Matter in Extreme Conditions At LCLS

Gilliss Dyer, December 5, 2018

Fusion Power Associates 39th Annual Meeting

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Switched on in 2009, the Linac Coherent Light Source was the world's first hard x-ray free electron laser

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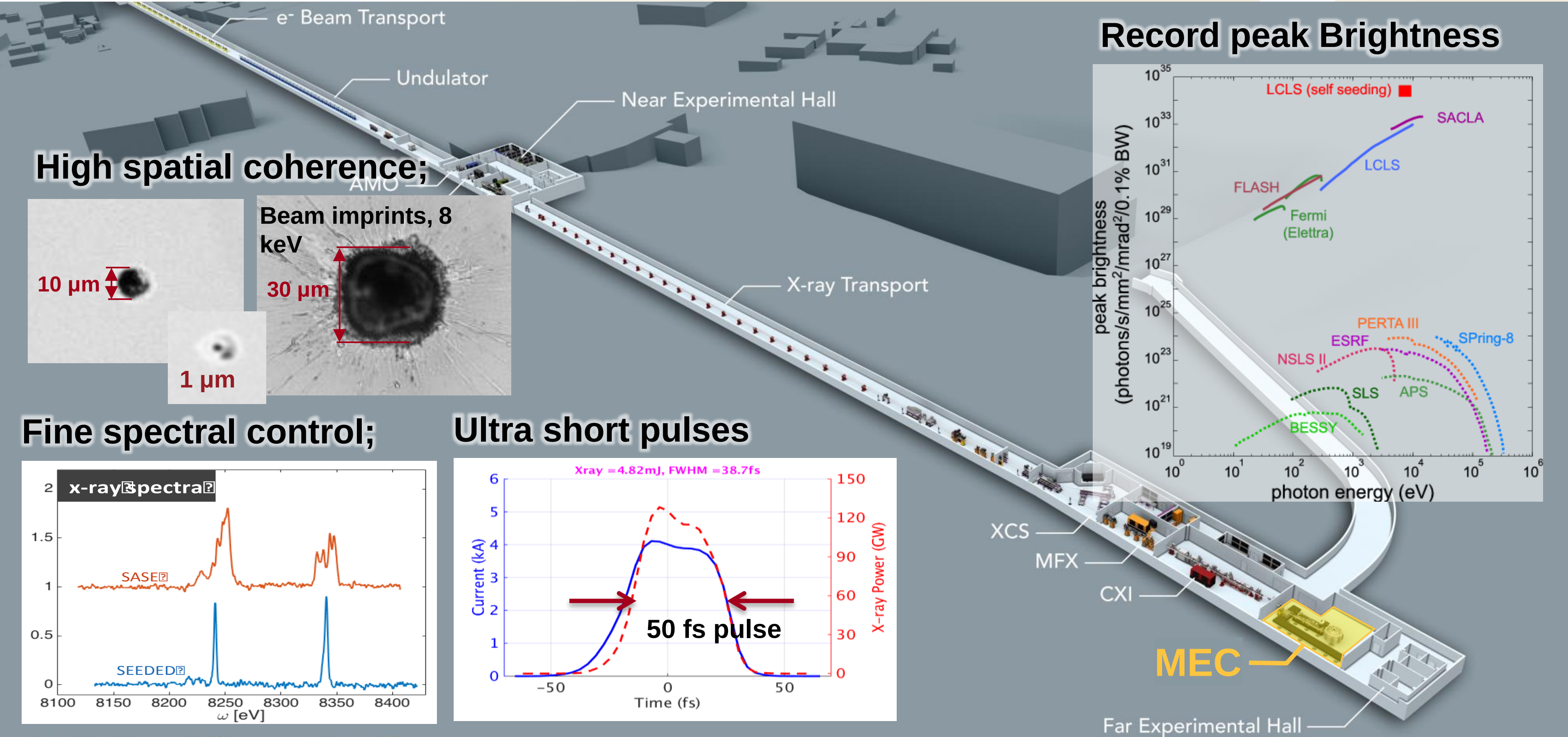
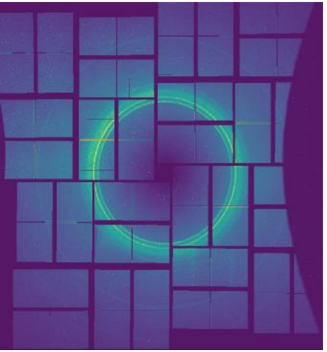
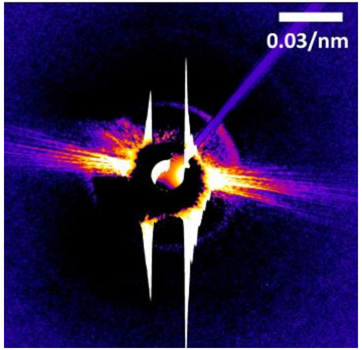
The extraordinary properties of the LCLS beam enable groundbreaking high energy density science



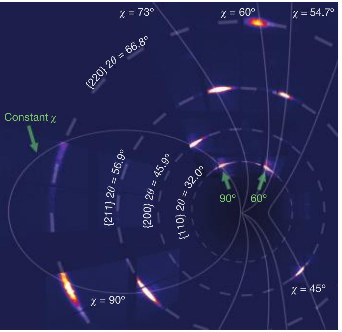
LCLS is an exquisite probe of dense plasma states



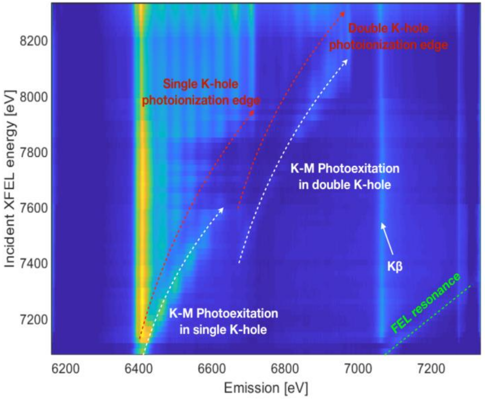
Wide Angle X-ray scattering:
WDM structure; properties; EOS
Witte, PRL (2017),
Sperling, PRL (2015),
Fletcher, Nature Photon. (2015)



Small Angle X-ray scattering
nm-scale plasma features
***Kluge et al., PRX (2018)**



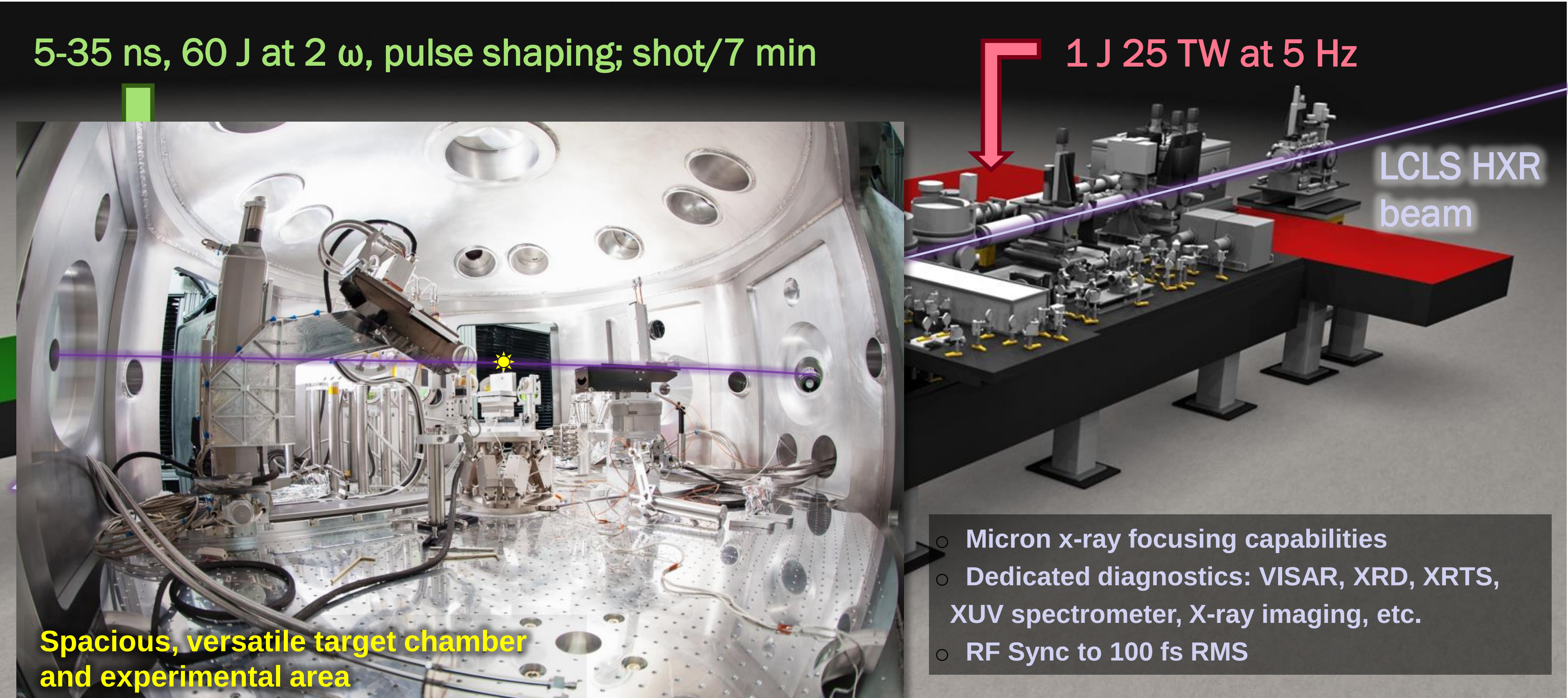
Ultrafast X-ray Diffraction :
Dynamic phase transitions; lattice dislocations
Brown, Science Advances (accepted)
McBride, Nature Phys, (2018)
Kraus, Nature Astr. (2017)
Gleason, Nature Comm. (2015, 2017)
Wehrenberg, Nature (2017)
Kraus, Nature Comm. (2016)



X-ray emission spectroscopy and resonant photo pumping
Population kinetics and transition rates in plasmas

Preston , PRL (2017)
Ciricosta, Nat. Commun. (2016)
Vinko, Nature (2012)
Several in preparation…

MEC combines the sub-micron focusable hard X-ray beam with high power and high energy lasers



- Micron x-ray focusing capabilities
- Dedicated diagnostics: VISAR, XRD, XRTS, XUV spectrometer, X-ray imaging, etc.
- RF Sync to 100 fs RMS

B. Nagler *et al*, J. Synchrotron Rad. 22

The optical lasers are used to create and/or probe high energy density and plasma states

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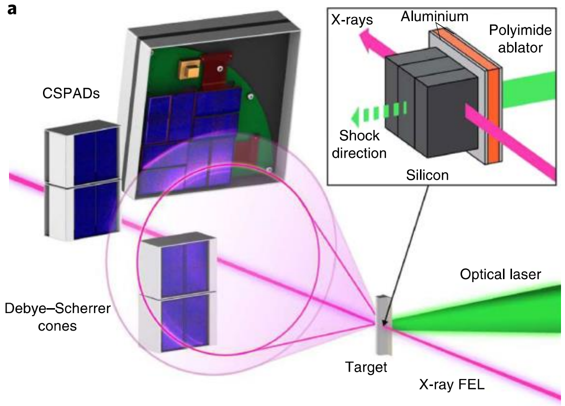
Compression laser

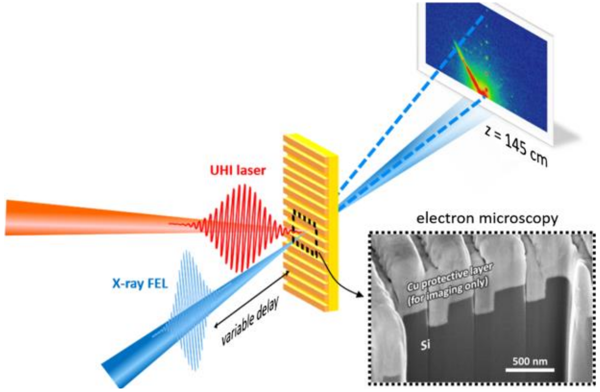
- Planetary interiors / impacts
- Shock dislocations / dynamics
- Warm dense matter
- Phase transitions

High power laser

- Relativistic laser-matter interaction
- Direct heating of structured targets
- Atomic physics in HED plasmas
- Ion heating



McBride, et al. Nature Physics (2018)
Phase transition lowering in dynamically compressed silicon



Kluge, et al. Phys. Rev. X (2018)
Observation of Ultrafast Solid-Density Plasma Dynamics Using Femtosecond X-Ray Pulses from a Free-Electron Laser

In 2020 the first part of the LCLS-II upgrade will deliver higher photon energies with faster energy switching

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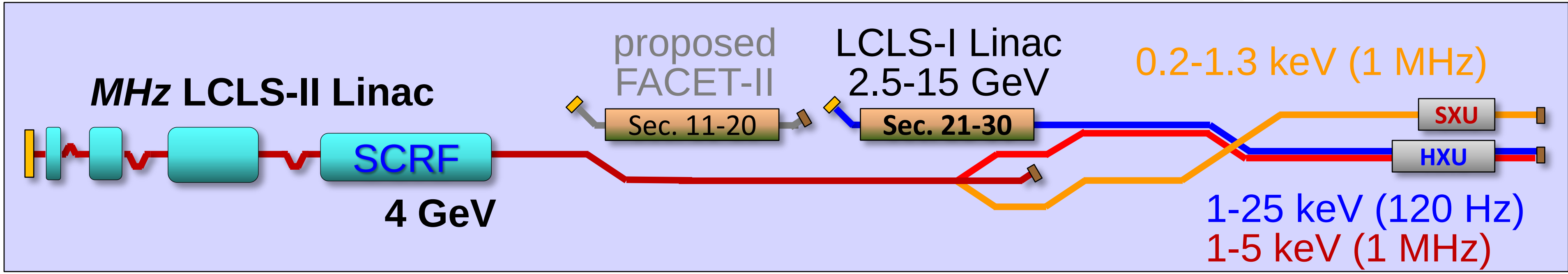
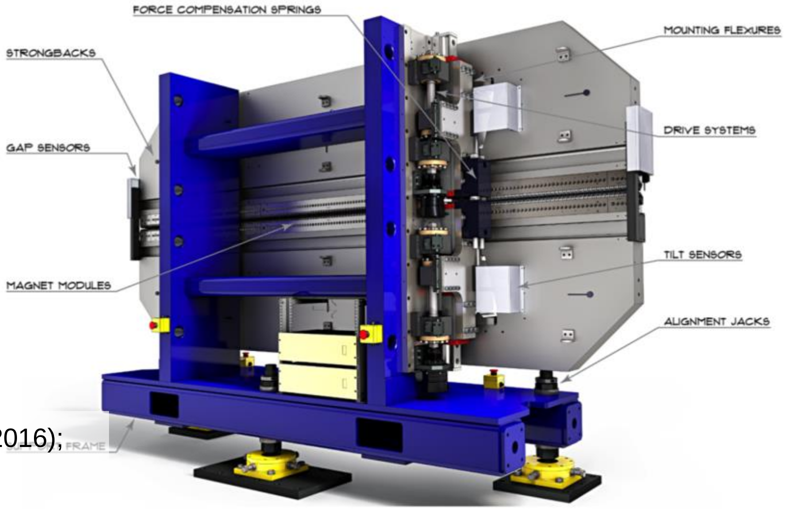


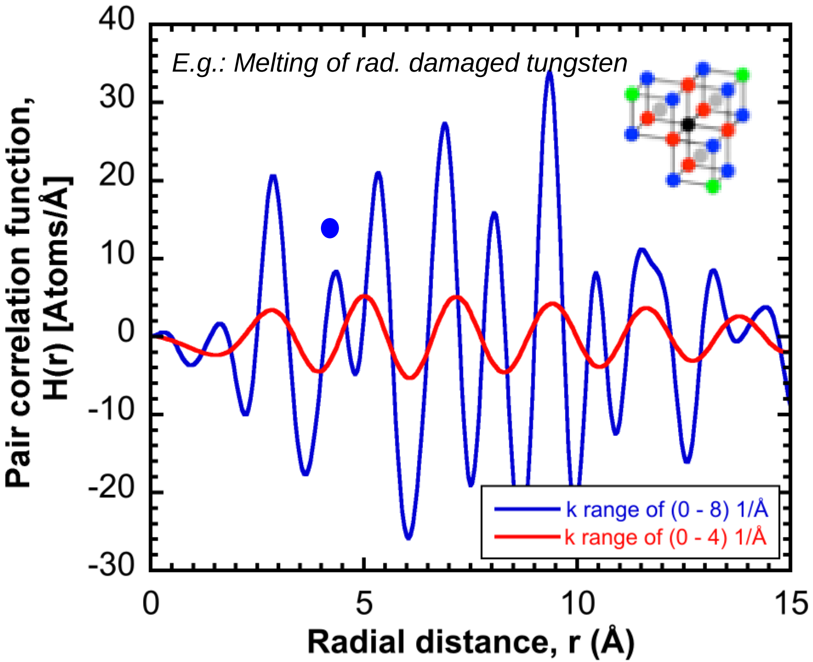
- LCLS-II upgrade will make first CW MHz XFEL in the world (2021)
- Current undulator replaced with HXR and SXR variable-gap undulators



AIP Conference Proceedings 1741, 020025 (2016); doi: 10.1063/1.4952804

Higher photon energies to be available from the new hard X-ray undulator will enable new science

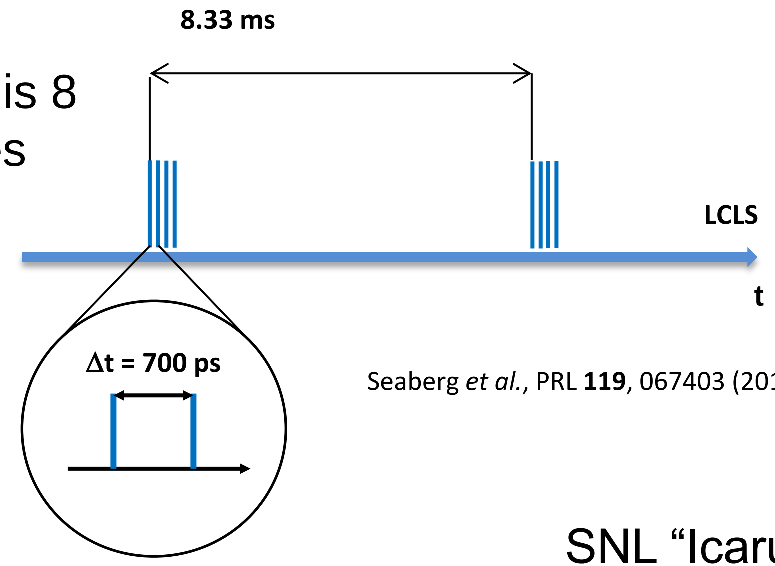
The Pair Correlation Function measures atomic dislocations



- High resolution from wide angle scattering
- Higher spectral resolution (ΔE/E)
- Access to higher Z materials
- Better bremsstrahlung filtering

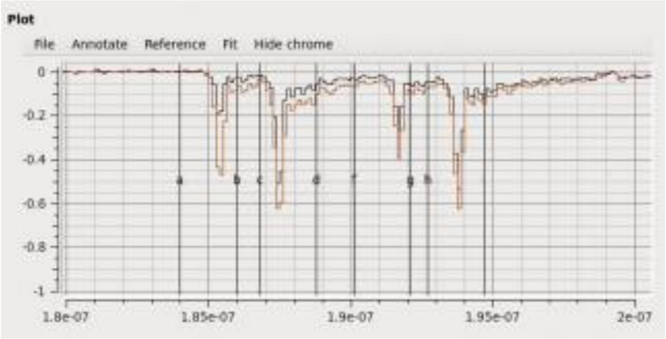
Development of multi-pulse capability will enable dynamic measurement on sub-ns timescale

Goal is 8 pulses

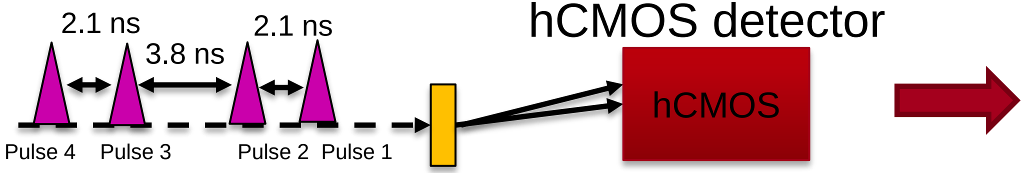


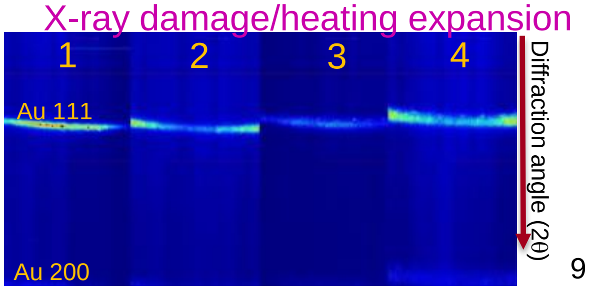
Seaberg *et al.*, PRL **119**, 067403 (2017)

Creation of <u>four</u> pulses with 700 ps separation has been demonstrated in October.



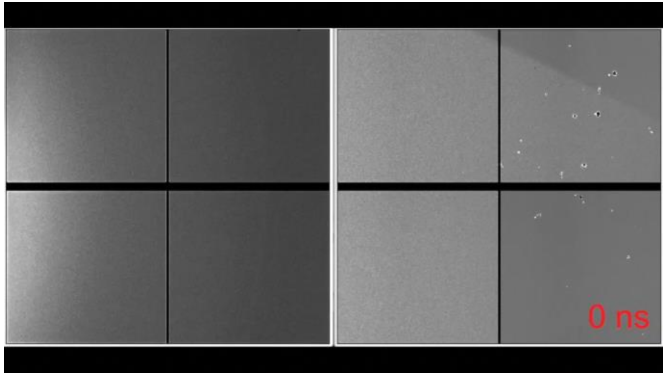
SNL "Icarus" hCMOS detector





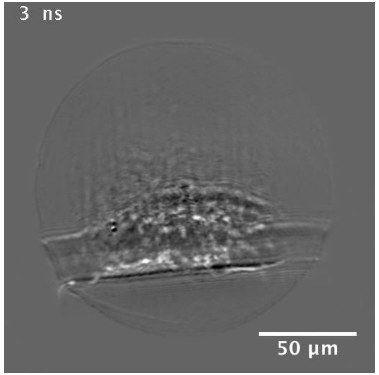
* Experiment led by **P. Hart (SLAC),** Dan Damiani, Arianna Gleason, Phil Heimann, Silke Nelson, Emma McBride, Sanghoon Song, Diling Zhu, Mike Glownia, XCS staff, ; LLNL: Arthur Carpenter, Matthew Dayton, Emily Hurd; SNL: Marcos Sanchez

Multi-pulse detector capabilities are a high priority for high energy density science at MEC



Shock compression of SiO2; Courtesy A. Gleason

Diffraction



PCI

Shock compression of Kapton; Courtesy B. Nagler

Current

Multiple shots on identical targets (destroyed each shot); subject to differences in:

- Impurities,
- Microstructure,
- History
- Beam conditions

Future

- Up to eight data sets for a single condition
- 4-fold or better improvement in kinetics models

International competition for MEC is growing

EuXFEL, Germany
XFEL HED end station:
10 J 300 TW
100 J (1 kJ) long-pulse
Pulsed magnet (10-50T)

SACLA, Japan
XFEL HED end station:
12 J, 500 TW x2
40 J (200 J) long-pulse

ELI-Beamlines; -NP; -ALPS
Variety of 1 to 10 PW lasers
Proposals for “table-top” XFEL

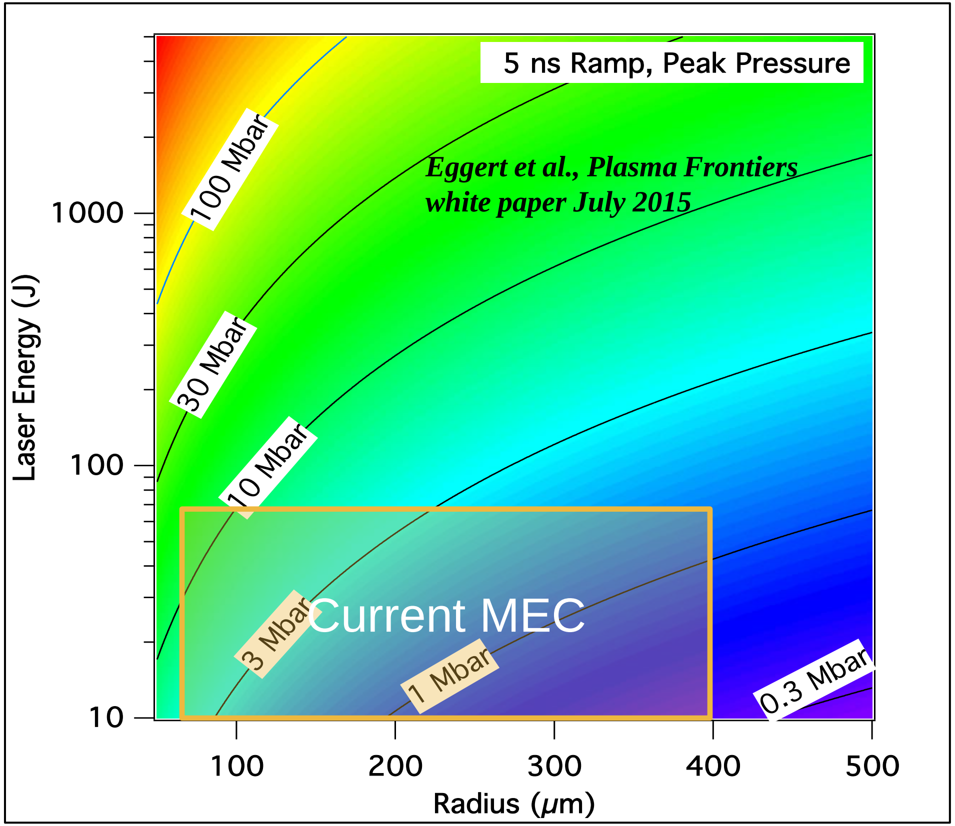
SCLF, Shanghai (~2025)
XFEL Station of Extreme Light:
1.5 kJ, 100 PW
(10 kJ long-pulse)

This competition must be met for the US to maintain world leadership

A higher energy shock drive laser will provide access to new phases of dense matter

Enabled by kJ class shock driver coupled to LCLS:
Exotic states, such as:
- Electrides
- BC-8 carbon state

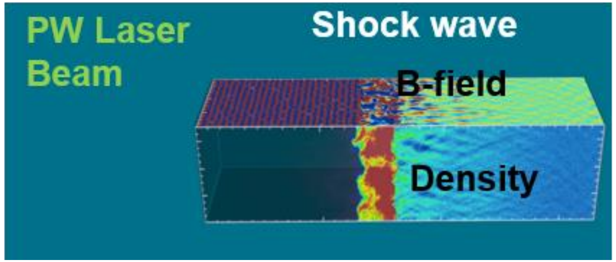
High pressure liquid / WDM EOS
Liquid-liquid phase transitions



A PW laser at LCLS would access important new physics regimes, opening scientific frontiers

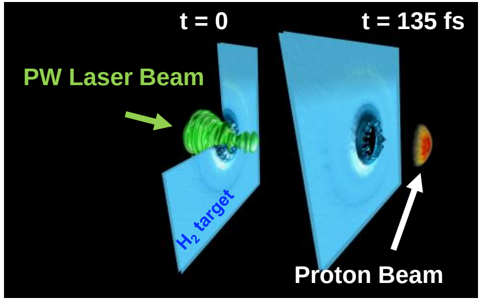
Basic Plasma Science

- Probe relativistic shocks with X-ray imaging and scattering techniques



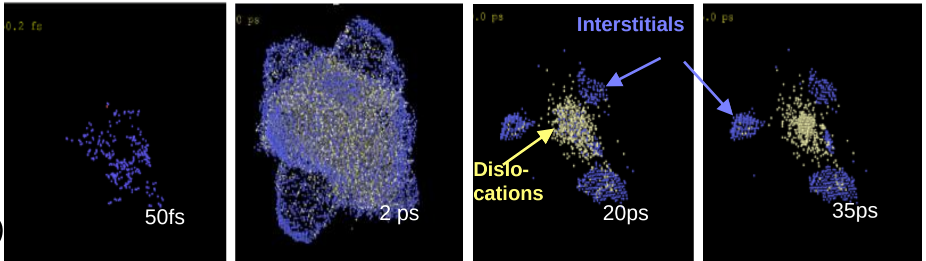
Extreme Conditions

- Utilize ion beams for, e.g., stopping power measurements in well-characterized plasmas



Materials for Fusion Research

- Resolve damage cascade on the atomic scale



Courtesy A.E. Sand (2018)

There is an opportunity to significantly upgrade the laser capabilities at LCLS

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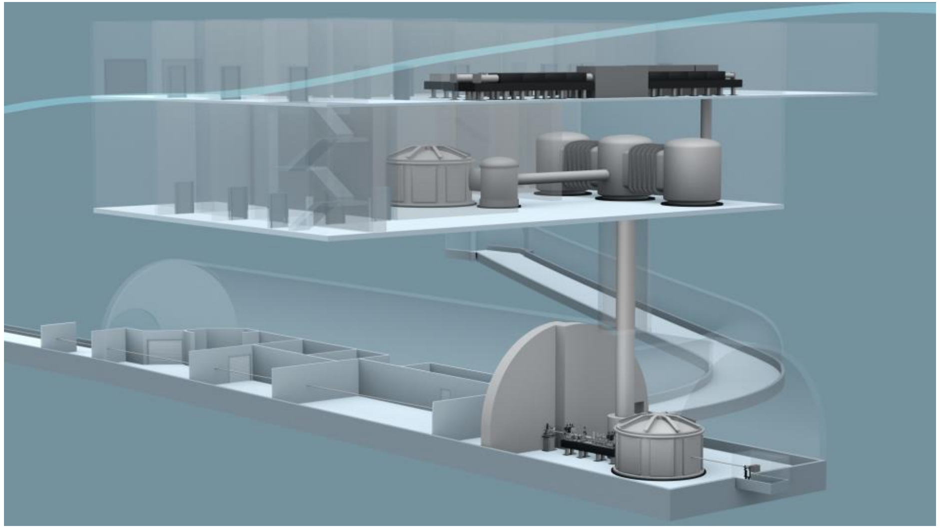
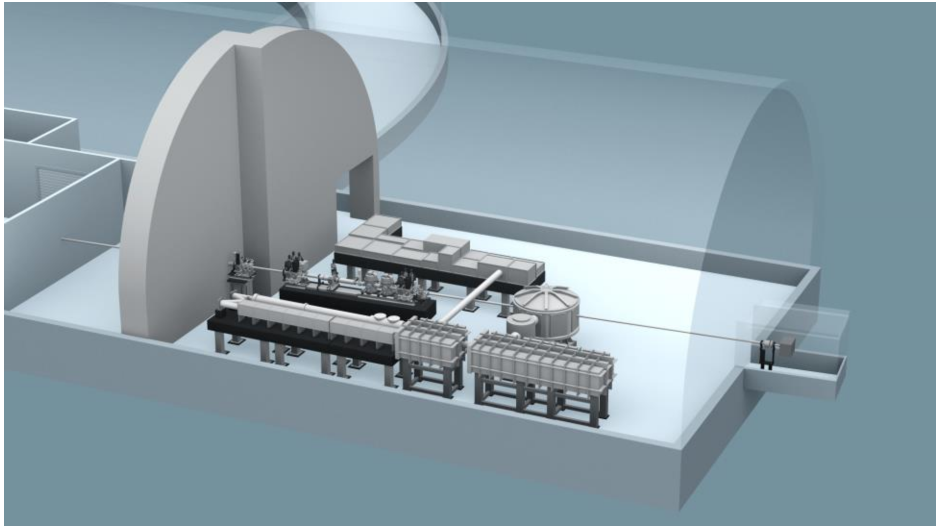
Additional space can be made available in the FEH for a major investment in high power, high repetition rate lasers. Timeframe for construction: ~2023



Scenario 1: Expand in FEH and add new building allowing for future growth



Scenario 2: Expand in FEH only and combine PW laser with target area

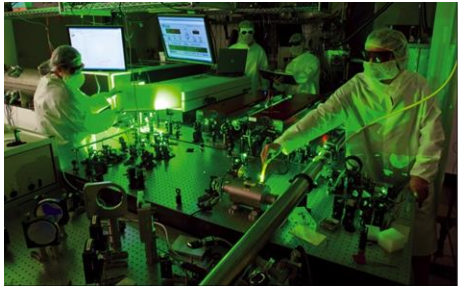
LaserNetUS Collaboration

- DOE Research Network, funded by the Office of Fusion Energy Sciences
- Intended to Give U.S. Scientists Access to the Most Intense Laser Sources Available
- Call for Proposals in February 2019

Colorado State University
Advanced Beam Laboratory
Jorge Rocca, jorge.rocca@colostate.edu

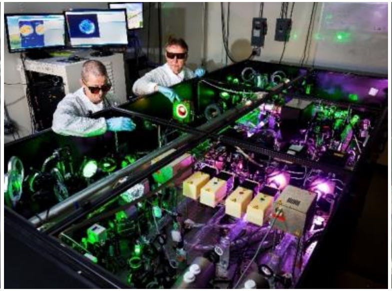
Lawrence Berkeley National Lab
Berkeley Lab Laser Accelerator (BELLA) Center
Thomas Schenkel, t_schenkel@lbl.gov

Lawrence Livermore National Laboratory
Jupiter Laser Facility
Robert Cauble, cauble1@llnl.gov

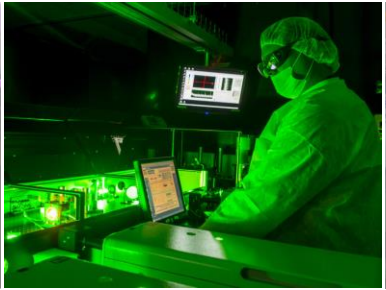


Ohio State University
Scarlet Laser Facility
Douglass Schumacher, schumacher.60@osu.edu

SLAC National Accelerator Laboratory
Matter in Extreme Conditions (MEC) Laser Facility
Gilliss Dyer, Gilliss@slac.stanford.edu

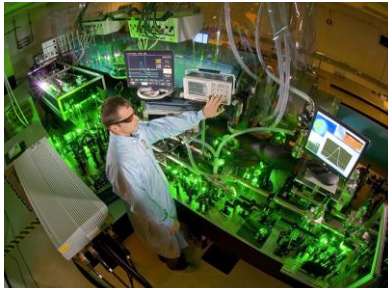


University of Michigan
Center for Ultrafast Optical Science: HERCULES
Karl Krushelnick, kmkr@umich.edu



University of Nebraska - Lincoln
Extreme Light Laboratory
Donald Umstadter, donald.umstadter@unl.edu

University of Rochester
Laboratory for Laser Energetics: OMEGA EP
Mingsheng Wei, mingsheng@lle.rochester.edu



University of Texas - Austin
Center for High Energy Density Science:
Texas Petawatt Laser
Todd Ditmire,

BACKUP SLIDES

Proposing A Flagship Facility at LCLS to Serve the HED Science Community

Configurations	Available Pulses	Repetition Rate	Energy on Target Baseline	Energy on Target Enhanced
High Peak Power	150 fs	Shot / min	150 J	>1 kJ (10 PW)
Averaged Power	80-150 fs	> 2 Hz	0.1-1 J	150 J (1 PW)
High Energy [compression]	10 ns shaped	Shot / min	200 J	>1 kJ

- A flexible laser architecture will support the whole user community
- All configurations will be available in combination with LCLS x-rays
- Switch-over between configurations will require 1 week setup time

The enhanced option will deliver the highest power laser in the U.S.

The recent NAS/E report recommends strengthening U.S. position in the field of high-intensity laser research

Conclusion 3:

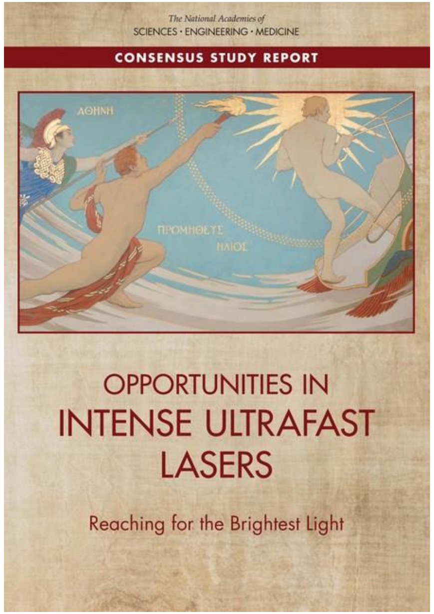
The community is large but fragmented. There is a large and talented technical community already, but it is fragmented across different disciplines. Coordination between industry and government is limited and often inadequate. The scientists and engineers trained in intense ultrafast lasers contribute to the workforce for applications in photonics and optics, including high-energy lasers for defense and stockpile stewardship

Recommendation 1:

The Department of Energy should create a broad national network, including universities, industry, and government laboratories, in coordination with the Office of Science and Technology Policy, the research arms of the Department of Defense, National Science Foundation, and other federal research organizations, as the cornerstone of a national strategy to support science, applications, and technology of intense and ultrafast lasers.

Full report (327 pages)

http://nap.edu/24939



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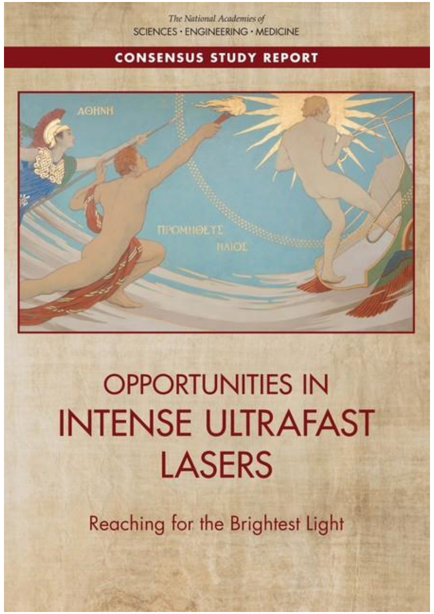

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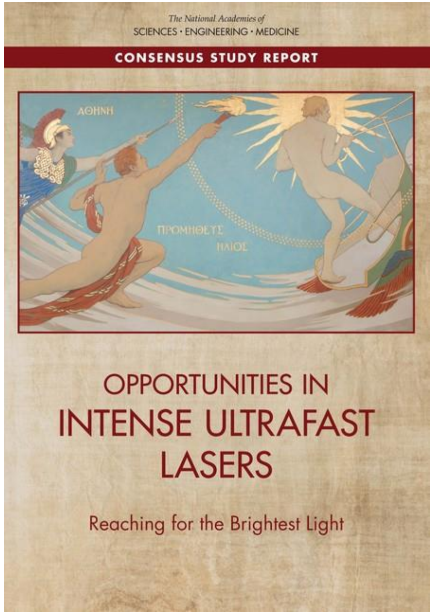


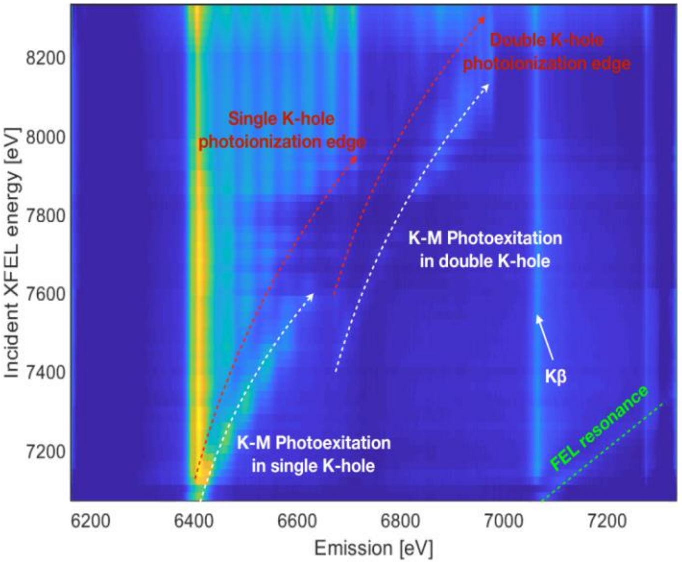
Conclusion 6:

Co-location with existing infrastructure is essential…

Recommendation 4:

The Department of Energy should plan for at least one large-scale open-access high-intensity laser facility that leverages other major science infrastructure in the Department of Energy complex.

Creation of keV temperature and solid-density plasma isochorically heated by nano-focused hard X-ray



Spectrally resolved Kα emission as a function of the hard X-ray LCLS incoming beam. The K-shell holes are created exclusively by intense, quasi-monochromatic LCLS beam. The LCLS beam is absorbed by photoinzing the K-shell and subsequent Auger recombination refills the K-shell, heating the valence band in the process. Depending on charged states, K-M photoexitation was observed

H. J. Lee *et al.*, analysis in progress

Work was performed at the CXI end-station at LCLS in April 2018

Scientific Achievement

Nano-focused hard X-ray beam by KB mirrors at the LCLS created K-shell holes and highly ionized states in extremely high temperature (10^6 – 10^7 K) in Iron solid system, marking the first measurement of spectroscopic data showing electronic structure in this condition

Significance and Impact

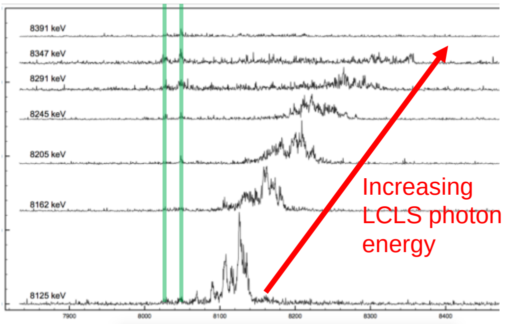
Hard X-ray heating on solid materials using nano-focused beam enables to access the regime of hot dens matter and study multiple processes involved in electronic structure, photoionization, and continuum lowering

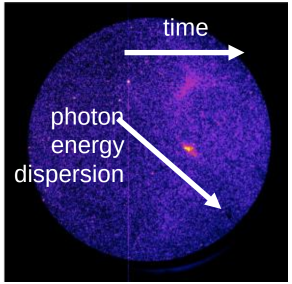
Research Details

- Nano-focused beam of ~140nm x 100 nm providing provides intensity of ~5 x 10^{19} W/cm^2 was measured using Talbot Interferometry and Double frequency shearing Interferometry
- Intense and tunable hard-X-ray pulses of LCLS could follow the change of charged states and record electron energy-level structure presenting multiple processes

Berkeley UNIVERSITY OF CALIFORNIA   UNIVERSITY OF OXFORD   SLAC NATIONAL ACCELERATOR LABORATORY

Ultra-precise atomic physics in High Energy Density Plasmas





Left : Each curve is a spectrum (spectral resolution of ~2500 and spatial resolution of about 10 μm) of the resonantly pumped copper plasma with increasing FEL photon energy (resonantly exciting different charge states inside the plasma) at a fixed time delay between the pump and probe beams. The spectrum gives new insight on the available charge states. Green lines are Cu K_α lines.

Right : Spectrum resolved in time (temporal resolution of ~1ps) of the oxygen-like Cu ions pumped at a fixed time delay. It provides new data to measure the transition rates directly in the plasma.

E. Galtier *et al*., analysis in progress.

Work was performed at the MEC end-station of LCLS.

Scientific Achievement

First measurements of atomic population and plasma kinetics in high intensity laser/matter interaction with simultaneous high spatial, spectral and temporal resolution.

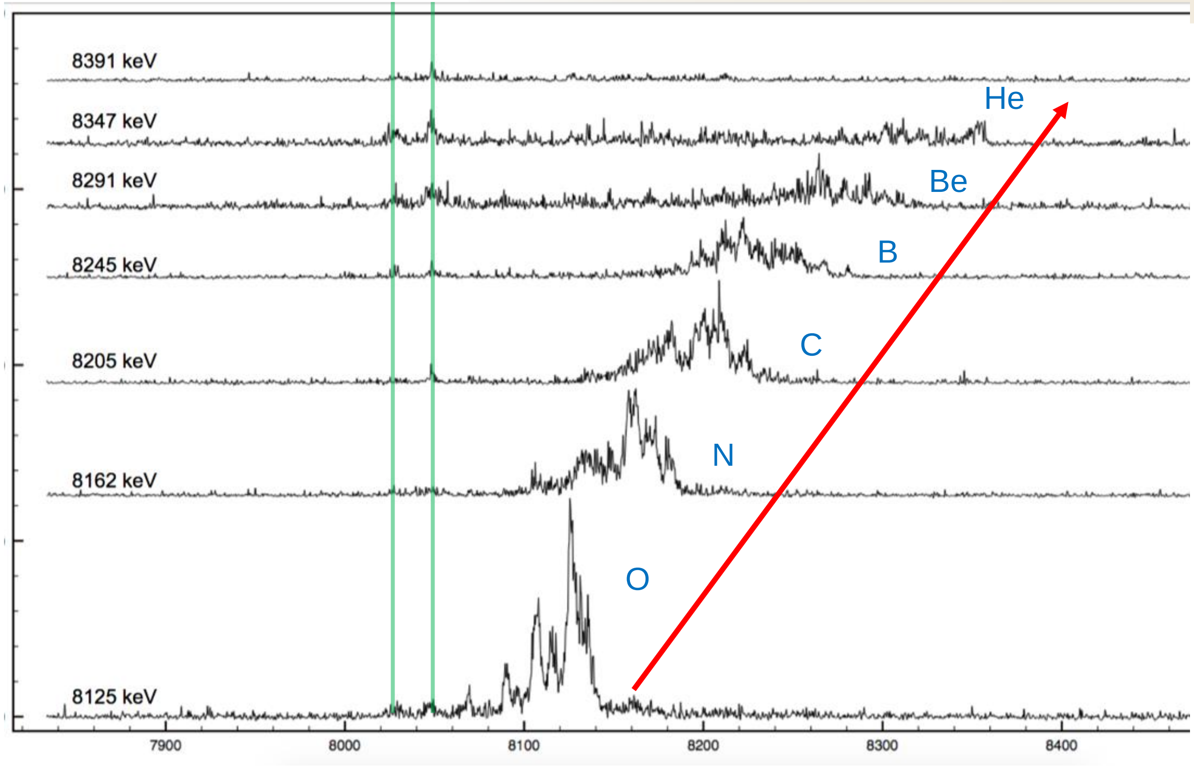
Significance and Impact

This work contributes to advance our knowledge of virtually all transient laser-produced plasmas found in laboratory astrophysics, fusion research or high energy density physics.

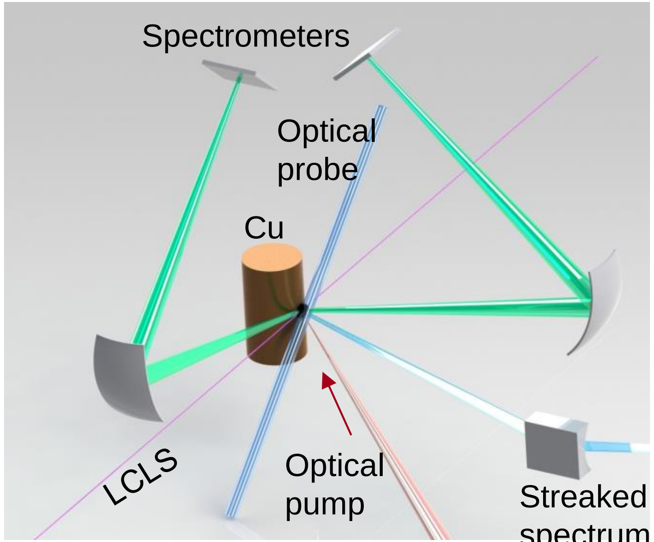
Research Details

- An optical laser produced a copper plasma, pumped at various time delays and photon energies (using the LCLS X-ray beam) to resonantly excite specific atomic populations and watch them recombine.
- An X-ray streak camera followed the temporal evolution of the re-emitted photons within the plasma, along with two spatially resolved high-resolution spectrometers.
- Scanned the X-ray pump photon energy (atomic population content) and its time delay with the optical laser (dynamics).

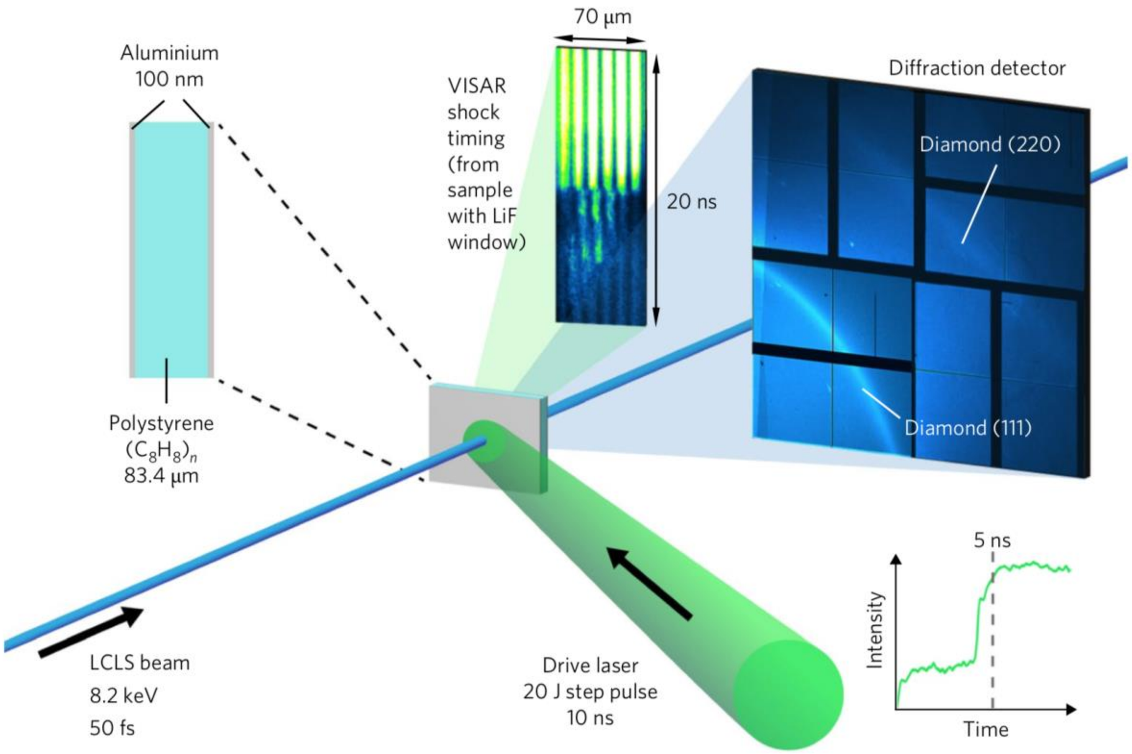
LCLS can be used for detailed measurements of plasma kinetics and transition rates



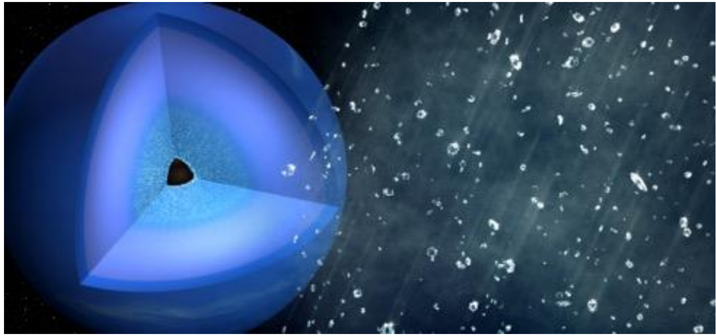
Example: Resonant photo-pumping of laser driven dense plasmas
E. Galtier, in preparation



The compression laser is used with diffraction to elucidate structure at extreme pressures

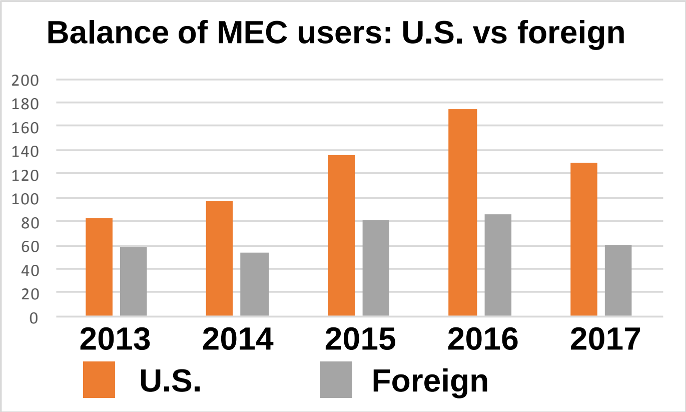


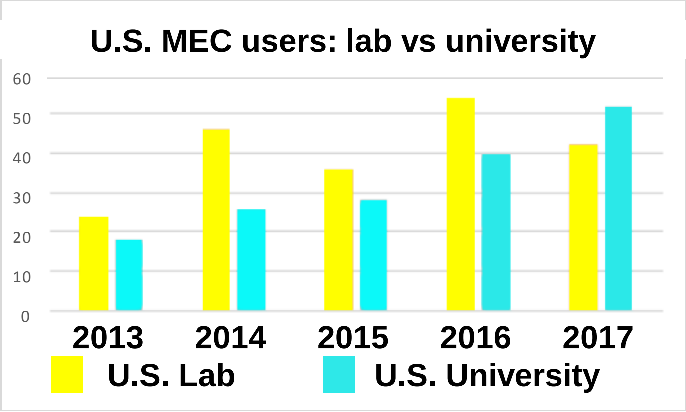
Example: Proof that hydrocarbons disassociate at Neptune interior pressures and form “diamond rain”



D. Kraus, et al, Nature Astronomy (2017)

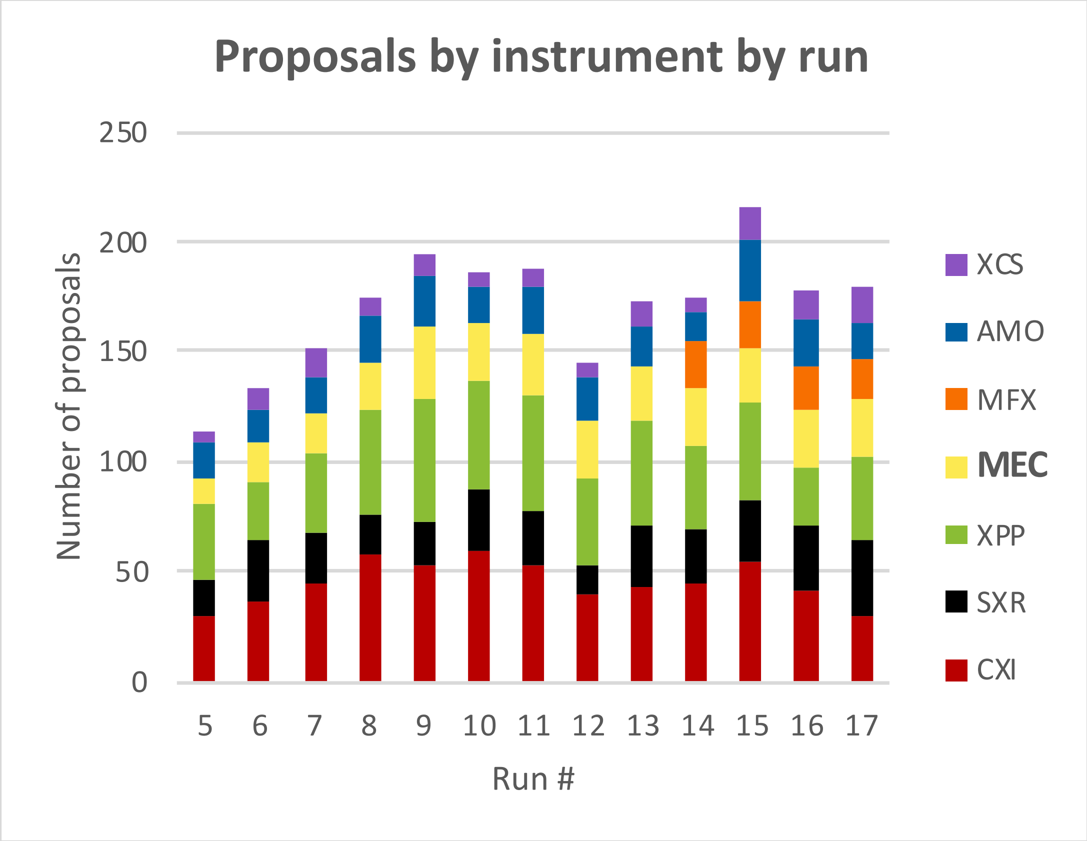
MEC has a large U.S. user base





- **MEC User statistics (from Run 5 to Run 16):**
  - 1287 user-visits
  - 407 unique users who have been granted beamtime,
  - … of whom 223 (55%) are from US institutions
  - 666 unique researchers submitted proposals, whether approved or not
  - MEC users are dominantly US-based (see chart 1)
  - US users (excluding SLAC) are roughly equally split between US universities and National Labs (see chart 2)

MEC experiments continue to represent a significant proportion of LCLS proposals



The MEC instrument has received about 15% of submitted proposals and 15% of accepted experiments in recent years

Historically, around 25% of proposals are accepted