Final Report

LaserNetUS Collaboration Network—University of Rochester

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1. Executive summary

LaserNetUS Collaborative Network established in 2018 is a network of high-power laser facilities supported by the Department of Energy (DOE) Office of Fusion Energy Sciences (FES) and operating effectively as a user facility. Its mission is to advance and promote intense laser science and applications by providing scientists and students with broad access to unique facilities and enabling technologies, advancing the frontiers of laser-science research, and fostering collaboration among researchers and networks from around the world. Users who submit proposals through an annual call are selected by an external and independent proposal review panel (PRP) not involving personnel from any of the facilities.

Besides the Omega Laser Facility at the University of Rochester's Laboratory for Laser Energetics (UR/LLE), the network during this project period includes high-intensity laser facilities from six other universities and three national laboratories, namely, the Colorado State University (CSU), the University of Michigan (UM), the University of Nebraska at Lincoln (UNL), The Ohio State University (OSU), Université du Québec, the University of Texas at Austin (UT Austin), Lawrence Berkeley National Laboratory (LBNL), SLAC National Accelerator Laboratory (SLAC) and Lawrence Livermore National Laboratory (LLNL), respectively. The network facilities span a wide range in laser pulse energy, pulse duration, repetition rate, and experimental diagnostic equipment enabling innovative research in a variety of exciting areas. Details of the LaserNetUS facilities, organization and committees, events, and accomplishments can be found at the network website (https://lasernetus.org/).

A very important role that the LaserNetUS fulfills is the training of students and young scientists who will be key for the future development of laser-plasma science and high-power laser technology itself. The network provides these students not only with access to the most advanced instrumentation and laser facilities, but also the opportunities to interact and collaborate with students from other institutions and with a large group of experienced scientists.

As the largest university-based laser users' facility in the world, the Omega Laser Facility at the UR/LLE has served the high-energy-density physics (HEDP) and inertial fusion science community for nearly 40 years. The multi-beam multi-kJ OMEGA EP Laser System brings unique capabilities to the LaserNetUS network. The combination of high intensity and high energy in short- and long-pulse operation together with solid or gas-jet targets and externally applied magnetic fields provides users a wide domain of experimental conditions. This award provides a total of eight shot days on OMEGA EP for LaserNetUS users. During the award period of performance (June 2019–November 2021), seven teams have fully utilized the eight shot days for their unique science experiments on OMEGA EP with a total of 83 target shots. These experiments involve 13 graduate students, two undergraduate students and six postdoctoral researchers. Results have been widely disseminated at international conferences including LaserNetUS annual meeting (~20 presentations including three invited), and in peer-reviewed journal publications (three published with several manuscripts in preparation).

2. Summaries of the project activities and accomplishments

2.1. LaserNetUS network activities

LaserNetUS, in a short time, has achieved very high visibility in the DOE and the national and international science communities, being viewed already as a major success and an important step for the U.S. laser-science and HEDP community. LaserNetUS science and user opportunities have been presented in invited talks at a number of international conferences. LaserNetUS has figured prominently in recent workshops and community-driven reports which all recommended to expand the capabilities of the network and suggested it as a model on how to conduct science efficiently.

The operations revolve around the network-wide proposal submission, review by an independent PRP and access implementation process, but significantly extend to interactions among the network facility PIs or points of contacts (POCs) and scientists through our annual meeting, and interactions with the network's Scientific Advisory Board (SAB) as well as the LaserNetUS User Group. UR/LLE PI/Co-PI and key team members have fully participated in all LaserNetUS activities including the weekly meeting on network operation and coordination governed by the facility PIs and POCs advised and guided by DOE through the FES Program Manager and our Program Coordinator, online presence (LaserNetUS website and social media), interactions with the PRP chair and conducting feasibility review of proposals, attending the PI and SAB meetings, organizing and participating in the annual LaserNetUS Users' meeting and engaging with the User Group, and promoting the network to domestic and international communities.

During the project period, LaserNetUS completed three solicitations for beam time in 2019 (Cycle 1), 2020–2021 (Cycle 2) and 2021–2022 (Cycle 3). Forty-nine (49) user experiments from the Cycle 1 and Cycle 2 have all been completed including seven on OMEGA EP during this project period. Thirty-seven (37) Cycle three experiments including six on OMEGA EP are well underway, scheduled to complete later this year. The call for Cycle 4 experiments is closed and proposals are under review.

2.2. Summaries of the LaserNetUS users' experiments completed on OMEGA EP

During the period of performance of this project, all seven experiments supported by the LaserNetUS program for the Cycle 1 and Cycle 2 runs have been successfully conducted on OMEGA EP over eight shot days. These experiments all require and utilize multiple beams with pulse shaping capabilities and benefit from the versatile experimental configurations and suite of precision diagnostics available on the OMEGA EP laser system. The completion of these experiments during the COVID-19 global pandemic is attributed to the Omega Facility RemotePI operation, a new protocol that enables experimental PI and collaborators to safely and effectively conduct experiments via remote access. Table below lists these seven experiments in the order of experiment completion and a brief summary of each experiment adapted from the report provided by the respective experimental PI is included in this section.

Run cycle and proposal number	PI	Title	Lead Institution	Shots conducted
Cycle 1—K003	M. P. Valdiva	Electron density imaging of irradiated foils through Talbot-Lau x-ray deflectometry	JHU	1 day—9 shots
Cycle 1—K024	H. Chen	Exploring novel target designs for high yield laser created relativistic pairs	LLNL	1 day—14 shots
Cycle 2—K068	W. Fox	Particle energization during magnetic reconnection in colliding magnetized plasmas	PPPL	1 day—14 shots
Cycle 2—K062	T. Duffy	Ultra-high pressure phase transition in (Mg,Fe)O: implications for exoplanet structure and dynamics	Princeton University	1 day—11 shots
Cycle 2—K089	J. Kim	Ion acceleration from multi-picosecond short pulse lasers interacting with under-dense plasmas	UCSD	1 day—10 shots
Cycle 2—K065	H. Ji	Plasma beta dependence of particle acceleration from magnetically driven collisionless reconnection using laser-powered capacitor coils	Princeton University	1 day—12 shots
Cycle 2—K054	Y.-J. Kim	Extreme chemistry of synthetic Uranus	LLNL	2 days—13 shots

JHU: Johns Hopkins University; LLNL: Lawrence Livermore National Laboratory; UCSD: University of California, San Diego

Electron density imaging of irradiated foils through Talbot-Lau x-ray deflectometry (TXD)

This experiment led by Dr. Pia Valdivia from the Johns Hopkins University with collaborators from University of Michigan, Virginia Tech, Los Alamos National Laboratory, LLE, and University of Bordeaux was conducted in November 2019 with a total of nine target shots. The team is developing a novel HEDP diagnostic utilizing the TXD technique to image the electron density profile at the ablation front of laser-driven solid foil targets. TXD has the potential to measure high density plasmas in the range of 10^{22}–10^{24} cm^{-3} with high spatial resolution, which is beyond the current capability. Such measurements will help validate radiation hydrodynamic modeling codes and enable the study of thermal transport in laser-produced plasmas. For this LaserNetUS experiment, the team first optimized the 8 keV x-ray backlighter source generated by a short pulse OMEGA EP beam (about 60 J in 10 ps) using copper foils in various geometries that were tested in a prior two-week campaign using the MTW laser at LLE. With the improved backlighter source and detector performance, the first Moire images of the ablation front of a long-pulse UV beam-irradiated CH foil target was obtained by the TXD diagnostic on OMEGA EP with a measured spatial resolution <10 µm (see Fig. 1). A refraction angle map [Fig. 1(c)] was retrieved manually from Moire fringe shifts recorded through TXD [Fig. 1(b)], demonstrating x-ray phase-contrast through x-ray refraction imaging has the potential to accurately diagnose HEDP experiments. Figure 1(b) shows a highly dense ablation front close to the left side of the foil, well above the 10^{25} cm^{-3} detection limit of the EP-TXD diagnostic.

Three graduate students (Max Schneider from Virginia Tech, Raul Melean from University of Michigan, and Victorien Bouffetier from University of Bordeaux) participated in the experiment. Results have been presented at various conferences and the detail of the experiments is published in a journal article [M. P. Valdivia *et al.,* "Talbot-Lau x-ray deflectometer: Refraction-based HEDP imaging diagnostic," *Rev. Sci. Instrum.* **92**, 065110 (2021)].

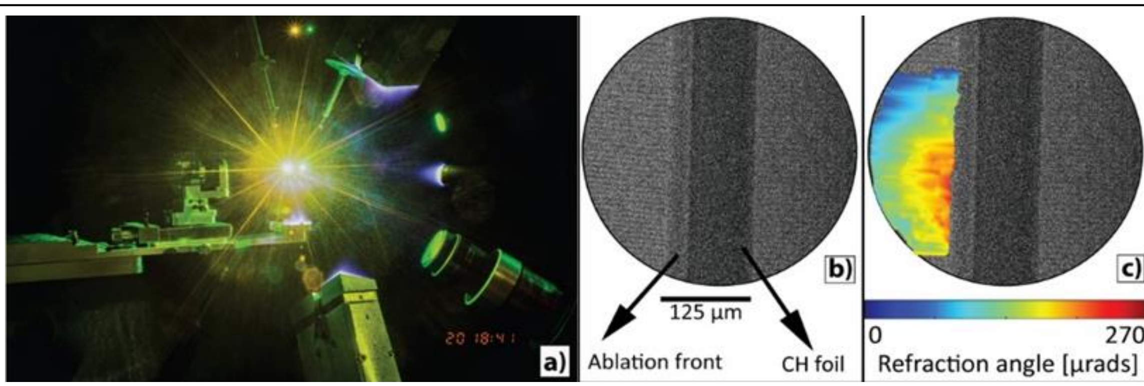


Fig. 1 (a) Visible camera image of the EP-TXD diagnostic in the LaserNetUS irradiated foil campaign. (b) Raw Moire image of the 125 µm CH irradiated foil (150 J, 1ns) obtained through TXD at 5 ns. (c) Refraction angle 2-D map retrieved through TXD methods.

Exploring novel target designs for high yield laser created relativistic pairs laser

A research team from LLNL led by Dr. Hui Chen with collaborators from LLNL, UCSD and General Atomics successfully explored innovative target designs to increase the yield of relativistic electron-position pairs using the high-energy, high-intensity OMEGA EP laser. As shown in Fig. 2(c), the data shows enhanced positron yield with the target of higher number of cavities, indicating a new direction for further exploration to maximize the laser-pair conversion. Relativistic pair jets and plasmas are novel HEDLP

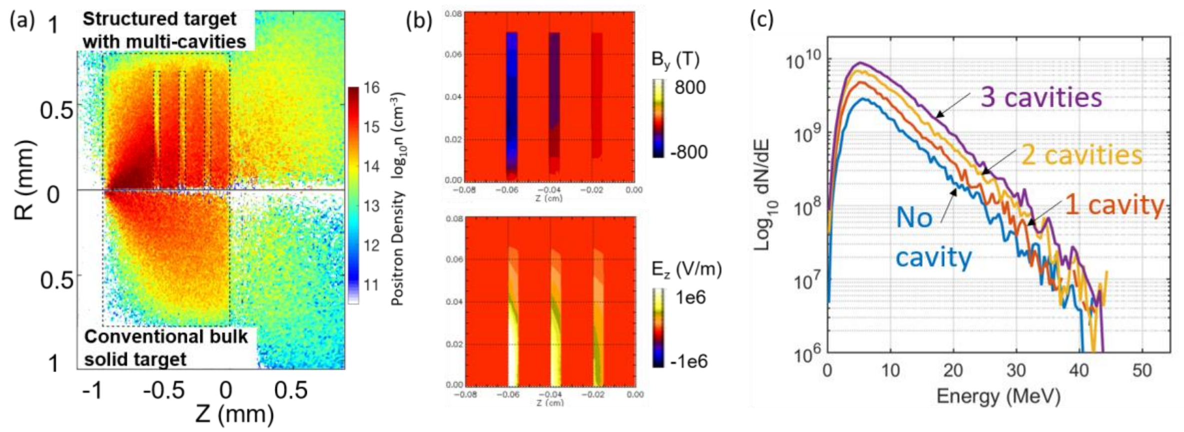


Fig. 2. (a) Simulated positron yield from multi-cavity target (top) and conventional solid target (bottom). (b) Azimuthal magnetic fields (top) and longitudinal electric field (bottom) developed by net current in the multi-cavity target. (c) Comparison of escaped positron spectra.

systems that are of great significance to basic HED plasma physics and to understanding some of the most fascinating astrophysical phenomena. They play important roles in a range of antimatter science applications, accelerator technology, and relativistic laboratory astrophysics. Enhancing the pair generation using lasers will enable a viable laboratory experiment platform using relativistic pair plasmas to address a variety of physics topics in this unique regime.

To increase the pair density, the most straightforward approach is to use lasers with more energy and a higher intensity to accelerate electrons that create positrons in the target. While it would be easy to reach orders of magnitude higher pair yield on future lasers, at the present, the effective way is increasing laser absorption and energy coupling from lasers to electrons. Another effective way to increase positron numbers in the beam is to extract more positrons out of solid targets, because simulations suggest that only 1% of the positrons created in conventional bulk high-Z targets can escape. To enhance number of positrons escaping from the target, the team has designed a novel target from which the simulation predicts higher positrons population escaping from the target. The key concept of the newly designed target is to use multiple vacuum gaps (cavities) inside of the bulk target to focus electron beam which can drive denser gamma rays to produce more positrons. Figure 2 shows the particle-in-cell simulation results showing higher density of positrons from a newly designed multi-cavities target [Fig. 2(a) top] compared with a conventional bulk target shown at bottom. Figure 2(b) shows self-generated magnetic field (top) as particles, mostly electrons, propagate cross the target. Here, negative B-field (azimuthal direction) built in the cavity is a focusing field for electrons preventing electrons going out from target side. In addition, as shown in Fig. 2(b) bottom, the positive electric field in the cavity is an accelerating field for positrons where low energy positrons can gain energy to escape from a target backside before they slow down and stop inside of the target. With these effects from multi cavity, created positron numbers increase as shown in the Fig. 2(c).

Based on the simulation study, the LaserNetUS experiment was conducted in December 2019. To have cavities inside targets, multiple washer (disk-shaped plate with a hole) and foils were stacked up as shown in Fig. 3 (left). The OMEGA EP short pulse beam (~900 J, up to 10 ps) irradiated the main gold target for pair jet production. The Electron-Positron-Proton-Spectrometer (EPPS) was placed behind the primary target to measure pair particle energy distribution. The data shows enhanced positron yield measured with the target of higher number of cavities as shown in the Fig. 3. Since positron yield depend on material mass electrons interact with, total measured positron numbers were normalized by target (Au) mass. These experimental results demonstrate the potential for this concept, but a more systematic study with varying cavity gap and numbers will be needed to optimize the electron transport and positron generation, which will be explored in the future experiments.

Two early career scientists, Dr. J. Kim (scientist from UCSD) and Dr. S. Kerr (postdoc at LLNL) led the PIC modeling and participated in the experiments as first-time users of the facility. A journal publication is in preparation.

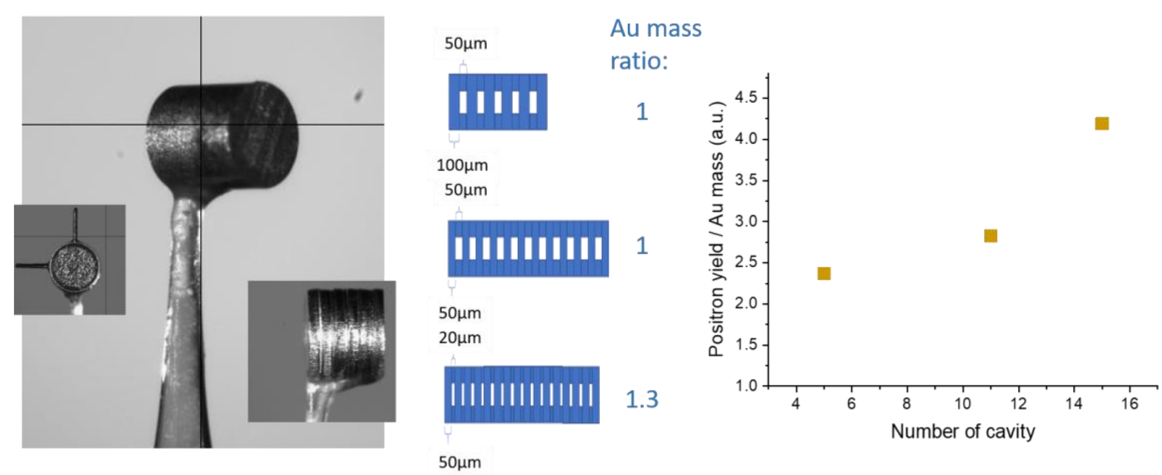


Fig. 3. Multi-cavity targets used in the experiments using OMEGA EP lasers (left). Experimental results show that positron yield (normalized by Au mass) enhances with larger number of cavities in the layer targets (right).

Particle energization during magnetic reconnection in colliding magnetized plasmas

A team of users led by Dr. Will Fox from PPPL with collaborators from Princeton University, University of Michigan, LLE and University of New Hampshire investigated acceleration of high-energy electrons in colliding magnetized plasmas. Understanding the physics of magnetized plasmas is key to unlocking a number of important problems in space and astrophysics. A key feature of explosive processes in astrophysical plasmas is the acceleration of particles to form populations of super-thermal, energized particles, such as cosmic rays. Magnetic reconnection is a fundamental mechanism behind these processes, which can explosively release stored magnetic energy, convert it to plasma heat and flows, and accelerate particles. This LaserNetUS experiment was designed to collide pairs of plasma plumes produced by two of

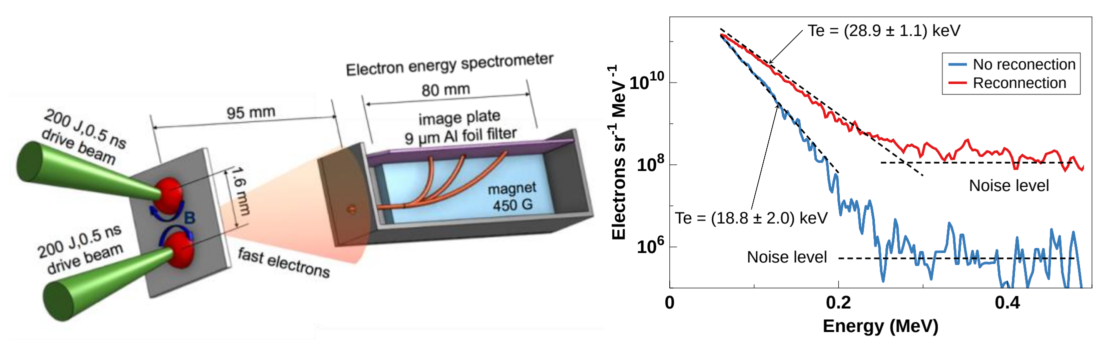


Fig. 4. (Left) Experimental setup: A plastic (CH) target is driven by one or two 351nm laser beams focused to a spot with a diameter of 750µm, Each beam has an energy of 200 J and a duration of 0.5 ns. The fast electrons were observed by a magnetic energy spectrometer with the image plate as the detector; (Right) Electron energy spectra for reconnection (red) and non-reconnection (blue) shots.

the four OMEGA EP long pulse beams (see Fig. 4). Interaction of Biermann-battery magnetic fields (~10 Tesla) from the two colliding plasmas drive the magnetic reconnection. For non-reconnection, or "null" shots, only a single beam was used. With the available four long pulse beams, the team obtained 14 target shots in March 2020. Comparing the measured energetic electron spectrum from shots using two-beam (magnetic reconnection) and one-beam (no reconnection), the two-beam reconnection experiments show a significant enhancement of the energized particles beyond the null experiment. This is reproduced over multiple beam pairs, with the error bars shown as the shaded regions (see Fig. 4, right). The spectra have approximately exponential profiles where the effective energetic electron temperature increases from 18 keV to 29 keV from non-reconnection to reconnection shots, an increase by a factor of 1.6. These results therefore have carefully shown the enhancement of energized particles in merging magnetized plasmas. Comparison of the experimental data with theory and models of particle acceleration is underway, which include processes such as direct acceleration by the strong electric fields associated with reconnection, Fermi-type processes in regions of contracting magnetic fields, and betatron energization in regions where fields rapidly compress.

Two graduate students, Jackson Matteucci (Princeton, now graduated) and John Donaghy (University of New Hampshire) and one early career scientist, Dr. D. Schaeffer (Princeton) were involved in this project. The work has been presented at various conferences and reported in a journal publication [G. Fiksel, W. Fox, M. Rosenberg, D. Schaeffer, J. Matteucci, A. Bhattacharjee, "Electron energization during merging of self-magnetized, high-beta, laser-produced plasmas," *J. Plasma Phys.* **87**, 4 (2021)].

Ultra-high pressure phase transition in (Mg,Fe)O: implications for exoplanet structure and dynamics

The experiment is led by Dr. Thomas S. Duffy from the Princeton University (PU) with collaborators from PU, LLNL and LLE. Ferropericlase (Mg,Fe)O is expected to be a key constituent in the deep interiors of large, rocky exoplanets. The phase transition from the B1 (rocksalt-type) to the B2 (cesium chloride-type) phase is a key feature that may strongly influence heat flow and dynamic evolution of such bodies. While the MgO endmember has been extensively studied at high pressures, there are no experimental or theoretical studies of more geologically relevant (Mg,Fe)O compositions at relevant conditions. The team performed laser-driven ramp compression experiments on ferropericlase, $(Mg_{0.60},Fe_{0.40})O$, and obtained 11 shots in June 2020.

Ferropericlase powders were synthesized at high temperature under reducing conditions. Powder X-ray diffraction patterns and energy dispersive X-ray spectra were collected to confirm the structure and compositions of the starting material. These powders were ground to ~2 µm average particle size, loaded into a short-piston diamond cell with 800-µm culets, and cold pressed to ~2.0 GPa resulting in 10–15 µm thick foils. The sample foils were adhered between a single crystal diamond (SCD) ablator and a LiF window for low pressure experiments, and a SCD-heat shield-SCD ablator/pusher and a SCD window for experiments with peak pressures in excess of ~450 GPa. A 6 to 10 ns ramp-shaped laser pulse was used to ablate the surface of the target sandwich and quasi-isentropically compress the sample. When the target was at approximately peak stress, a 1 or 2-ns laser pulse was used to irradiate a Fe or Ge foil, generating quasi-monochromatic x-rays that were directed onto the sample and produced an x-ray diffraction pattern. The active shock breakout diagnostic monitored the particle velocity at the sample-LiF interface or diamond free surface, which was then used to infer the stress history in the sample.

Ferropericlase was ramp compressed to stresses ranging from 269 ± 17 GPa to 774 ± 26 GPa in these experiments. Up to 429 (21) GPa, two sample diffraction lines were observed that could be indexed as corresponding to reflections from the (002) and (111) planes of the B1-type structure when compared to the expected *d*-spacings of MgO and FeO. Above 429 GPa and as high as 594 (20) GPa, only one sample diffraction line was observed. As the Bremsstrahlung radiation background scales with increasing ablation energy, the weaker (111) diffraction line was not observed at these elevated pressures. At 599 (19) GPa, the onset of the B2-type structure was observed and at the highest achieved stress, 774 (26) GPa, both the B1 and B2 phases were observed. Previous ramp compression experiments on the MgO endmember showed complete transformation from the B1 to the B2 phase at ~600 GPa. In the FeO endmember, only the B2 phase was observed at pressures in excess of 300 GPa. Using these transition pressures and assuming an ideal solid solution model, the expected onset of the B2 phase for a $(Mg_{0.60},Fe_{0.40})O$ composition would occur at ~440 GPa with complete transformation at ~520 GPa. The observations for the B2 phase are far in excess of these predictions suggesting enhanced kinetic barriers for intermediate compositions in the (Mg,Fe)O system.

Two graduate students from PU, Ian Ocampo and Donghoon Kim are trained on this project. Ian Ocampo gave a presentation titled "Effect of iron on the B1-B2 phase transformation in (Mg,Fe)O under laser-driven ramp compression" at the 2021 LaserNetUS Annual User Meeting and won the best student poster award. A journal publication is in preparation.

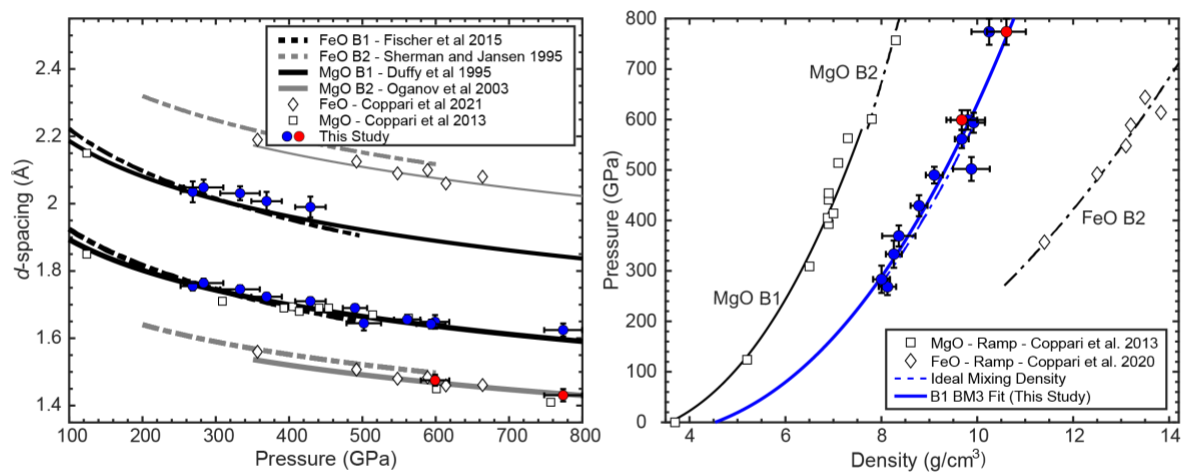


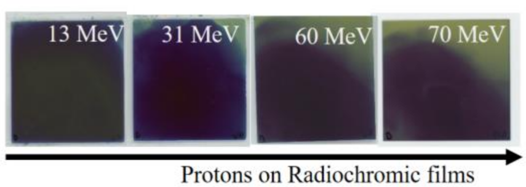
Fig. 5. (Left) *d*-spacing as a function of pressure for $(Mg_{0.6}Fe_{0.4})O$ under ramp compression. Blue circles correspond to diffraction from the B1 phase whereas red circles correspond to those from the B2 (011) reflection. These are compared to previous ramp compression experiments on MgO and FeO. Solid black and gray lines represent the expected *d*-spacings for MgO B1 and B2 reflections, where dashed black and gray lines represent the expected *d*-spacings for FeO B1 and B2 reflections. (Right) Pressure vs. density relationship of MgO and FeO endmembers as well as data from this study. Solid black and dashed black lines are reported equation of state fits to previous ramp compression experiments. The solid blue line is an equation of state fit to our data. This is in excellent agreement with that predicted using linear mixing of the endmember oxide densities (dashed blue line).

<u>Ion acceleration from multi-picosecond short pulse lasers interacting with under-dense plasmas</u>

The experiment is led by Dr. Joohwan Kim from UCSD with collaborators from UCSD, GA, LLNL and MIT. The team successfully completed one-day experiment with ten target shots on OMEGA EP in September 2020. The goal was to explore short-pulse laser-driven ion acceleration with multi-ps pulses and ultra-thin targets in which the synergetic effects of laser-induced target transparency and continuous field acceleration efficiently enhance the flux and peak cutoff energy of accelerated ions. The data shows the maximum proton energy of higher than 70MeV from the moderate-intensity, ~10^{19} W/cm^2 with sub-micron thick targets, and significantly higher yield of protons in higher energy than expected from a typical target normal sheath acceleration (TNSA) mechanism. The computational study indicates the enhanced temperature of electrons from laser interaction with expanding plasma drives a strong electric field for further ion acceleration.

Proton beams from the OMEGA EP short pulse beams with laser duration from 0.7 to 10 ps and targets of parylene (CH) or aluminum with thickness from 100 nm to 3 µm were measured. The primary diagnostic was a stack of radiochromic film (RCF) and filters designed to have a proton punch-through energy of 70 MeV for the last layer. For a control shot using the best compressed pulse duration (nominally 0.7 ps) and 3 µm thick parylene, protons reached the 45+ MeV film layer but not the 58+ MeV layer, an unsurprising result as expected if the process is TNSA. Another shot with the best compression on 100 nm Al produced the same result. However, all the shots with 2–3 ps duration and full energy laser produced signals all the way to the last layer of the film (70 MeV). 70 MeV is the most energetic protons measured from the facility to date, and the result motivates the design of a film stack to measure to higher energy. Fig. 6(a) shows the several layers of RCF film for the 300nm CH producing the strongest signal and Fig. 6(b) summarizes the shot conditions and corresponding results. The trend clearly seen in the data set is higher maximum proton energies from the thin targets with longer pulse duration, > 2.5 ps, indicating that the new approach using synergetic effects of target transparency and continuous field far exceeds TNSA in their maximum energies. Fig. 6(c) compares these improved proton energies with previous studies as a function of laser intensity. The new data, 70 MeV on RCF (blue dots) and higher signal on Thompson Parabola (blue arrows), shows higher maximum energies than other results that use higher laser intensities, more than an order of magnitude.

a)



b)

Duration (ps)	Intensity (Wcm^{-2})	Target Thickness	Proton Max.E
0.7	4e19	3 µm	~ 45 MeV
0.7	6e19	< 400 nm	~ 45 MeV
> 2.5	6e18 - 1.5e19	< 400 nm	> 70 MeV

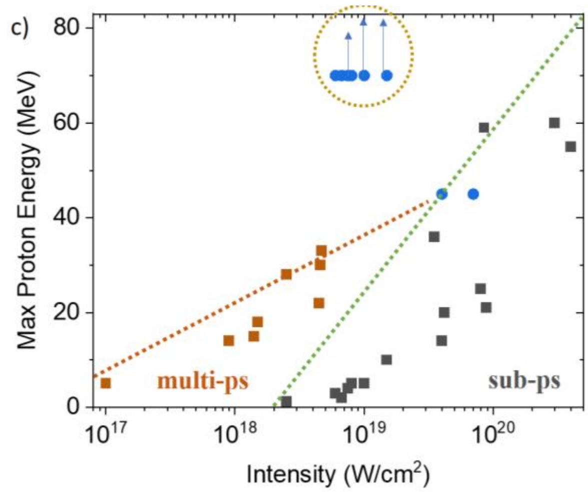


Fig. 6. Experimental results from the OMEGA EP shots. (a) Example of the measured proton signal on RCF. (b) Conditions of laser pulse and target with corresponding maximum proton energies. (c) Comparison of maximum proton energies with previous TNSA data. Blue dots in a circle represent the results from shots using multi-ps (>2.5 ps) pulse with thin foil (<400 nm).

Another advantage of the new acceleration concept is to enhance the accelerated proton yield. While TNSA typically shows most protons in a low energy range (< 10 MeV), and proton number falls quickly for higher energy, the new results present a relatively higher number of protons even for the high energy component, indicating that more protons are efficiently accelerated to high energy. This trend is shown in Fig. 7, where exploiting the TNSA mechanism, the target is 3 µm thick, with more protons at near 10 MeV but a much lower number of protons for energy above 15 MeV compared to thin target cases (200–300 nm). The data clearly demonstrates the continuous ion acceleration with multi-ps pulses in the target transparency regime as a promising method for efficient ion acceleration.

Four graduate students, Krish Bhutwala (UCSD), Jacquelynne Vaughan (UCSD), Dana Zimmer (UCSD), Raspberry Simpson (MIT) and have participated in the experiment. PI (Joohwan Kim) is an early career scientist. Results have been presented at various conferences and a journal publication is in preparation.

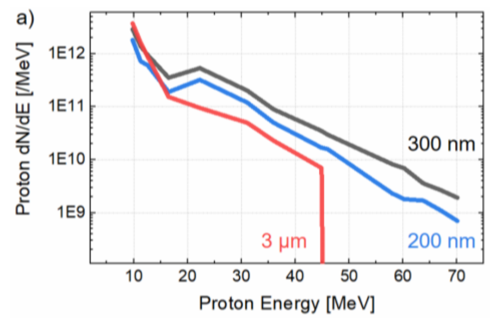


Fig. 7. Comparison of measured proton energy spectra. Proton results from the thin targets (300 nm and 200 nm) with >2 ps pulse show higher proton yield than the 3 um thick target case.

Plasma beta dependence of particle acceleration from magnetically driven collisionless reconnection using laser-powered capacitor coils

The experiment is led by Dr. Hantao Ji from Princeton University with collaborators from PU, PPPL, University of Rochester, LLE, LLNL and Los Alamos National Laboratory (LANL). The team successfully completed one-day experiment with 12 target shots on OMEGA EP in September 2020.

Magnetic reconnection is a ubiquitous astrophysical phenomenon that rapidly converts magnetic energy into some combination of plasma flow energy, thermal energy, and non-thermal energetic particles. The latter is often an observational signature of magnetic reconnection environments, which can be even more efficient accelerators than competing processes such as isolated collisionless shocks. Experimental diagnostics have long limited most reconnection experiments to focus on the physics of reconnection rate and generation of plasma flow or thermal energy, but not on the particle acceleration. To overcome this limitation, the PI and his team have developed a robust platform to generate and measure non-thermal energetic electrons from magnetically driven quasi-axisymmetric reconnection using laser-powered capacitor coils on the OMEGA EP Laser System. An extensive set of diagnostics, including ultrafast proton radiography, 4ω probe, and particle spectrometers are available to characterize the reconnecting plasma and the resultant accelerated particle spectra. The goal of this experiment is to take advantage of this capability and study particle acceleration dependence on plasma β (the ratio of plasma pressure to magnetic field pressure), with β ranging from $\ll 1$ to order unity, allowing relevant conditions to astrophysical environments. In particular, direct measurements of charged particle spectra are possible due to a large electron mean free path relative to the detector distance. Using the well-established experimental reconnection platform, the team has directly detected non-thermal electron acceleration from reconnection. Supported by particle-in-cell simulations, the data indicate a primary acceleration mechanism of direct electric field acceleration by the reconnection electric field.

Figure 8 shows the experimental setup with diagnostic locations. The capacitor-coil target is driven with two laser pulses, each delivering 1.25-kJ of laser energy in a 1-ns square temporal profile at a wavelength of 351 nm. Due to the laser interaction, strong currents are driven in the coils. In targets with two parallel coils, a magnetic reconnection field geometry is created between the coils, and in targets with one coil, a simple magnetic field around a wire is produced, representing a non-reconnection control case. In this LaserNetUS shot day, the team used a multi-channel electron spectrometer—the Osaka University electron spectrometer (OU-ESM)—to measure the electron energy spectra. It was located 37.5 cm away from the coils, at a polar angle of 39° and scanned an azimuthal range of 179°–199° with five equally-spaced detection channels. The OU-ESM channel orientation is shown in Fig. 8(b, c). Particle spectrometer data were collected for a total of five shots, with three double-coil reconnection shots, and two single-coil control shots. The OU-ESM data for the five shots are shown in Fig. 9.

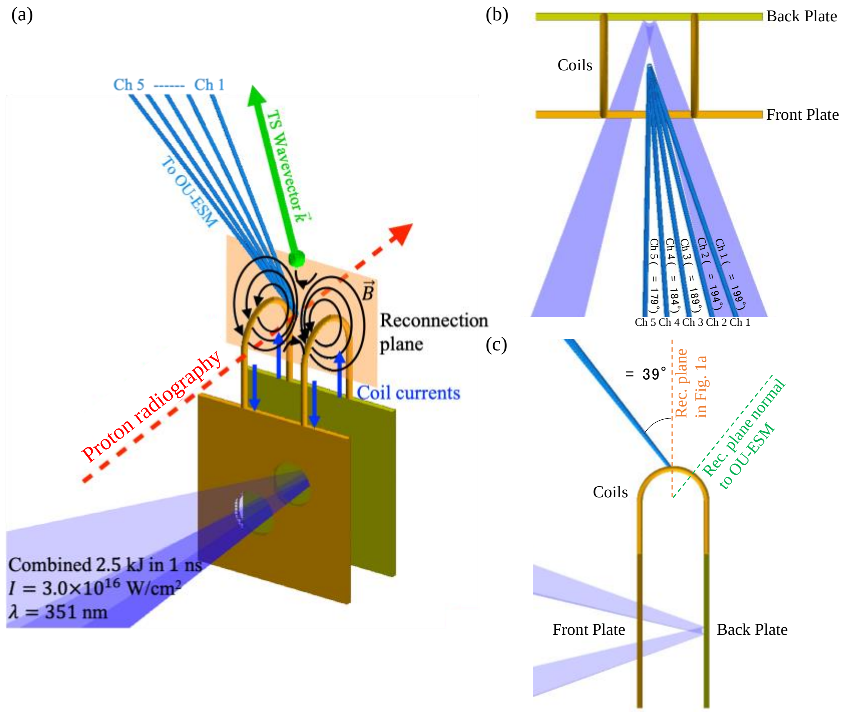


Fig. 8: Experimental setup of low-β, magnetically driven reconnection using laser-powered capacitor coils. (a) The capacitor-coil target is driven by two long-pulse lasers, passing through the front holes and irradiating the back plate. (b) and (c) are the top-down view and the side view of the target along with the OU-ESM channel orientation.

Small differences in the laser energy profile and target properties between shots causes variations in otherwise nominally identical cases as seen in Fig.9. However, focusing on the angular dependence across the channels for each shot reveals a key feature in the electron spectra: non-thermal "bumps" in the reconnection cases that do not appear in the control cases. The bumps span the 50–70 keV range, and they are most pronounced at the near-normal Channel 5 (ϕ =179°) and weaken with increasing angle from normal. In contrast, the one-coil control cases do not exhibit consistent spectral bumps, and generally exhibit lower signal level. One exception is Fig. 9(e), which represents a one-coil shot with the coil on the left side (as viewed from the front of the target). Due to the coil magnetic field, low-energy electrons are deflected toward higher ϕ, resulting in an electron deficiency in Channel 5 and to a lesser extent, Channel 4. The background "thermal" signal does not represent the T_e = 400 eV plasma: it is the quasi-Maxwellian suprathermal distribution with a hot "temperature" of $T_{eh} \simeq$ 40-50 keV, created by laser-plasma instabilities (LPI), such as stimulated Raman scattering (SRS) and two-plasmon decay (TPD).

These spectral bumps demonstrate non-thermal electron acceleration, and the detection angle dependence of the bump sizes suggests a directional anisotropy in the accelerated electron population. The strongest non-thermal population is seen in the direction out of the reconnection plane, anti-parallel to the reconnection electric field, indicating its responsibility for the direct acceleration. Interpretation of this particle acceleration mechanism is supported by particle-in-cell simulations. Scaled energies using the direct reconnection electric field acceleration mechanism show direct relevance to astrophysical observations.

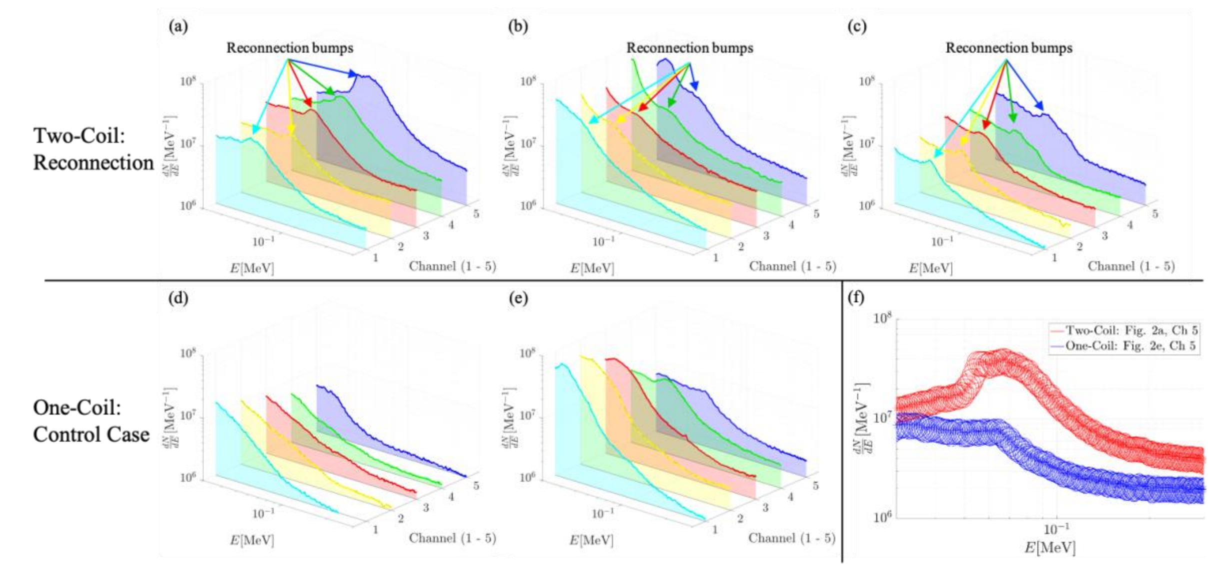


Fig. 9: Experimental particle spectra exhibit conspicuous evidence for non-thermal acceleration bumps in reconnection cases, that are absent in non-reconnection cases. Particle spectra from the OU-ESM are presented for five experimental shots: three two-coil reconnection cases (a, b, c) and two one-coil control cases (d, e). (f), a plot of reconnection (a) and control (e) shots, Channel 5 are shown with ellipses representing the vertical and horizontal error bars at each point.

The experiments have involved two students, Abraham Chien (PhD student at Princeton University, graduated in Sept 2021) and Omar French (undergraduate at University of Maryland) and one postdoc, Shu Zhang (Princeton University). It is part of Abraham Chien's PhD thesis work. Results have been presented at multiple conferences including one invited presentation at the 62nd Annual Meeting of the American Physical Society (APS) Division of Plasma Physics. The details of the experiments and simulations are described in a manuscript submitted to *Nature Physics* (under revision) (Abraham Chien *et al.*, "Direct measurement of non-thermal electron acceleration from magnetically driven reconnection in a laboratory plasma").

Extreme chemistry of synthetic Uranus (H:C:N:O mixtures at the interior conditions of icy planets)

The experiment is led by Dr. Yong-Jae Kim with collaborators from LLNL, University of Michigan and École Normale Supérieure de Lyon· Synthetic Uranus (SU) is a H:C:N:O mixture having similar composition to the interior of icy planets such as Uranus and Neptune. The IcyPlanetsDAC-EP-21 campaign on OMEGA EP under the support of the LaserNetUS program aims at measuring the microstructure of the H:C:N:O ices with in-situ nanosecond x-ray diffraction during dynamic compressions. This work expands on the team's recent discovery of superionic water ice [M. Millot *et al.*, *Nature Phys.* **14**, 297 (2018); M. Millot and F. Coppari *et al.*, *Nature* **569**, 251 (2019); B. Cheng *et al.*, *Nature Phys.* (2021)], and provides new insights into the chemistry (e.g., new bonding, mixing/demixing, polymerization, and precipitation) at the interior pressure-temperature conditions of the icy planets.

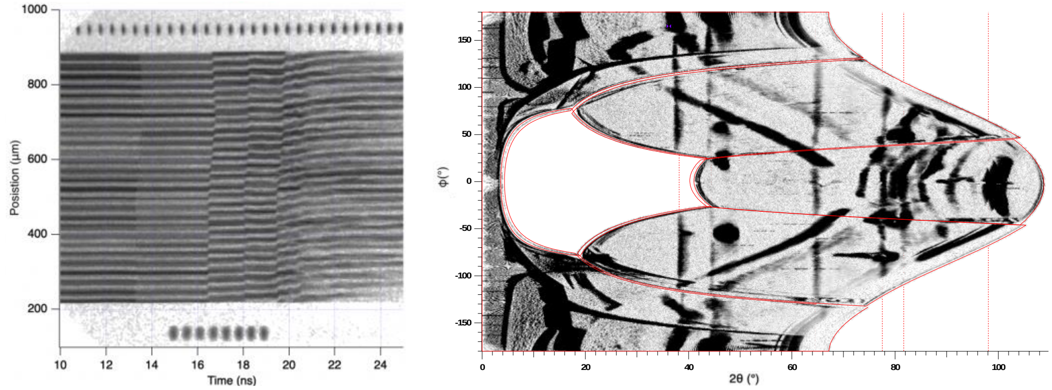


Fig. 10: Example of VISAR (left) and XRD (right) data obtained from 50 µm thick Synthetic Uranus mixture at ~280 GPa and ~2300 K on OMEGA EP.

The team prepared liquid H:C:N:O mixture with water, ammonia, and isopropanol, and documented its optical property at the ambient condition [Y.-J. Kim *et al., Sci. Rep.* **11**, 5610 (2021)]. For laser-driven dynamic compressions, this mixture was loaded into thin sample chambers fabricated with a chemical-resistive polymer, and sealed by ablator and window materials. With excellent laser performance and support, the team collected 13 target shots in the two-day allocations. Two OMEGA EP beams were stacked to produce a 20-ns drive, and another two beams were focused on a Cu backlighter for generating a 1-ns x-ray emission. At a steady shock state during a shock wave reverberation, the x-ray diffraction (XRD) pattern of the mixture was recorded using the PXRDIP diagnostic Doppler velocimetry (VISAR) was used to track the free surface velocity of the window which was compared with hydrodynamic simulations for determining pressure-density-temperature conditions of the samples. Figure 10 shows the example VISAR and XRD data obtained from the experiments. The on-going data analysis on the diffraction patterns, surface velocities, and simulations will be used to improve our understanding on the interior structure of the icy planets.

The PI of the experiments is a postdoctoral researcher at LLNL and one graduate student, Michael Wadas from the Univeristy of Michigan has contributed to the data analysis. The details of the experiments and results have been presented as invited talks at the 10th Asian Conference on High Pressure Research (November 2021) and the APS 2022 March Meeting. Journal publications are in preparation.

3. Summary of training and professional development provided

An important role that LaserNetUS fulfills is the training of students and postdocs who will be key to the future development of HED science and high power laser technology itself. Through LaserNetUS, students and postdocs have the opportunity to collaborate and learn from experienced scientists from different institutions. This provides a well-rounded education for students, first giving them experience at a high-power laser laboratory and teamwork, ultimately providing expertise that they will bring to the broader workforce and future facilities.

The seven LaserNetUS experiments completed on OMEGA EP discussed above have involved about 70 researchers from 16 institutions including 13 PhD students, two undergraduate students, six postdocs, 39 scientists and research engineers, and nine professors. Graduate students and postdocs have played a leading role in planning and execution of experiments as well as data analysis and modeling. Data obtained from these experiments are significant part of graduate students' theses, e.g., Abraham Chien (PhD 2021).

Dr. Joohwan Kim, an early career scientist at UCSD who participated in a 2019 Cycle-1 experiment as a new user was awarded and led a Cycle-2 experiment as PI. Dr. Yong-Jae Kim (postdoc at LLNL) led a Cycle-2 experiment as PI. Dr. Shu Zhang (postdoc at Princeton University) who was key team member on a Cycle-2 experiment has been awarded two days on OMEGA EP for a Cycle-3 experiment as PI.

The LaserNetUS experiments have also provided opportunities to cross training students and professionals on different platforms, e.g., laser and pulsed power HED systems. This directly benefits the development of a talent pool for the national labs, academia and high technology industry.

4. List of journal publications and conference presentations

Results from the LaserNetUS users' experiments are expected to be widely disseminated at international conferences and in peer-reviewed journal publications. Seven LaserNetUS experiments completed on OMEGA EP during the project period so far have produced one PhD thesis, three journal publications including one under review, and 18 conference and workshop presentations. Several manuscripts are in preparation for submission to peer-reviewed scientific journals. Dr. Wei, Co-PI of the LaserNetUS program at UR/LLE, also gave two presentations promoting the network to a broad user community.

Publications – PhD Thesis and Journal

1. Abraham Chien, "Particle acceleration due to magnetic reconnection using laser-powered capacitor coils," PhD Thesis (September 2021), Princeton University, Princeton, NJ.
2. M.P. Valdivia *et al.*, "Talbot-Lau X-ray deflectometer: Refraction-based HEDP imaging diagnostic," *Rev. Sci. Instrum.* **92**, 065110 (2021).
3. G. Fiksel, W. Fox, M. Rosenberg, D. Schaeffer, J. Matteucci, A. Bhattacharjee, "Electron energization during merging of self-magnetized, high-beta, laser-produced plasmas," *J. Plasma Phys.* **87**, 4 (2021).
4. Abraham Chien, Lan Gao, Shu Zhang, Hantao Ji, Eric G. Blackman, William Daughton, Adam Stanier, Ari Le, Fan Guo, Russ Follett, Hui Chen, Gennady Fiksel, Gabriel Bleotu, Robert C. Cauble, Sophia N. Chen, Alice Fazzini, Kirk Flippo, Omar French, Dustin H. Froula, Julien Fuchs, Shinsuke Fujioka, Kenneth Hill, Sallee Klein, Carolyn Kuranz, Philip Nilson, Alexander Rasmus, and Ryunosuke Takizawa, "Direct measurement of non-thermal electron acceleration from magnetically driven reconnection in a laboratory plasma," submitted to *Nature Physics* (under revision).

Publications – Conference papers and presentations:

1. M.S. Wei (on hehalf of LaserNetUS PIs), "LaserNetUS" (talk), Laserlab-Europe Conference, Florence, Italy, 11 October 2019.
2. M. S. Wei, "Omega Basic Science User Program Update" (talk), the 12th OLUG Workshop (virtual), April 27–30, 2021.
3. M.P. Valdivia *et al.*, "The Talbot-Lau X-ray Deflectometer: A refraction-based electron density diagnostic for High Energy Density experiments" (poster), Livermore, CA, USA, February 3–5, 2020.
4. M.P. Valdivia *et al.*, "Phase-contrast imaging of irradiated foils through Talbot-Lau X-ray Deflectometry on OMEGA EP" (talk), the 62nd Annual (virtual) meeting of the APS Division of Plasma Physics, November 9–13, 2020.
5. M.P. Valdivia, "Development and Implementation of Talbot-Lau X-ray Deflectometry" (talk), 2021 Stewardship Science Academic Program (SSAP) Symposium (virtual), February 16–18, 2021.
6. M.P. Valdivia *et al.*, "Phase-contrast imaging of laser-irradiated CH foils through Talbot-Lau X-ray Deflectometry" (poster), the 12th OLUG Workshop (virtual), April 27–30, 2021.
7. M.P. Valdivia *et al.*, "Talbot-Lau X-ray Deflectometry (TXD) Electron Density Diagnostic in Laser Target Interactions" (talk), 2021 LaserNetUS User Meeting (virtual), August 17–19, 2021.
8. L. Gao, "Magnetically Driven Collisionless Reconnection at Low Plasma Beta Using Novel Laser-Powered Capacitor Coils" (Invited talk), the 62nd Annual (virtual) meeting of the APS Division of Plasma Physics, November 9–13, 2020.
9. A. Chien *et al.*, "Particle Acceleration in Magnetic Reconnection Using Laser-Powered Capacitor Coils" (talk), the 62nd Annual Meeting of the APS Division of Plasma Physics, November 9–13, 2020.

10. A. Chien *et al.,* “Pulse width dependence of magnetic field generation using laser-powered capacitor coils” (poster), the 12th OLUG Workshop (virtual), April 27–30, 2021.
11. A. Chien *et al.,* “Direct measurement of non-thermal electron acceleration from magnetically-driven reconnection in a laboratory plasma” (talk), 2021 LaserNetUS User Meeting (virtual), August 17–19, 2021.
12. I. K. Ocampo *et al.,* “Stability of the $(Mg_{0.6},Fe_{0.4})O$ B1 phase under laser-driven ramp compression to 561 GPa,” 2020 Consortium for Materials Properties Research in Earth Sciences (COMPRES) Annual meeting (virtual), August 14, 2020.
13. I. K. Ocampo *et al.,* “In-situ x-ray diffraction of zinc oxide under laser-driven ramp compression: Extreme metastability of the B1-type structure,” the 12th OLUG Workshop (virtual), April 27–30, 2021.
14. I. K. Ocampo *et al.,* “Effect of iron on the B1-B2 phase transformation in (Mg,Fe)O under laser-driven ramp compression” (poster), 2021 LaserNetUS User Meeting (virtual), August 17–19, 2021.
15. J. Kim *et al.,* “Efficient ion acceleration by continuous field in target transparency regime,” the 12th OLUG Workshop (virtual), April 27–30, 2021.
16. J. Kim *et al.,* “Efficient Ion Acceleration by Continuous Fields in Target Transparency Regime” (talk), the 63rd Annual Meeting of the APS Division of Plasma Physics, Pittsburgh, PA, November 8–12, 2021.
17. G. Fiksel *et al.,* “Electron energization in merging magnetized plasmas” (talk), 2021 LaserNetUS User Meeting (virtual), August 17–19, 2021.
18. Y.-J. Kim *et al.,* “Study of extreme chemistry in H:C:N:O mixtures at the interior condition of icy planets” (talk), 2021 LaserNetUS User Meeting (virtual), August 17–19, 2021.
19. Y.-J. Kim *et al.,* “Laser-driven Shock Compression of Precompressed H:C:N:O Mixtures in Diamond Anvil Cell” (invited talk), the 10th Asian Conference on High Pressure Research (ACHPR-10), November 21–25, 2021.
20. Y.-J. Kim *et al.,* “Dynamic compression of statically precompressed low-Z materials” (invited talk in “Frontiers of High Energy Density Physics” symposium), APS 2022 March Meeting, March 14–18, 2022.