White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	P
• Turbulence and transport	
• Interactions of plasmas and waves	
• Plasma self-organization	
• Statistical mechanics of plasmas	P

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	X

Title:	Opacity of astrophysical metals
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**(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of s may also be included. *Submit in PDF format.*)**

- ***Describe the research frontier* and importance of the scientific challenge.**

Understanding the transmission of x-rays through metals, defined in the astrophysical literature as elements heavier than hydrogen and helium, is of primary importance to a wide set of scientific fields including astrophysics[1] and cosmology[2], planetary science[3], particle physics[4], and fusion energy research[5,6]. In particular, the metal content of a star has a dramatic effect on the efficiency of the energy transfer from the fusion reactions in the core[7], with implications for planetary habitability and the search for extraterrestrial life[8].

While the x-ray absorption cross sections of the chemical elements are well known, the difficulty of measurements means there are considerable uncertainties for these properties in heated, partially ionized atoms. The detailed measurements of the iron x-ray opacity by Bailey[7] et al show substantive disagreements with modeling (Figure 1). Delivering these results required multiple experiments over a three-year period. Using the ultrahigh brightness of the LCLS free electron laser (FEL) beam we aim to greatly increase the throughput of opacity experiments.

Creating high-energy density material conditions in the laboratory usually entails depositing large amounts of energy (mJ to kJ) into a small sample (tens of μm to cm) in a very short amount of time (μs to fs)[9]. There are a variety of experimental facilities where researchers perform these experiments from

high-energy glass lasers and pulsed-power machines to ultrafast, high-power Ti:Sapphire and free electron laser facilities[10]. Measuring the x-ray opacity is then a relatively simple task: back-illuminate the high-energy density sample with a broadband source and measure the transmitted spectrum.

Carrying out this procedure and interpreting the data are difficult for several reasons. The samples usually contain strong spatial and temporal gradients in the temperature and density so that the opacities are sampled over a range of conditions. These conditions are often characterized by comparing the self-emission spectra to theoretical modeling, the validity of which may depend on the opacities being measured.

The ideal source to shine through the samples would be a short duration, broadband pulse with no spectral features. This is no easy task for x-ray energies above a few keV. Lasers can excite L and M-shell transitions of heavy elements creating a bright, yet spectrally complex series of emissions from the various transitions[11]. Bremsstrahlung x-rays from energetic Z-pinches yield a much brighter and featureless x-ray continuum that can be ideal for these studies[12]. However, building up large datasets is particularly challenging because of the extensive downtime needed to refurbish the machine after each shot.

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

We propose to develop a platform for measuring the opacity of astrophysically-relevant plasmas using the LCLS free electron laser and a petawatt optical laser (Figure 2). This method will be generally applicable to materials that can be shaped into freestanding foils, including plastics and most transition metals. The measurements will occur at high-repetition rates (>1 Hz), returning an unprecedented amount of high quality opacity data over a variety of well-characterized material conditions. Our initial experiments will focus on measuring the opacity of three metals common to the radiative zone of the sun: iron, silicon, and aluminum.

By tightly focusing the x-ray beam onto a foil, a few-μm^3 region will be volumetrically heated by photoelectric absorption. For a typical 1 μm-thick target, the x-ray beam will deposit up to a few keV/atom in energy. This will heat the sample to temperatures of order 100 eV[13] and pressures of nearly 1 TPa (Figure 3). With this capability, it is relatively simple to access a range of conditions of interest to the astrophysical community and beyond. The densities of the samples may be varied either by compression from a high-energy, laser driven shock or allowing free expansion into the vacuum. Likewise the heating can be controlled by changing the FEL intensity, delay between the x-ray and probe pulse, or x-ray energy.

We will generate x-rays by betatron emission to probe the sample with an ultrafast, spectrally broad source[14]. Assuming a spectrometer collection angle of 10^{-5} sr, a sample transmission of 0.01, and the solid angle of the aperture with respect to the source of 0.01 sr, we will require 10^9 betatron x-rays/eV to yield high-quality spectra from a single laser shot. These signal levels will necessitate the commissioning of a petawatt-class laser facility at the LCLS.

Using diffraction grating and crystal x-ray spectrometers, we will measure the transmission over a broad spectral range, from 100 eV – 10 keV, yielding the opacity. The region illuminated by the betratron x-rays will be restricted to only the x-ray heated area by *in-situ* machining of entrance apertures using the x-ray beam. Finally, we will independently measure the material conditions in the sample using spectrally resolved x-ray scattering in the forward direction[15]. By the principle of detailed balance, we will have a first-principles measurement of the temperature[16] (Figure 4). With a robotic sample holder these

experiments may be performed rapidly[17], limited only by the 1 Hz repetition rate of the proposed high-power laser driving the betatron source.

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

By developing this technique, we will enable future researchers to easily measure the opacities of almost any material driven to a high energy density state. No special targets are needed beyond commercially available high purity foils and samples can easily be switched or modified during an experimental run. Relative to other large-scale facilities where these experiments are possible (OMEGA, NIF, Z-Machine), we will be able to perform these measurements at a significantly reduced complexity cost.

An improved understanding of metallic opacities will have a direct impact on understanding the preheating of fuel in inertial fusion targets, mitigating radiative losses from the first wall in magnetic fusion, and modeling the properties of extrasolar planetary systems.

References (Maximum 1 page)

[1]F.J. Rogers and C. A. Iglesias. Science. 263, 50 (1994)

[2]R. Cayrel et al. Astron. Astrophys. 416, 3 (2004)

[3]L. Fossati et al. Astrophys. J. 714:L222–L227 (2010)

[4]J.N. Bahcall and C. Peña-Garay. New. J. Phys. 6, 63 (2004)

[5]J. Lindl. Phys. Plasmas. 2, 11 (1995)

[6]M. Arnaud and J. Raymond. Astrophys. J. 398 (1992)

[7]J.E. Bailey et al. Nature 517 (2015)

[8]C. Lineweaver at al. Science. 303, 5464 (2004)

[9]R P. Drake. High-Energy-Density Physics: Fundamentals, Inertial Fusion, and Experimental Astrophysics. Springer (2006)

[10] B.A. Remington. Plasma Phys. Control. Fusion. 47 (2005)

[11]P. A. Keiter et al. Rev. Sci. Instrum. 79,10 (2004)

[12]R.B. Spielman et al. Phys. Plasmas 5, 5 (1998)

[13]D.S. Rackstraw et al. Phys. Rev. Lett. 114, 015003 (2015)

[14]A. Rouse et al. Phys Rev. Lett. 93, 13 (2004)

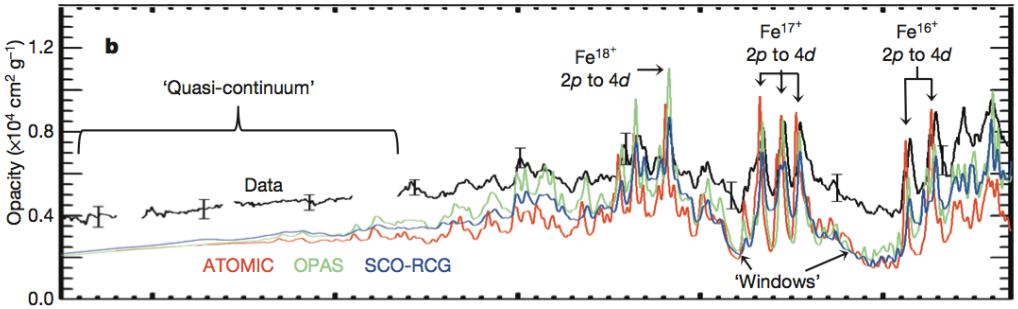
[15]S.H. Glenzer and R. Redmer. Rev. Mod. Phys. 81, 1625 (2009)

[16]T. Doeppner et al. High Energy Density Phys. 5, 182-186 (2009)

[16]L.B. Fletcher et al. J. Inst. 8, 11 (2013)

Figures (maximum 1 page)

Figure 1: Comparison of experimental iron opacity data with theoretical models



From J.E. Bailey et al. Nature 517 (2015)

Figure 2: Experimental setup

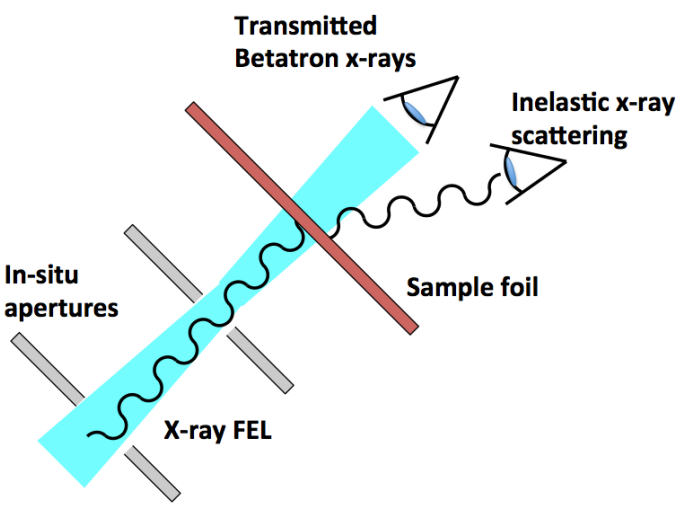
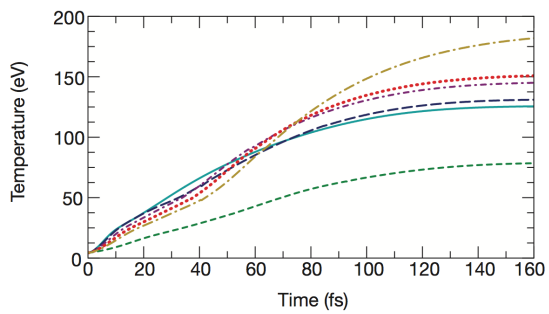


Figure 3: Isochoric heating of 1 µm Al foil using the LCLS FEL beam



From S.M. Vinko et al. Nature 482 (2012)

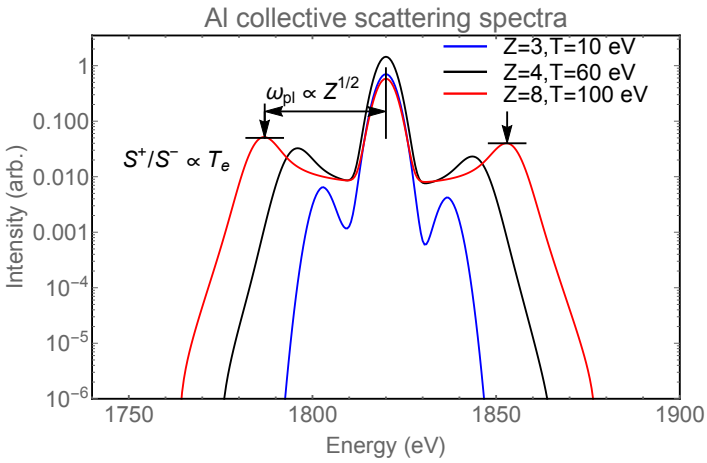



Figure 4: Simulated spectra showing the sensitivity of the x-ray scattering to T_e and Z