White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***19 June 2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
Indicate secondary area or areas by placing "S" in right column

	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	P
• Turbulence and transport	S
• Interactions of plasmas and waves	S
• Plasma self-organization	
• Statistical mechanics of plasmas	S

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	X
Poster	
Either Oral or Poster	
Will not attend	

Title:	X-ray Free Electron Lasers (XFELs) as a preeminent tool for plasma science
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- ***Describe the research frontier* and importance of the scientific challenge.**

X-ray Free Electron Lasers (XFELs) such as the Linac Coherent Light Source (LCLS) offer a revolutionary potential for plasma physics, and are already demonstrating this potential in many areas of atomic and molecular physics, ultrafast chemistry, biology, and extreme material science, with 25 publications to date in *Science* and *Nature*, and 113 in other high impact journals since the instruments became operational in the 2009-2012 timeframe. See White *et al.* (2015), Nagler *et al.* (2015), and references therein.

XFEL sources can drive unique studies across a broad span of the FES Plasma Science portfolio, including areas as diverse as fundamental plasma and atomic physics, astrophysical and space plasmas, High Energy Density Plasmas (HEDP), Warm Dense Matter (WDM), intense charged particle beam dynamics, radiation-matter interactions, high pressure material science and shock wave phenomena.

Topics studied in the first 3 years of LCLS operation in the FES field include the following:

- **WDM**: Due to the large absorption depth of hard X-rays coupled to the high source brightness, solid samples can be isochorically heated into the WDM and HEDP regimes. Experiments using space and time resolved interferometry have shown that matter heated in this way is highly homogeneous: silver samples of 0.5 micron thick were heated to 10-15eV with a temperature gradient less than 1eV/micron, and at known (solid) density (Levy et al, 2015).
- **ATOMIC PHYSICS**: At higher intensities, temperatures in the 100-200 eV were achieved in Aluminum, creating uniform samples that can act as a platform for a wide variety of studies (Vinko et

al., 2012). In such high-density plasmas, the characteristic screening (Debye) length becomes shorter than the inter-particle distance. The free electrons and neighboring ions affect the distribution of the electrostatic potential surrounding an ion, which leads to the phenomenon of ionization potential depression. These phenomena strongly affect the ionization, equation of state, and opacity of the system by changing the number of bound states and the charge state distribution. These phenomena can be probed by emission spectroscopy of K-alpha photons, when the holes in the inner shells created by the incident LCLS X-rays are refilled. Such measurements have already yielded information on ionization potential depression for the various ionization states of aluminum, which was shown to overturn a long-standing model (Stewart and Pyatt, 1966). In addition, emission spectroscopy allows for the direct measurement of collisional rates in dense plasmas (Vinko et al, 2014). These past and future experiments show that LCLS is uniquely placed to measure many fundamental properties of dense plasmas.

- **HEDP**: LCLS is well suited to address fundamental aspects of radiation transfer, detailed kinetic processes and kinetics rates measurements of high energy density plasmas. Slow progress has been made over the last 40 years mainly due to the lack of in situ measurements connected to the large number of states that need to be included in the models for laser produced plasmas, their rapid time evolution and large spatial gradients. However, the high brightness, tunable wavelength and short pulse length of LCLS allows us to selectively pump a specific electronic state of a laser produced plasma, creating a distribution of states which is accurately known. Time resolved spectroscopy allows us to measure the redistribution in the available plasma states, giving unique and detailed information about the population kinetics, which is essential for predictive models of high energy density plasmas.
- **PLASMAS/WAVES**: X-ray Thomson scattering with X-ray FEL radiation provides quantitative characterization of plasma parameters with unprecedented precision. The seeded LCLS beam has allowed the accurate measurement of a plasmon spectrum under shock compression (Fletcher et al., 2015) where the plasmon frequency is sensitive to the free electron density and defines the degree of compression in the plasma. The elastic scattered feature indicates the electron temperature of the plasma. It was necessary to include additional repulsion from overlapping bound electron wavefunctions. Several theoretical approaches have been applied to experimental data to validate theoretical models of WDM for simulations in planetary conditions (Brown et al., 2014).
- **ASTROPHYSICS**: The interaction of an ultrashort, high-intensity optical laser pulse with a gas or solid has been shown to enable investigation of new scientific regimes in many facilities worldwide. It is, however, challenging to diagnose relevant phenomena at the appropriate spatial and temporal resolution using conventional techniques. X-ray FELs can be key to observing and understanding this emerging new field, via the provision of highly quantitative data and the ability to scan a very wide phase space by making use of the high repetition rate, and tunability of the coherent x-ray pulse. Some example areas include the study of relativistic particle dynamics, and the study of collisionless shocks, which are central to astrophysical events such as supernovae remnants, Earth bow shocks, quasar jets, and cosmic rays (Blandford and Eichler, 1987). The electromagnetic turbulence or Weibel instability is believed to be the leading mechanism for shock formation in weakly magnetized plasmas (Medvedev and Loeb, 1999), and can now be directly imaged using phase contrast techniques that take advantage of the unique properties of the XFEL beam.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

The emergence of LCLS in 2009 as the world's first hard-x-ray free electron laser (XFEL) has provided a powerful new tool for plasma science. The peak brightness of X-ray FELs is 8 to 9 orders of magnitude higher than storage rings, representing a fundamental shift in the paradigm for x-ray driven science. The emerging, next-generation (such as LCLS-II and European-XFEL, available in the 2017-2020 timeframe)

will also provide an average brightness that is 4 orders of magnitude higher than storage rings. They will provide higher repetition rate (moving from 120 Hz to ~MHz), higher stability, fully coherent beams and an extended photon energy reach (<0.25 to >25 keV). Key characteristics include:

- Narrow bandwidth and high brightness that allows measurements with unprecedented signal-to-noise for high resolution spatial, temporal, spectral and wavenumber resolution.
- The ability to create uniform, solid-density plasmas with temperatures of up to hundreds of eV.
- The ultrafast nature of the pulses can probe plasmas within the few-femtosecond X-ray duration. On this timescale, hydrodynamic motion is negligible, with very limited displacement of ions.
- The high repetition rate provides a fundamentally new capability for statistically meaningful results in the fields of WDM and HEDP. It also provides the ability to scan across a broad multi-dimensional phase space to study detailed dependencies of complex phenomena. This change – from the pulse-per-hour paradigm of high energy laser facilities – drives a host of new opportunities, such as the potential to borrow techniques from the highly-developed field of x-ray light sources, including coherent diffractive imaging, photon correlation spectroscopy, dynamic x-ray scattering, etc.
- The focused x-ray intensity of 10^{17}-10^{20} W/cm^2 and the ability to focus to the sub-micron scale are driving new regimes of non-linear optics, atomic physics and plasma science studies.

The Linac Coherent Light Source (LCLS) is uniquely positioned in the world because it was the first X-ray FEL in operation and because the Matter in Extreme Conditions (MEC) instrument combines high energy and high intensity laser systems with the ultrafast, high brightness coherent X-rays.

However, the international X-ray FEL environment is evolving rapidly. The SACLA facility in Japan is now operational, and has recently commissioned a dedicated X-ray nanofocusing capability. SACLA is also installing high energy and high intensity laser systems with parameters exceeding those at MEC. In Germany, the European XFEL facility is under construction and will hold first operations for users in 2017, and will offer high energy lasers at high repetition rates (100J / 10Hz), along with high intensity laser systems to enable access to a very broad suite of conditions. The United Sates can maintain its leadership in the field of X-ray FEL plasma physics with an appropriate investment in the LCLS optical laser systems, to complement the existing B$-scale upgrade of its x-ray capability via the LCLS-II Project. This presents a timely opportunity to create and characterize plasmas over a wide range of the temperature/density phase space of interest to the fundamental plasma science program within DOE-FES. The precise specification for MEC development will be responsive to the needs of the user community[1], and informed by the FES "Frontiers of Plasma Science" workshops. In particular, there is a need to achieve a balance between high repetition rate for data return, high drive energy for achieving high pressures and shock planarity, and high peak power for accessing the relativistic plasma regime.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit***.

As discussed above, the coupling of optical and x-ray laser systems available at facilities such as LCLS provides a platform for studying beam-plasma interactions that are of fundamental interest, and have applications in areas such as ICF ignition, plasma/wall interactions for fusion reactors, and exploration of the potential for advanced hadron therapy of deep-seated tumors. The development of high brightness sources of secondary radiation has application in industrial and security imaging, as well as for next-generation particle accelerators for light source and/or HEP applications. The broader study of WDM and high strain-rate, high-pressure material science has applications for NNSA, geo-science programs, and extreme industrial applications (e.g. aerospace).

[1] See, for example "*New Science Opportunities enabled by LCLS-II x-ray lasers*", https://portal.slac.stanford.edu/sites/lcls_public/Documents/LCLS-IIScienceOpportunities_final.pdf

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For more information on LCLS, see: http://lcls.slac.stanford.edu

For a full publication list from LCLS, see link below. In the last 2 years (2013-14) there were 245 publications from LCLS, of which 64 (26%) were in high impact journals, as defined by the DOE Office of Science:
https://portal.slac.stanford.edu/sites/lcls_public/Pages/Publications.aspx

Figures

Figure 1: Peak and average brightness of the existing (LCLS) and upgraded (LCLS-II) x-ray FEL facility in comparison to synchrotron (storage ring) x-ray sources.

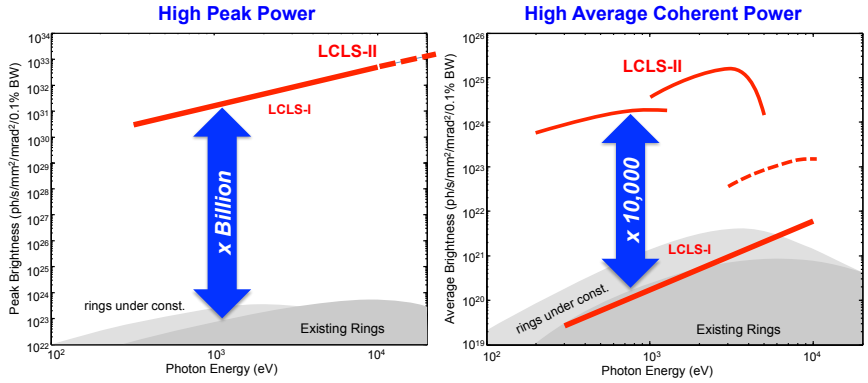

Figure 2: The LCLS facility, and the Matter in Extreme Conditions (MEC) instrument