White Paper for *Frontiers of Plasma Science Panel*

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

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Title:	Ultrafast photon and particle probes for and via plasma science
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- ***Frontiers in photon and particle probing, and research impact***

Plasma-based X-ray and EUV radiation sources are both important frontiers in plasma physics with broad application, and at the same time an enabling technology to provide diagnostics for high energy density plasma (HED) science. Compact sources with narrow-divergence, producing femtosecond bursts, are enabled by, and probe the physics of, Laser-Plasma Acceleration (LPA) of electrons [1, 2]. Sources range [3,4] from broadband betatron emission, to nearly monoenergetic Thomson scattering and coherent emission from harmonics or plasma undulators. These, combined with particle probes [5,6] that give information on electromagnetic fields, are integral parts of comprehensive plasma science platforms [7].

X-ray sources are vital to applications throughout medicine [8], industry [9], material science [10], nuclear science and nuclear nonproliferation [11]. While it is well known that tunable and monoenergetic sources offer important increases to resolution together with reduced radiation dose [8,11,12], current techniques are limited, with the exception of a few large facilities, to broadband X-rays. This is because the Thomson process used to produce monoenergetic X-rays uses electron energies requiring large conventional accelerators, scattering systems and beam dumps. Precision control and understanding of plasma acceleration and beam oscillation processes provides a path to compact techniques for each.

For HED science, ultrafast x-ray probes are a cornerstone of many measurement techniques, and the most straightforward include laser-driven K-shell and L-shell sources, which produce both broadband and

line emission in the few keV to tens of keV range. These typically have > picosecond temporal resolution, many micron emission size, and 4π divergence. K_α fluxes are in the range of 10^{12}ph/shot/SR and broadband fluxes in the range of 10^8ph/shot/SR/keV using 300J/40ps lasers [13]. New sources that are brighter, smaller, more tunable in energy, and with separation of line and broad emission could improve measurements. Use of multiple colors can provide discrimination between different materials. Coherent sources in the sub-keV range could provide vital data to probe plasma formation and preplasma dynamics beyond the density range of optical lasers. Systems compatible with HED platforms are needed.

- ***Research path, capabilities and tools for advanced photon and particle probing.***

LPAs produce the energies required to enable high-energy, tunable, fs-pulse X-ray sources in centimeter-scale distances [2], offering potential for broad application. They can be generated by a small split-off fraction of the lasers used for laser-driven ion acceleration and other HED science, facilitating integration with experiments. Meeting application needs and enabling new diagnostics for plasma science requires development of both accelerator and radiation production techniques.

Betatron radiation, emitted from focusing oscillations of the electron beam in the LPA, is simplest to realize (Fig. 1). Accelerating beams emit broadband radiation up to a cut-off energy, beyond which radiation rapidly diminishes. Emission is regulated by beam energy and emittance. Using Joule/40 fs class lasers (which provide few hundred MeV electron beams) radiation in the tens of keV is routine [15]. Picosecond lasers can be used at higher energies [14]. Broadband photon fluxes are in the range of 10^8-10^{10}ph/shot/SR/keV [3,4,15,16] providing high brightness and femtosecond pulses using low laser energy. Emission spot sizes of ~0.1-1 μm [15] allow very high spatial resolution. It provides sensitive probes of wave-particle interaction [15]. Development needs include ionization or off-axis injection to increase photon yield and to reduce the required laser energy.

Thomson scattering produces tunable, narrow bandwidth X-rays [3,4] of higher energy and flux than betatron radiation, and can extract detailed beam evolution information for studying beam interactions with plasma waves (Fig. 2). Moderate bandwidths of 10-20% could be achieved by direct scattering from the beams of high quality LPAs [17] for HED science experiments that require setup simplicity. A plasma mirror [18] may be used to back-reflect the drive laser of an LPA onto the electron beam, producing photon beams without a separate laser pulse [19] at modest yield. Simulations show that tuning of laser chirp could produce high flux and narrow energy spread from such a high-intensity configuration [20,21], which must be developed in experiments. Radiation at the few keV-50 keV range implies LPA energy of 10-50 MeV which could use < Joule laser energies. Specific development of such low-energy LPAs is required, with attention to energy spread and emittance that dominate Thomson bandwidth. Like betatron radiation, femtosecond pulses with emission spot sizes of ~0.1-1 μm [15] can be produced to allow very high temporal and spatial resolution. Scanning the Thomson intersection provides a unique probe of beam evolution in the plasma. For applications, and for high performance HED experiments, reducing bandwidth and increasing flux are imperative. Bandwidth from LPA-generated sources is dominated by electron beam divergence, due to the strong focusing forces. Refocusing can allow bandwidths down to the limit of the electron beam energy spread [17], around 1-2% at present [22,23]. To preserve beam emittance this must be done in short (~cm) distances. Laser-plasma [17, 24] and plasma discharge [25] lenses with suitable focal lengths have been demonstrated and must be developed. Photon fluxes are presently limited by the fact that the scattering laser diverges much more rapidly than the electron beam for equivalent spot size, limiting overlap and potentially requiring very large scattering

lasers (> 10x the LPA drive energy). Using plasma waveguides for the scattering laser [17], together with laser pulse shaping, is a promising approach to breaking this limit with laser energies of order the LPA driver and approaching one photon/electron. This would provide high fluxes at tunable energies and in femtosecond pulses using low (≤few Joule) laser energy, for example at 50keV of order 10^{12}ph/shot/SR in 1-10% bandwidth with potential to scale higher. For applications, energies range from tens of keV for thin-sample radiography to few MeV for thick material radiography (e.g. cargo, machinery) and ~10 MeV for photonuclear applications, requiring development of LPAs at energies of ~50-700MeV with reduced emittance and energy spread, using Joule/40 fs-class (<100TW) lasers [12] .The residual high energy electron beam, co-propagating with the photon beam, is an important limit on system size for applications, and may also be undesired for HED experiments. Simulations [17] and initial experiments [25] show that the LPA can be used to decelerate the electron beam to mitigate shielding requirements, and that plasma fields [24,25] can be used to steer or focus the beam at cm-scale. These sources require, and provide unique tools for, control and understanding of wave-particle interactions.

Compact coherent radiation sources are possible using either harmonics or plasma undulators. Relativistic harmonic generation has been demonstrated up to ~0.3 keV [26] at modest intensities of 10^{20}W/cm^2. Scaling with intensity and use of Joule-class lasers need to be demonstrated. An undulator based on the plasma wakefields [27], achieved by inducing centroid oscillations of the laser pulse in a plasma channel, has a wavelength proportional to the Rayleigh length of the laser pulse which can be sub-millimeter, together with high undulator strength. For example, simulations show that undulator or free electron laser radiation at ~0.3 keV could be produced using a 250 MeV electron beam in a cm-scale structure. Such structures, and their extension to multimode and multicolor laser pulses to provide greater tunability, is a challenging frontier in wave particle control and an enabler for compact precision probes.

Proton radiography (Fig. 3) can image electric (magnetic) fields on the order of GV/m (MG) [5,6]. High resolution is enabled by the low transverse emittance (5×10^{-3} π mm mrad) and the short bunch duration (ps) of the laser generated proton beam, while broad energy spread allows time of flight to provide temporal resolution. Developments in laser ion acceleration are detailed in [7], and the low proton energies required for probing allow use of few-Joule lasers, similar to X-ray sources.

- ***Plasma science and applications impact of ultrafast photon and particle probes***

The new radiation sources available from LPAs can provide probes of unprecedented temporal and spatial resolution for HED science. These have the potential to revolutionize the backlighters and probe beams that are a cornerstone of many measurement techniques. They can be combined with charged particle probes from ion acceleration [5,6] which add field information. Each can be produced with small fractional splits of the lasers that drive other experiments, or with femtosecond lasers of modest scale which can be easily locked to a common oscillator, facilitating implementation in HED experiments. Their development both requires and enables frontier plasma science in beam/wave/ radiation interaction.

Compact and tunable sources have the potential revolutionize X-ray applications throughout medicine, industry, material and nuclear science. Development specific to nuclear nonproliferation is now in progress, and broader development would enable significantly lower dose and higher resolution to be extended to the broad field of X-ray applications. Related areas include studies of radiation damage and single event effect in electronics, as well as fast ignition inertial confinement fusion [7].

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Figures

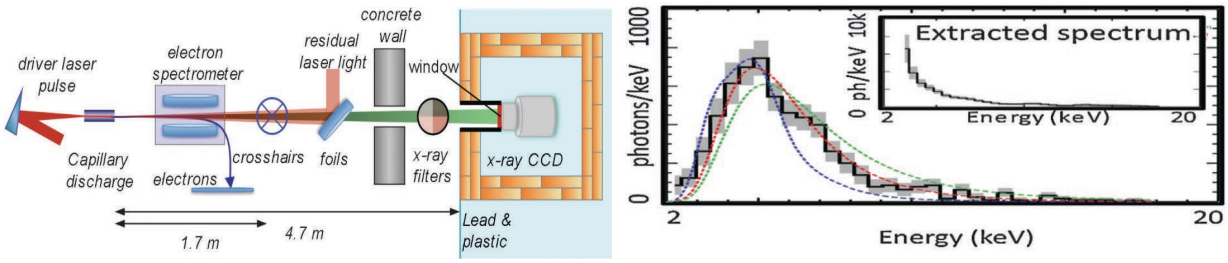

Fig. 1: (left) Betatron experimental setup (photon beam green) and (right) broadband, femtosecond photon spectrum. [15]

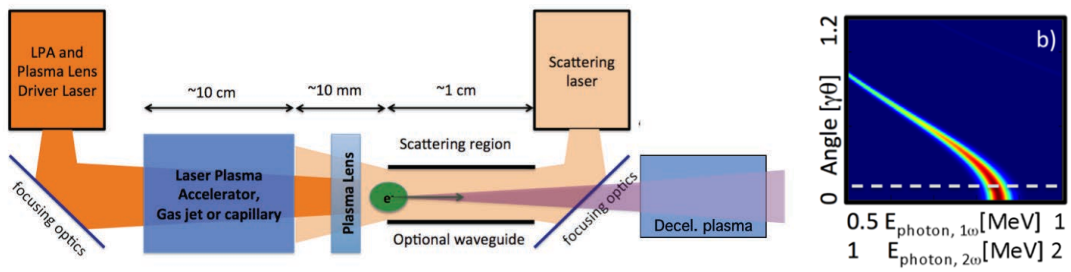

Fig. 2: (left) A compact Thomson photon source would include LPA-based cm-scale electron acceleration to ~0.5 GeV, a plasma-based cm-scale electron lens to re-collimate the beam and reduce divergence, a plasma waveguide to extend scattering for increased yield (photon beam purple), a plasma mirror, and deceleration to reduce shielding needs. (right) Collimated, narrow-bandwidth photon spectrum (simulated) [17].

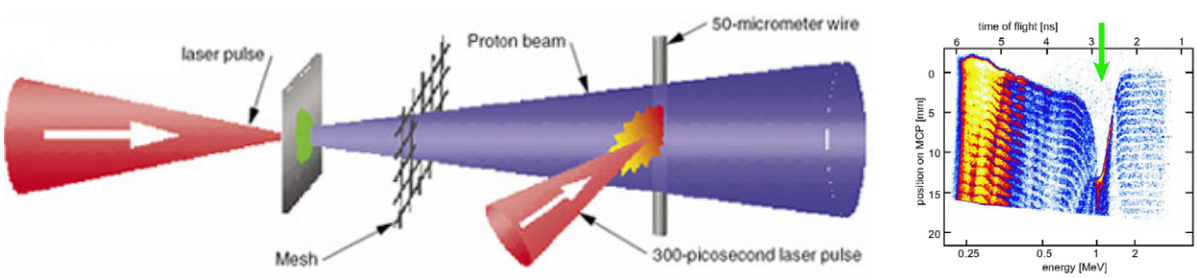

Fig. 3: (left) Proton beams can be used to probe the field structure of targets. (right) Field structure is visible as deflection, in this example using time of flight of 1.2-2.4 MeV protons to obtain a temporal profile of the effect a laser irradiation at 10^{18}W/cm^2 (at the time shown by the green arrow) [6]. This complements the detailed structural information available from X-ray probes.