Compact photon sources based on laser-plasma accelerators

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Introduction Laser Plasma Accelerators (LPAs), see Refs. [1, 2], offer an attractive technology towards production of short (few-fs) and energetic (GeV-class) electron beams. The quality of the electron beams can be assessed based on the six-dimensional phase space, including final energy, energy spread, charge, bunch length, beam divergence, transverse source size, repetition rate, as well as long-term and shot-to-shot stability. Recently, 8 GeV energy gain has been reported [3], as well as percent-level energy spread [4], 10-100 pC charge, few-fs beam duration [5], sub-mrad divergence, few-μm source size [6], and repetition rates up to 10 Hz (and planned for kHz). These beam parameters not only reinforce the role for LPAs to play for future collider concepts, they also spur the development of unique radiation sources in the THz, XUV, X-ray and gamma ray regime, offering compactness (due to the high accelerating gradient in the plasma), few-fs radiation pulse lengths for high temporal resolution, strong fluxes), and intrinsic femtosecond synchronization to a host of hyper-spectral pump-probe beams. These novel sources have attracted interest for applications throughout medicine [7], industry [8], material science [9], nuclear science, and nuclear nonproliferation [10]. Diagnosing and optimizing the light sources through precision and control will not only enable the high societal impact applications, but also provide novel insight and a handle on the rich physics at play during the complex laser-plasma interaction. The latter is critical for elevating laser-plasma acceleration to the ultimate goal of supporting the next generation of linear colliders.

Coherent undulator emission (FEL radiation) from LPAs One of the key indicators in validating the quality of LPA electron beams for the collider application is the ability to drive a free-electron laser (FEL). To do so, the peak current, transverse emittance, energy spread, and longitudinal phase space, need to be optimized and controlled to meet minimal FEL lasing requirements, making FEL emission a perfect diagnostic to the six-dimensional phase space.

For (sub-)GeV-class electron beams, the undulator radiation wavelength covers the UV to soft X-ray domain. It is possible to boost the photon flux by many orders of magnitude (to $> 10^{11}$ photons/pulse) if the electron beam is dense (>10 pC in a sub-100μm beam size), short ($\sim$10 fs), and with a small energy spread (of order 0.1%). In this free-electron lasing (FEL) regime, the electron beam will develop a longitudinal micro-structure at the radiation emission wavelength, allowing the individual electrons to emit coherently in phase [11]. The most critical demands on the electron beam are low emittance and low energy-spread. The energy spread might appear to be a critical problem (percent-level for LPAs), but with advanced phase space manipulation this hurdle can be mitigated (for example with a chicane [12, 13, 14], or a transverse gradient undulator [15]). Simulations based on realistic parameters have shown that coherent gain at UV and soft X-ray wavelengths is achievable, giving potential users access to a unique ultra-intense compact light source.

Further improvements in FEL gain can be accomplished by tapering the undulator, or optimizing the electron beam phase space. The latter is intrinsically beneficial to the collider application as well. For example, de-chirping techniques [16] can be applied to reduce the energy spread, while recent work [17] has focused on the transverse emittance by comparing ionization-based injection [18, 19] and down-ramp injection [20]. The energy-dispersed emittance diagnostic in [17] allowed for methodical study of the LPA emittance, with down-ramp injection being favorable at the 1μm level (normalized). Future efforts towards high-quality acceleration will benefit from novel concepts to expand control over injection, for example with two-pulse two-color ionization [21, 22].

Betatron radiation from LPAs In terms of LPA-based hard X-ray production, betatron radiation has been extensively pursued, emitted from oscillations of the electron beam inside the LPA. These oscillations are driven by the strong radial focusing fields from the laser-driven plasma wave. Emission is determined by the plasma density, electron beam energy, and emittance. Using multi-joule, 40 fs class lasers (which produce GeV-class electron beams), radiation in the multi-keV range is routine [23, 24, 25, 26]. Picosecond lasers can also be used at higher laser energies [27].

Emission source sizes of 0.1-few μm [24], related to the (sub-)μm electron source size, allow high spatial resolution in phase-contrast imaging configurations. As such, betatron emission provides a sensitive probe of the wake-particle interaction in the plasma, with the transverse motion of the electrons during the acceleration process translating directly to photon beam properties (imaging resolution, flux, spectral cut-off) [28]. Besides biology and material science applications [29, 30, 31], betatron emission is thus a critical tool in studying LPA-based collider applicability. Future development needs to include research on stability [32] and triggered injection techniques, such as ionization, off-axis, or two-color [21] injection, to balance an increase in photon yield with a reduction in the source size, required laser energy.

Thomson scattering from LPAs Thomson scattering produces tunable, narrow bandwidth X-rays of higher energy and flux than betatron radiation [25]. Scanning the Thomson intersection provides an insightful opportunity to diagnose and precision-tune the accelerator. In terms of photon flux, moderate bandwidths of 10-20% could be achieved by direct laser scattering, with potential improvements from optimized laser chirp [33, 34]. Similar to betatron radiation, femtosecond radiation pulses with emission source sizes of $\sim$1 μm [24] can be produced to allow high temporal and spatial resolution. Besides being proportional to electron beam current, photon fluxes are also limited by the scattering laser divergence. Using plasma waveguides for the lasers [35], together with laser pulse shaping, is a promising approach to flux increase. Thomson scattering in channels also directly relates to application of guiding channels in colliders stages, proposed to be an integral part of the LPA-based collider [36, 37].

Muon production from LPAs Although largely unexplored, high-energy (>MeV) and low-energy (eV-keV) muon beams are attractive for applications such as muon spin spectroscopy [38], where spin-polarized muons are implanted in a sample to act as a localized probe. Compact LPA-based setups could provide a means to produce sufficient amount of short-pulse muons, through the interaction of LPA-produced gamma rays with matter [39]. Exploratory studies need to be executed to map out the LPA-based muon production advantages and capabilities.

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