simulation of the kinetics of magnetized collisionless shock formation;
- analytical scaling laws for the radiative properties of magnetic filaments;
- deriving a scale-dependent turbulent magnetic Prandtl number using magnetohydrodynamic simulations;
- a demonstration of triton beam production using target normal sheath acceleration; and
- cross-phase modulation to produce "flying-focus" spatiotemporally shaped pulses.

High-Energy-Density Physics

High-energy-density physics (HEDP) is the study of matter at extreme conditions. Understanding HED conditions, often defined as an energy density (in pressure units) in excess of 1 Mbar (at high temperature), is foundational for ICF ignition and national nuclear security (weapons physics) in a broad range of temperatures. These conditions are also ubiquitous in the universe and lead to basic science experiments at the Omega Laser Facility that include the study of star formation and stellar interiors, primordial magnetic fields and reconnection, giant planets and exoplanets (including those in the solar system), supernovae explosions, and unique chemistry. LLE has a leading role in the national HEDP Program with the work carried out (often, in collaboration with scientists from the national laboratories) by LLE scientists and graduate students. This report presents eight summaries of the work by LLE including:

- equation-of-state measurements of CO_2 up to 800 GPa;
- using density functional theory (DFT) to determine stable high-pressure carbonaceous sulfur hydride compounds and their critical temperature for superconductivity;
- a novel free-energy DFT-based methodology for calculating x-ray absorption in warm dense plasmas;
- equation-of-state measurements of CO_2 up to 800 GPa;
- the metastability of the liquid-to-ice VII phase transition;
- the observation of the *hP4* phase of sodium at 480 GPa;
- large-scale *ab initio* molecular-dynamics simulations to understand the subcritical character of the insulator–metal transition in warm dense liquid hydrogen; and
- an improved first-principles equation of state for deuterium.

Diagnostic Development

Better science/understanding comes from better measurements. Therefore, advanced diagnostic research and development is a core mission at LLE. The work is part of the general education mission at LLE and is often part of the thesis work of both internal and external graduate students (and a popular topic at the annual Omega Laser Users Group workshops). As a national priority, diagnostic development is managed by the National Diagnostics Working Group that includes experts from all of the national laboratories, LLE, and a number of academic institutions. There are five research summaries on diagnostics work in this Report including:

- a transmitted beam diagnostic for diagnosing the time-resolved power spectrum of the wavelength-tunable TOP9 beam on OMEGA;
- a technique for reconstructing the hot-spot velocity, apparent ion temperature, and areal density in ICF implosions using neutron spectroscopy;
- a forward-fitting technique for analyzing neutron time-of-flight spectra;
- a description of the new scattered-light time-history diagnostic (SLTD) on the NIF; and
- a new generation of fast UV photodiodes using $Al_xGa_{1-x}N$ substrates.

Laser System Science

Safe, efficient, and effective operation of the Omega Laser Facility requires a dedicated team of scientists and engineers that can solve the various challenges presented by the operation of ultrahigh-power laser systems at their performance limits. This Report contains a summary of research on the optical characterization of OMEGA laser beams at target chamber center using the updated full-beam in-tank diagnostic (FBIT). FBIT is capable of accurate measurements of the beam-to-beam focal-spot variation in target-plane fluence. This year the dynamic range of the focal-spot diagnostic was increased tenfold, improving the ability to answer longstanding questions of on-target uniformity. An additional capability, implemented in FY21, allows FBIT to capture the wavefront of the pulsed UV beams at chamber center. Data sets will be acquired on many of the OMEGA beams with this new capability in FY22.

Laser Technology and Development

Laser technology and development (LTD) is a primary technical mission for LLE (along with ICF/HED science, education/training, and facility operations). The generation of a 100-J broadband 3ω laser to confirm computational predictions of laser–plasma instability mitigation is highly anticipated by NNSA as broadband and is likely to be a key part of the technical design for the construction of a high-yield (nominally 100-MJ) facility in the 2040–2050 time frame. LLE is also developing technology for the generation of ultra-intense lasers (tens to 100 PW) using the Multi-Terawatt (MTW) Laser System and submitted an RI-1 proposal to NSF at the end of FY21 to provide resources to solve the remaining technical questions and design an EP-OPAL (OMEGA EP optical parametric amplifier line) Laser System. LLE will be resubmitting a modified proposal to NSF in 2022. EP-OPAL will be a laser both to advance fundamental science and to create new diagnostics and platforms for NNSA stewardship research. There are 12 research summaries spanning laser technology and development in this Report including:

- developing a novel two-wavelength phase-matching technique for measuring the deuteration level of partially deuterated KPD crystals;
- achieving high-efficiency fifth-harmonic generation in large-aperture ADP crystals;
- developing a method for laser wavefront phase retrieval in the presence of chromatic aberrations;
- demonstrating high-efficiency (37%) optical parametric chirped-pulse amplification on the MTW Laser System using large-aperture DKDP crystals;
- developing a novel sum-frequency generation technique for broadband frequency conversion;
- developing a frequency-domain transfer-matrix approach to solving temporal reflection and refraction with finite rise time;
- calculating a temporal analog of a Fabry–Perot resonator;
- demonstrating first light on the MTW-OPAL (MTW optical parametric amplifier line) Laser System;
- deriving an analytical model for angular alignment tolerance in divided-pulse nonlinear compression;
- the design and capabilities of the MTW laser at LLE;
- analytic phase solutions for three-wave interactions showing the signal beam has a pump-beam intensity-dependent phase profile; and
- an experimental demonstration of divided-pulse nonlinear compression.

Optical Materials Science

A strong materials science effort underpins laser facility operations/engineering and the laser development and technology efforts at LLE. The work involves materials research and characterization, optical surface preparation (polishing, etching, figuring and cleaning) and optical surface laser-damage evaluation. This report includes the following two summaries of materials science research at LLE:

- laser-induced–damage testing of silica and hafnia monolayers; and
- electric-field enhancement simulations that show particles as small as 1/4 the laser wavelength can induce field strengths exceeding coating design parameters.

Omega Laser Facility Operations

Under the facility governance plan, experimental time at the Omega Laser Facility is allocated to four NNSA-supported programs: ICF, HED, NLUF, and LBS. FY22 will be the final year under these programs; beginning in FY23 the allocation will be determined by the combined HED Council per guidance from the NNSA Office of Experimental Science. During FY21, the Omega Laser Facility conducted 1221 target shots on OMEGA and 877 target shots on OMEGA EP, with a total of 2098 target shots (see Fig. 1 for the fractional use by the various programs including shot time that is purchased by outside users). OMEGA investigators rated the overall experimental effectiveness of the facility at 93.9% while OMEGA EP was rated at 94.2%. The ICF and HED Programs conducted 67% of the NNSA-supported facility shots in FY21. Nearly half of these experiments were conducted by scientists from Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), Sandia National Laboratories, and the Naval Research Laboratory. About 5% of the facility shots were used to maintain operational effectiveness. The NLUF and LBS programs described below conducted 33% of the NNSA target shots. The facility also delivered 181 shots (~9% of the total) for external users who purchased the shot time. Overall, externally led investigators used 57% of the facility time.

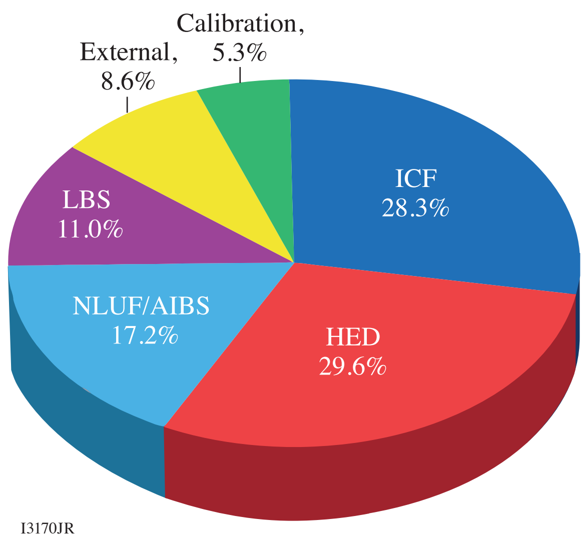

Figure 1
Fractional breakdown of FY21 shots at the Omega Laser Facility by NNSA supported programs.

The remote PI system was available to users on both laser facilities throughout FY21. Neither the effectiveness nor the availability of the facilities was compromised by remote PI operations. This Report includes quarterly summaries of the facility operations and a detailed summary of the Remote PI development and implementation.

Fundamental Science and External Users' Programs

The NNSA-supported Fundamental Science Program at the Omega Laser Facility is allocated target shot days, with individual campaigns selected through a well-defined open-call and peer-reviewed process. The Fundamental Science program has two components: (1) the NLUF Program (biennial call) makes shot time awards for the Omega Laser Facility to principal investigators (PI's) at U.S. academic institutions and commercial companies [note: a special one-time Academic and Industrial Basic Science (AIBS) Program was created to provide shot opportunities in FY20–FY21 with beam time from the unassigned NLUF allocation]; and (2) the LBS Program (annual call) makes shot time awards for basic science experiments conducted by NNSA (including LLE) and Office of Science laboratories.

Education and graduate student training is an important aspect of the NLUF and the DOE Office of Fusion Energy sponsored LaserNetUS programs (shot time is purchased for the LaserNetUS projects). Graduate student education and training at the Omega Laser Facility is also possible through collaborations between the national laboratories and academic partners and LLE. There were 66 graduate students from 20 universities involved in external user-led research programs at the Omega Laser Facility (see Table I in **National Laser Users' Facility and External Users' Programs**, p. 256).

FY21 was the second year of a two-year period of performance for eleven NLUF grant projects and ten AIBS beam-time awards with Omega shot allocations (see Table I in the **FY21 National Laser Users' Facility Program**, p. 259). PI's performed 360 target shots during 17 NLUF/AIBS campaigns, accounting for 17% of the overall Omega Laser Facility shots.

In FY21, 22 LBS projects were allocated 23 shot days for experiments at the Omega Laser Facility along with five LBS shot days that were postponed in FY20 due to COVID-19 restrictions. The initial COVID guidance caused Omega to suspend operations for two months to adjust to a new operational model. Scientists from LLNL, LANL, LLE, and Lawrence Berkeley National Laboratory conducted ~230 target shots (11% of the total) for 21 LBS projects (see Table I in the **FY21 Laboratory Basic Science Program**, p. 295).

During FY21, LLE issued a solicitation for LBS proposals for shot time in FY22. Twenty-seven proposals were submitted, requesting 36 shot days, more than double the NNSA allocation for the LBS program. After review, 15 proposals were selected and allocated 15.5 shot days for experiments at the Omega Laser Facility (see Table II in the **FY21 Laboratory Basic Science Program**, p. 297).

Through a coordinated call for proposals and an independent Proposal Review Panel (PRP) process, the FES-funded LaserNetUS network makes available a variety of ultrafast, high-peak-power and high-energy petawatt-class lasers (including the OMEGA EP laser) to users who do not have routine access to ultrahigh-intensity lasers. During FY21, six LaserNetUS Cycle-3 proposals along with one LaserNetUS Cycle-2 project were awarded nine shot days on OMEGA EP for experiments in FY21 and FY22 (see Table I in the **FY21 LaserNetUS Program**, p. 323). Scientists from LLNL, General Atomics, and the University of California, San Diego conducted 29 target shots over four shot days in FY21 for three LaserNetUS projects.

Since FY21, the newly established Center for Matter at Atomic Pressures (CMAP) hosted at the University of Rochester and funded by the National Science Foundation (NSF) has been using the Omega Laser Facility for experiments to explore "matter under the uncharted, extreme conditions at which most of the known mass in the universe resides." CMAP is the first NSF Physics Frontier Center in the field of HED science. Members of the CMAP team from UR, Massachusetts Institute of Technology (MIT), Princeton University, the Universities of California at Berkeley and Davis, the University of Buffalo, and LLNL conducted 66 target shots on OMEGA and OMEGA EP in FY21.

Omega Laser Facility Users Group

LLE hosted the 12th meeting of the Omega Laser Facility Users Group (OLUG) on 27–30 April 2021. The three-day virtual meeting smashed the attendance record that had been previously space limited for in-person meetings at LLE with registered attendees including 217 students and scientists from 40 institutions around the world. The enhanced international participation was reflected in the poster session where three of the six best poster prizes in the graduate student and post-doctoral categories were won by international participants. The highlight of the meeting (at least for the LLE management) was the identification and discussion of Findings & Recommendations (F&R's) to enhance Omega Laser Facility capabilities and experimental preparations/operations. The 29 F&R's include expanded ten-inch manipulator (TIM) access to active shock breakout (ASBO)/streaked optical pyrometer (SOP) and the addition of an optical Thomson-scattering diagnostic on OMEGA EP, improved navigation on the Diagnostics Usage page on the LLE website, the addition of a time-resolved x-ray history diagnostic for high-neutron-yield environments, a third VISAR (velocity interferometer system for any reflector) leg, and opposing UV beams on OMEGA EP. Professor M. Koepke (University of W. Virginia), the outgoing OLUG chair, welcomed the new chair J. A. Frenje (MIT) and co-chair P. Valdivia (Johns Hopkins University) for two-year terms. This Report contains a summary of the FY21 OLUG workshop. Additional information on past OLUG workshops and the FY21 workshop (e.g., the agenda) are available on the LLE website at Omega Laser Facility Users Group 2021 Workshop – Laboratory for Laser Energetics (rochester.edu).

Education

As noted above, education/training is a primary technical mission for LLE. LLE is the only place where students can be trained at scale for careers in National Security related to the science of Stockpile Stewardship. The education programs at the Laboratory include a high school program that exposes students to a professional environment where they work alongside scientists and engineers for a summer; undergraduate programs where students work part-time with scientists and engineers often throughout an academic year (or longer) to understand how classroom education is applied to real world problems; graduate education where students are immersed in the science of HED physics to earn MS and Ph.D. degrees; and a new high school program for under-represented minority students and their teachers in the local Rochester area. This report provides a summary of these activities in FY21, including:

1. Summer High School Research Program

Since 1989, LLE has held an annual Summer High School Research Program for Rochester-area high school students who have just completed their junior year. The eight-week program provides an exceptional opportunity for highly motivated students to experience scientific research in a professional environment. Eight students participated in the virtual 2021 program (see **LLE's Summer High School Research Program**, p. 251). To date, 399 from 55 high schools have participated in the program, including 137 female students. Thirty-nine students have become Scholars in the prestigious Regeneron Science Talent Search based on the research projects they carried out at LLE. To date, 105 students from this program have obtained doctorate degrees.

2. Broad Exposure to Science and Technology Student and Teacher Research Program

During the summer of FY21, LLE ran a pilot program for the research and education initiative called BEST (Broad Exposure to Science and Technology). Started during FY20 by T. J. Kessler, the LLE Diversity Manager, the goal of this initiative is to involve underrepresented high school students and their teachers from the Rochester City School District (RCSD) in various aspects of science and technology that support laser science and applications research at LLE. The summer 2021 pilot program included two RCSD high school science and technology teachers and four high school students of color. Ten LLE scientists, engineers, and technicians inspired and guided the students and their teachers, encouraging them to explore the next generation of STEM-related jobs and careers. The RCSD teachers gained knowledge and experience that enhanced the science and technology curricula going into the 2021–2022 school year. In addition, both the teachers and students acted as BEST ambassadors to encourage participation in the FY22 summer BEST program. Both an RCSD teacher and student participated in a visit by the director of the National Science Foundation to UR/LLE during the spring of 2022.

3. Undergraduate Student Program

LLE provides unique work–study opportunities for undergraduate research and co-op internships by involving undergraduate students and community college students in its research activities. These students come from the University of Rochester, the Rochester Institute of Technology, the State University of New York (SUNY) at Geneseo, Cornell University, Monroe Community College, and other institutions. LLE scientists also host and mentor students participating in the Research Experience for Undergraduate Program funded by NSF, and from 2022 the new Plasma and Fusion Undergraduate Research Opportunity Program funded by FES. During FY21, LLE employed 32 undergraduate and nineteen co-op students. LLE also funded 21 undergraduate students and six faculty advisors from SUNY Geneseo (one of the long-standing academic partners at LLE) and Houghton College to conduct research in physics and engineering and training students in the area of nuclear and plasma diagnostics.

4. Graduate Student Programs

Graduate students use the Omega Laser Facility as well as other LLE facilities to conduct ICF and HEDP research to earn advanced degrees. These students make significant contributions to LLE research output (e.g., they write a large fraction of the manuscripts published annually by LLE). Thirty-five University of Rochester faculty members (across eight academic departments) hold secondary appointments with LLE, increasing the breadth of leadership in science and technology. Eighteen scientists and engineers at LLE hold secondary faculty appointments with the University in five different academic departments. The large number of faculty and LLE staff enable the Laboratory to pull together a new high-energy-density science curriculum and educate a large number of graduate students. Approximately 90 UR graduate students were involved in research at LLE in FY21. LLE directly sponsored 63 Ph.D. students via the NNSA-supported University of Rochester Frank Horton Fellowship Program (see Table I in the **Appendix**, p. 406). Their research includes theoretical and experimental plasma physics and fusion science, HED physics, x-ray and atomic physics, nuclear physics, material properties under extreme pressure, astrophysics, ultrafast optoelectronics, high-power laser development and applications, nonlinear optics, optical materials and optical fabrication technology, and target fabrication.

In FY21, LLE directly funded graduate/undergraduate research with academic partners including the University of Delaware, the MIT Plasma Science and Fusion Center, the University of Michigan, the University of Nebraska-Lincoln, the University of Nevada at Reno, Stony Brook University, Imperial College London, and Oxford University. These programs involved two undergraduate students, 21 graduate students, four postdoctoral researchers, eight scientists and research staff, and eight faculty members.

In addition, the Omega Laser Facility and LLE significantly facilitated the education and training of more than 250 graduate students and postdoctoral researchers in the HEDP and ICF science areas from other universities through their participation in NLUF, LBS, LaserNetUS, and collaborations with LLE and the DOE national laboratories. Sixty-six graduate students (including 16 mentioned above) from 20 universities (see Table I in the **National Laser Users' Facility and External Users' Programs**, p. 256) were involved in these external user-led research programs with experiments conducted at the Omega Laser Facility in FY21.

Fifteen graduate students, including ten from the University of Rochester and eight from other academic institutions have successfully completed their thesis research and obtained Ph.D. degrees in calendar year 2021. Table II (**Appendix**, p. 410) lists their name, university, and current employer. Six of them (40% of the total), including five from UR, joined one of the DOE NNSA laboratories, five stayed within academia, and four work in the private sector.