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Fourth User Workshop on High-Power Lasers at the Linac Coherent Light Source

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Participants at the Fourth User Workshop on High-Power Lasers at the Linac Coherent Light Source held at SLAC National Accelerator Laboratory in Menlo Park, CA

The fourth international user workshop focusing on high-power lasers at the Linac Coherent Light Source (LCLS) was held in Menlo Park, CA, USA on October 3-4, 2016.[1-3] The workshop was co-organized by Los Alamos National Laboratory and SLAC National Accelerator Laboratory (SLAC) and garnered the attendance of more than 110 scientists. Participants attended to discuss the warm dense matter and high-pressure science that is being conducted using high power lasers at the LCLS-Matter in Extreme Conditions (MEC) endstation. During the past year, there have been seven journal articles published from research at the MEC instrument.[4-10] The specific topics discussed at this workshop were experimental highlights from the past year, current status and future commissioning of MEC capabilities, and future facility upgrades that will enable expanded science reach of the facility.

The MEC instrument is an endstation of the LCLS. It currently accesses x-ray photon energies in the range of 4-12 keV. It has two major laser systems, an ultrafast laser operating at 30 TW (1 J, 40 fs, 5 Hz) and a ns laser capable of 20 J in 10 ns (one shot per 7 minutes). MEC introduced two experimental standard configurations this year to perform x-ray diffraction (XRD) and to perform concurrent XRD and x-ray Thomson scattering.

The workshop participants were welcomed by SLAC Director Chi-Chang Kao who conveyed a brief introduction on the importance of high power lasers in many scientific fields. Kramer Akli, the Program Manager for High Energy Density Laboratory Plasma (HEDLP) at the Department of Energy's Fusion Energy Sciences (FES), followed with a presentation from HEDLP, which funds the MEC instrument. Kramer expressed his view that MEC has been very productive for the scientific objectives of HEDLP, and FES is committed to continuing its support of the facility and of the science that it enables. In fiscal year (FY) 2017, FES is investing in an upgrade of the ns laser system at MEC and has modest funding available for supporting MEC user experiments.

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Recent experiments at LCLS-MEC

Many exciting experiments were performed in the past year at LCLS-MEC. Several of these experiments focused on measuring properties of iron at high pressure and/or temperature. Arianna Gleason (Los Alamos National Laboratory) led an experiment to determine the strength of iron under shock compression at pressures and temperatures that are similar to the Earth's core. She observed texture in the iron diffraction and demonstrated the ability to resolve deviatoric strain under these dynamic compression conditions. The data will be used to refine polycrystalline plasticity models. Marion Harmand (Université Pierre et Marie Curie) led a team investigating properties of shock-compressed iron alloys that are related to the inner Earth and other rocky planets. This experiment built on others at the X-ray Pump Probe (XPP) instrument at LCLS [11] and at SACLA, Japan. The effects of iron alloying were examined using both x-ray diffraction and spectroscopy. Félicie Albert (Lawrence Livermore National Laboratory) led an experiment performing ultrafast absorption spectroscopy of dense iron plasmas created by LCLS using betatron radiation. This experiment capitalized on the flux and narrow bandwidth of the LCLS x-rays for diffraction and used the high intensity optical laser at MEC to create betatron x-ray pulses for absorption spectroscopy. The betatron x-ray production showed a marked decrease in source performance from 2015, which resulted in averaging of many more shots to provide a reasonable data quality. Improvements in the wave front and focus of the optical laser will be pursued to increase betatron source performance. Andrew McKelvey (University of Michigan) presented about thermal conductivity measurements of warm dense Fe. The thermal conductivity of iron in the Earth's core determines the nucleation history of the solid inner core. The value of thermal conductivity of iron at conditions relevant to the inner Earth has been highly contested, including in two recent papers in Nature, which concluded that the values were at opposite ends of the commonly accepted range of values.[12, 13] The experiment used x-ray differential heating of double-layer targets[14], and three models for thermal conductivity predicted very different experimental observables. In addition to x-ray diffraction, this experiment used a streaked optical pyrometer to measure temperature.[15] Eliseo Gamboa (SLAC) presented on measurements of K-shell iron line shapes from solid density plasmas. This experiment demonstrated an *in situ* method for characterizing the x-ray beam focus based on resonant two-photon absorption in iron.

Carbon and hydrocarbons were another topic of great interest in the past year. Luke Fletcher (SLAC) led an experiment to measure strength of shock-compressed polycrystalline diamond near the Hugoniot elastic limit. These experiments were performed in concert with calculations of the Debye-Scherrer diffraction patterns in the Reuss limit.[16] Mike Armstrong (Lawrence Livermore National Laboratory) presented an experiment pursing the mechanism and kinetics of the graphite to diamond phase transition under ultrafast compression. Dominik Kraus (Helmholtz-Zentrum Dresden-Rossendorf) led an experiment on phase separation in hydrocarbons, which is relevant to planetary interiors and the first shock in compression for inertial confinement fusion. The experiments employed polymers with different carbon:hydrogen ratios. Analysis is being performed in combination with density functional theory – molecular dynamics calculations (DFT-MD).

Tom Duffy (Princeton University) presented about shock-compressed silicon and boron carbides. Silicon carbide (moissanite) is proposed as a major interior constituent of so-called “carbon planets” that may exist around stars with high carbon:oxygen ratios. XRD data showed differing mechanisms of strength loss for these two ceramics under shock-compression. Malcolm McMahon (University of Edinburgh) presented on shock compression of structurally complex metal phases. Using the standard configuration for XRD, the host-guest structure in scandium was examined. McMahon noted the huge improvement in XRD data quality with two additional CSpad quad detectors, which is necessary for complex structures and allowed full Rietveld refinement of the host-guest structure. Emma McBride (SLAC/European XFEL) led an experiment using transverse diffraction from dynamically compressed silicon. Plasticity and phase transitions in shock-compressed silicon were probed in two experimental geometries with the x-rays travelling co-linearly and orthogonally to the shock propagation direction.

Frederico Fiuza (SLAC) spoke about relativistic laser-plasma interactions and that the coherent LCLS x-rays allow spatially and temporally resolved direct measurements of hole boring. Quantitative data analysis is underway with 3D particle-in-cell (PIC) simulations. This presentation highlighted the opportunities to a wider range of relativistic processes with a laser upgrade to 100 TW. Gerald Seidler (University of Washington) presented recent work on warm dense crystallography[17] and pursuit of two-color XRD at MEC. For these experiments, using a single x-ray pulse as both the pump and probe is not ideal, but future facility developments will advance these capabilities. Paul Mabey (Oxford University) presented an experiment examining low frequency collective modes in warm dense aluminum using x-ray Thomson scattering. Improvements in DFT calculations of the dynamic structure factor are being completed for the data analysis.

Each evening of the workshop included a poster session, vendor exhibit, and reception, which encouraged discussion and collaboration among the workshop participants. Poster awards were inaugurated this year, and we congratulate the winners: Alison Saunders (University of California, Berkeley) for her poster on phase separation of hydrocarbons at high pressures and Abe Levitan (SLAC) for his poster on stacking faults in a hydrogen microjet.

User feedback

Staffing: Feedback from the recent user experiments lauded the dedication and helpfulness of the beam staff. However, due to the high difficulty level and complex experimental configuration of many of the experiments, the most universal feedback was that MEC was understaffed for the work level. This concern has been partially addressed by the addition of a dedicated laser manager to the MEC staff and increased technical support for the optical laser systems in FY17.

Optical lasers: The betatron x-ray source generated by the short pulse optical laser exhibited a significant decline in stability and flux this year, but changes with the focusing are planned. It was noted that stability of the laser energy is critical for producing good temporal data sets since kinetics are commonly measured with data from multiple shots in which the time delay is varied between the optical laser and LCLS x-ray pulse. The phase plates that shape the spatial profile of the ns laser produce a strong speckle pattern in its profile. The spatial homogeneity of the dynamic conditions that it generates would be significantly improved with reduction in the F/# of the drive optics and a modest investment in new continuous phase plates (CPP) similar to those used on large laser systems such as OMEGA at the University of Rochester, NY and the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory.

LCLS x-rays: LCLS is currently receiving some new x-ray mirrors that will improve the beam profile when they are installed during the upcoming six-month shutdown period. In the experiment presented by Eliseo Gamboa, it was identified that the best focus of the x-rays using beryllium compound refractive lenses was significantly larger than the theoretical estimates. The disparity between the calculated and measured focal spot sizes should be further investigated. Additionally, there are some diffusely scattered x-rays when the beam is in the MEC target chamber. This diffuse scatter seemed to cause XRD patterns from undriven regions of targets for some of the experiments. The diffuse scatter can be screened from the target interaction volume using a series of upstream apertures in the MEC target chamber, but a better option would be to remove the sources of scattering upstream. There have also been problems with oscillations of the harmonic rejection mirrors (HRMs) in the last two years. The mounts for the HRMs have recently been modified, which should remove the instability that resulted in motion of the x-rays at the target of several hundred microns.

Detectors: Users expressed great pleasure with the improvements in diffraction quality due to the addition of two new CSpad quads in the last year. There were several experiments in which the signal collected was very broad (e.g. liquid diffraction patterns) and covered multiple detector tiles on the CSpads. The background corrections and adjustments between tiles are particularly difficult to deal with in these situations. Additionally, fluctuations in the baselines of the tiles and loss of data from laser-generated electromagnetic pulses (EMP) continue to be an issue. Beam line staff and the LCLS detector group have acquired additional diagnostics to investigate this issue.

Diagnostics: There is damage on the image intensifiers in the streak cameras used for the line-imaging VISAR diagnostic. The damage can obscure data in the central region of the cameras. Refurbishment to correct the damage will be done during the upcoming six-month shutdown period. Discussion about future development of diagnostics requested temperature measurement, perhaps with a permanent streaked optical pyrometer.

Facilities: Space for target preparation was universally desired by the user groups. The lab space should include a fume hood and a microscope in addition to the recently acquired stereoscope.

Operations: Users suggested some improvements and further automation in alignment and sample positioning. Higher resolution imaging of the sample was requested, but may prove challenging since the imaging components are stationed outside of the 2 m diameter MEC target chamber. A graphical user interface for controlling the CSpad detectors was also suggested.

Experiments at other facilities

For proper perspective in discussing capability investments and plans for high power laser experiments at LCLS, we had several presentations about science that is being performed by the global HED community. Tilo Doeppner (Lawrence Livermore National Laboratory) presented about the generation and characterization of dense plasmas at Gbar pressures. In a discovery science campaign on NIF, a spherically convergent shock was used to generate high pressures.[18] In these experiments, diagnostics of nuclear reactions and X-ray self-emission constrained the EOS of matter at 40 Gbar. In the last 2 years, a new X-ray Thomson scattering platform at NIF has been developed for near-degenerate plasmas at mass densities >25 g/cc.

Sam Vinko (Oxford University) spoke about measurements of collisional dynamics and opacity in solid density plasmas. Hot dense plasmas can be created using free electron lasers on fs timescales via X-ray photoionization. Measurements of the collisional dynamics have resulted in a number of recent publications.[19, 20]

David Reis (Stanford University/SLAC) presented on anomalous non-linear Compton scattering experiments that were performed at the Coherent X-ray Imaging hutch of LCLS.[21]

Dirk Gericke (University of Warwick) discussed the experiments that are needed to test WDM theory. He articulated particular physics experiments for testing theory, including phase transitions for EOS modeling, ion structure for micro-physics, conductivity or stopping power for collisionality, and reflectivity for dielectric properties.

Norimasa Ozaki (Osaka University) presented recent research in HED material using GEKKO and SACLA. This research was included in a recent publication about the universal Hugoniot of fluid metals.[22]

Karen Appel (European X-ray Free Electron Laser (EXFEL)) presented on the upcoming capabilities for free electron laser experiments in Germany.[23] The HED instrument at EXFEL will begin commissioning starting in February 2017 and have first experiments in June 2017. The HED instrument will be focused on physics of highly excited solids, near solid density plasmas, and quantum states of matter. It will include a split and delay line based on multi-layer mirrors[24] and will have two target chambers.

MEC status and outlook

MEC department head Andy MacKinnon presented the vision for MEC to develop and exploit the unique LCLS source for HED physics and extreme material science, to broaden its impact across the community, to expand the scientific reach of the facility through enhancing the high power laser capabilities, and to be responsive to the scientific community's priorities. In FY16, MEC increased its number of experiments by 50% compared to FY15, and it implemented experimental standard configurations, which were responsible for 30% of the increase. MEC achievements also included implementing a wave-front sensor and deformable mirror to optimize short pulse focal spot and working on DAQ upgrades for laser diagnostics and VISAR data acquisition. The facility faced a few challenges in the past year, most of which concerned laser-induced damage to equipment (damage to the final short pulse laser amplifying crystal from backscattered light, increased area of peripheral damage to targets with the long pulse laser, and damage to the streak cameras' MCPs). Repairs or mitigation plans will be implemented during the LCLS shutdown period during the first half of 2017. User experiments were also impacted by the failure of a laser power supply, which was repaired with the loss of only one shift, and by the failure of a water tank that is part of the cooling system for the LCLS accelerator.

MEC is planning several upgrades. An additional experimental standard configuration will be implemented in run 16 and will be a configuration with concurrent PCI and XRD. MEC is seeking feedback on the proposed candidates for short pulse standard configurations of electron acceleration in gas targets, betatron secondary x-ray source, and solid or liquid targets at 30-100 TW. The commissioning of the short pulse laser at 100 TW will be carried out during the first half of 2017. The long pulse laser will be upgraded during 2017 to 40 J in a 10 ns square pulse, initially at the second harmonic wavelength (527 nm), with improved temporal pulse shaping, improved energy stability (from replacing the flash lamp pump preamplifiers with a diode pumped system), and incorporation of a suite of laser diagnostics into the DAQ. Further conversion to the third harmonic wavelength (351 nm) will be provided on the 2018/2019 timescale. Future upgrades to increase the long pulse laser to 200 J with a repetition rate of one shot per minute and to create a shielded hutch for high intensity laser experiments above 200 TW are in the planning stages.

X-ray free electron laser status and future plans

LCLS Director Mike Dunne presented exciting recent developments with LCLS, including several new modes of operation that can provide polarization control of the x-rays, multiple options for two-pulse and two-color x-rays, bandwidth control using an electron beam dechirper, and an extended photon energy range of 0.25 to 12.8 keV. There is also a current research and development project to obtain sub-fs x-ray pulses. While the accelerator is off during the first half of 2017, the hard x-ray mirrors will be upgraded, which will significantly improve the x-ray beam profile at the hutches and the x-ray transport efficiency, and experimental support laboratories will be added in the tunnel into the far experimental hall.

The LCLS-II upgrade is underway with scheduled completion in 2020. It will include four new instrument areas, and there is a website for communicating its on-going developments and to seek feedback from users.[25] During the workshop presentations, there were several mentions of the desire to use separate x-ray pulses to pump and to probe. The planned tender x-ray hutch will afford this opportunity with its ability to simultaneously receive pulses from both the hard and soft x-ray undulators.

The vision for a future XFEL facility at Los Alamos National Laboratory was presented by Cris Barnes (LANL). This facility, named Matter-Radiation Interactions in Extremes (MaRIE), would construct a 12 GeV electron linac to feed a 42 keV XFEL. The primary scientific objective will be to address national security science challenges in the mesoscale regime, including prediction of material microstructure and performance based on knowing the material processing conditions.[26]

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Additional information may be obtained at the workshop website: https://conf-slac.stanford.edu/hpl-2016/

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