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”
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Title:	Laser-driven x-ray sources for High Energy Density science
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Laser-driven x-ray sources for High Energy Density science

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The nascent field of High Energy Density (HED) science aims to resolve grand challenges to understand how the Sun works, how the planets were formed, how to harness fusion energy, or how to explain the mechanisms of stellar explosions. It is now possible to recreate astrophysical conditions of extreme temperatures and pressures at large scale laser and x-ray free electron laser (XFEL) facilities; however such conditions are transient in nature and can be extremely difficult to probe. Phenomena such as shock physics, opacity, ultra-relativistic laser-matter interactions and x-ray-matter interactions are central to this field of physics, but their investigation often requires diagnostics that are massive, costly and limited in temporal or spatial resolution. Laser-wakefield accelerators (LWFAs) [1], relying on intense laser fields to drive plasma waves and subsequently accelerate particles, are starting to show real potential to solve the most ambitious questions in HED science [2]. Just like conventional accelerators, they can produce bright x-ray sources at a fraction of the cost but with a 1000-fold increase in time resolution, and they have not yet been fully exploited for applications in HED science, especially at large-scale facilities.

With this white paper, we propose to combine laser-driven light sources with the field of HED and fusion sciences, in order to probe HED physics experiments at large scale user facilities. In the U.S., these include the Linac Coherent Light Source (LCLS and LCLS-II) at SLAC, the National Ignition Facility (NIF) and the Jupiter Laser Facility (JLF) at LLNL, and OMEGA-EP at LLE.

Betatron radiation from laser-wakefield accelerators: One way to produce x-rays from LWFAs is through Betatron motion [3, 4, 5]. When a short, intense laser pulse with an intensity I $> 10^{18}$ W/cm^2 is focused inside a plasma, the laser ponderomotive force expels the plasma electrons away from the strong intensity regions to form an ion bubble in the wake of the pulse. Electrons trapped at the back of this structure are accelerated and wiggled by the focusing force of the more massive and immobile ions to produce broadband, synchrotron-like collimated (a few mrad) radiation in the keV energy range. Due to its size, femtosecond pulse duration and synchronization with its drive laser system, Betatron radiation can potentially have many advantages over synchrotrons. This source can help characterize dynamic properties in LWFAs, however its real potential is in HED science. It should be tailored for applications and used as a probe at various facilites (including LCLS and NIF), to address a number of physics issues related to x-ray-matter interaction, relativistic laser-plasma interactions, absorption spectroscopy, shock physics and opacity.

Compton scattering: Instead of being wiggled by the laser wakefield, electrons can oscillate in the laser field directly, with a much shorter period than in the case of Betatron radiation [6, 7]. For a head-on collision between the photons and electrons, the scattered photon energy roughly scales as $4\gamma^2 E_{ph}$, where γ is the electron relativistic factor and E_{ph} the incident photon energy. This makes Compton scattering sources very attractive because one can obtain high-energy (beyond 100 keV) scattered photons with relatively modest electron beam energies, when compared to Betatron x-ray radiation produced in the same regime. Therefore, applications such as high energy radiography, phase contrast imaging or nuclear physics can be undertaken. This should also be developed with LWFA

electrons at LCLS, NIF and other facilities to perform pump-probe experiments requiring higher energy x-rays than currently achievable from Betatron radiation.

Future research directions: In response to the needs of the HED research community, the proposed research described in this white paper brings together, for the first time, one of the most promising applications of laser-wakefield accelerators - x-ray sources - into HED science experiments to probe HED plasmas with unprecedented time resolution. This research revolves around four objectives: (i) Improving x-ray sources based on laser-wakefield accelerators for applications, (ii) performing optical pump - x-ray probe experiments using Betatron x-ray and Compton scattering sources to address a number of physics issues related to absorption spectroscopy, shock physics, opacity and potentially nuclear physics ; (iii) performing x-ray pump - x-ray probe experiments at LCLS, where we can take advantage of the unique colocation of high intensity, high-repetition rate lasers with the LCLS to probe x-ray heated plasmas with Betatron radiation; and (iv) working on the Development of LWFA sources on large HED drivers such as NIF-ARC at LLNL or OMEGA-EP at LLE to support applications in HED and fusion energy sciences. The mechanisms of LWFA and subsequent x-ray production on these large scale facilities differ from what is typically done with $\sim$100 TW class, femtosecond laser systems, and they remain largely unexplored.

In summary, this white paper responds to an urgent need of the HED science community by bringing together some of the most promising applications of laser-wakefield accelerators (Betatron x-ray and Compton scattering radiation) to probe HED plasmas with unprecedented time resolution. Strong experimental and theoretical resources are already in place to successfully conduct this effort. Experiments can take place at large scale facilities: LCLS at SLAC, JLF at LLNL, OMEGA-EP at LLE, and NIF-ARC at LLNL. It will open up new possibilities to inform and design future high optical and x-ray intensity experiments and to improve current opacity and radiation transport models that are essential for many areas of HED science: planetary and solar sciences, fusion energy research, intense laser-plasma interactions and geophysics.

Figures

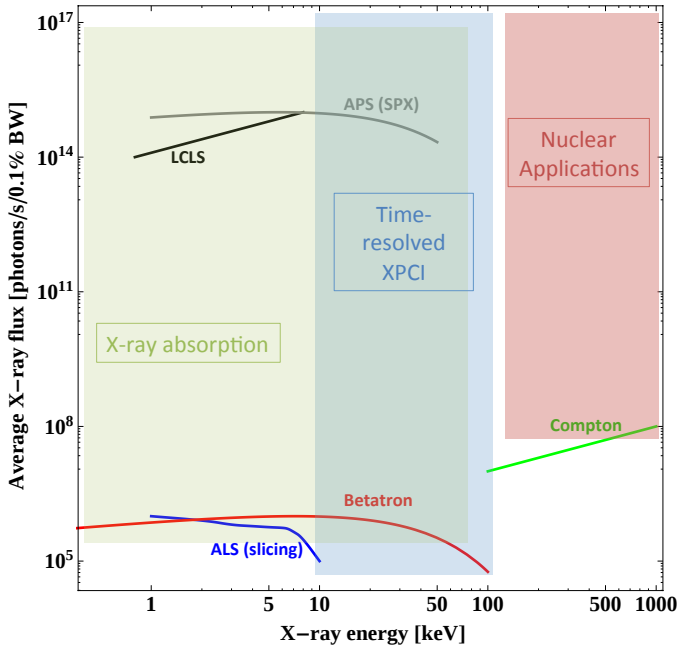

Figure 1: Summary plot, showing the desired space-parameters for several applications of interest for HED science: X-ray phase contrast imaging (XPCI), x-ray absorption and nuclear physics applications. Existing source parameters are also shown for the APS and ALS synchrotrons, the LCLS, Betatron radiation and Compton scattering from laser wakefield accelerators.

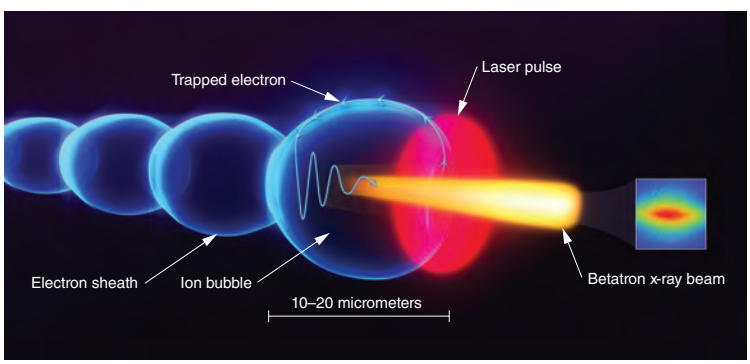

Figure 2: Principle of betatron x-ray emission from a laser wakefield accelerator. Electrons trapped at the back the wakefield accelerated and wiggled by the electrical fields produce broadband, synchrotron-like radiation in the keV energy range.

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