Snowmass2021 Letter of Interest; August 31, 2020

“High brightness injectors based on PWFA”

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Introduction Dense high-energy particle and photon beams are the building blocks for high energy and strong field physics exploration. To achieve high luminosity $\mathcal{L} = fN^2/(4\pi\sigma_x\sigma_y)$ as key parameter for colliders, small transverse beam spot sizes σ_x, σ_y are desirable. This requires high quality beams in terms of low emittance ϵ_n and energy spread. $\mathcal{L}$ primarily benefits from the number of particles *N* arriving with frequency *f,* while short beam durations can cause disadvantageous space charge effects in collider scenarios. However, the associated high fields resulting from short bunch duration and high current facilitate fundamental strong field and QED research.

Electron beams as extreme form of nonneutral plasma accelerate efficiently to high energies via plasma wakefield acceleration [1]. The associated accelerating and focusing fields ranging from tens of GV/m to TV/m nurture prospects for a collider based on electron beam driven plasma wakefield accelerators [2] as they may scale down the accelerator and simultaneously preserve the beam quality. However, not only can plasma be used as an accelerator, but also as a source of high-quality electron beams: The plasma-based version of a photocathode gun is the "Trojan Horse" approach, wherein a focused laser pulse liberates cold electrons via tunnel ionization directly inside the plasma wave [3]. These electrons carry negligible initial transverse momentum and are rapidly compressed and accelerated. Theory and simulation predict normalized beam emittance of the order of few tens of nm rad or less in both planes without need for damping rings, and kA-level currents I_p. Such beams display ultrahigh 5D brightness $B_\mathrm{5D} = 2I_\mathrm{p}/(\epsilon_\mathrm{n,x}\epsilon_\mathrm{n,y})$, orders of magnitude brighter than even in state-of-the-art linac-based XFELs. Beam loading modifying the accelerating wakefield can control the energy chirp ΔW_res of accelerated bunches [4] and produce beams of ultrahigh 6D brightness $B_\mathrm{6D} = B_\mathrm{5D}/0.1\%\,(\Delta W_\mathrm{res}/W)$. The anticipated ultralow emittance and ultrahigh brightness of such electron beams would open transformative prospects for hard x-ray plasma-based free-electron-lasers as highly impactful intermediate goals [5] towards their long-term exploitation for high energy and strong field physics.

Impact of low emittance high brightness beams for HEP and strong field physics Access to beams with nm-level normalized emittance would enable a variety of unique contributions to high energy as well as strong field physics.

First, such beams can probe ultralow emittance collider building blocks since they provide a litmus test for emittance growth sources and effects. Those are well-known to deteriorate beam emittance during extraction and re-injection between multiple plasma accelerator modules [4]. Such staging of hundreds of plasma accelerators is required to reach multi-TeV energies. While tailoring of the plasma density profiles at the exit and wentrance of each plasma accelerator module in theory prevents emittance growth, even nm-scale increase per stage will cause substantial accumulation, thus deteriorating the achievable luminosity. One would hardly attempt building a plasma-based linear collider if suitable emittance preservation techniques have not been demonstrated with nm-scale emittance test beams. Test beams – even of variable duration- could be generated by the Trojan Horse method to optimize emittance preservation. Therefore, the development of measurement techniques capable of monitoring the emittance evolution on the nm rad level remains a joint challenge.

Second, plasma photocathodes may be used as injectors for traditional HEP colliders [6]. The ultimate goal would be the generation of electron beams with ultralow emittance and high charge for high luminosity. While arbitrary charge levels up to the overloading limit of the plasma wave can be released by plasma photocathodes, space charge effects can compromise the obtained emittance. Extended beam duration along with tailored beam density profiles can solve this problem, for example via precisely controlled laser profiles and composite beam production from multiple plasma photocathode laser pulses. The resulting luminosity can be further increased by generating bunch trains inside one or consecutive plasma cavities, thus increasing *f* without directly increasing the repetition rate of the plasma accelerator.

Third, the Trojan Horse process may allow production of spin-polarized electron beams e.g. by using pre-polarized targets and/or ionization via (circularly) polarized [7] photocathode laser(s). This would further increase attractiveness of such beams for HEP applications.

Fourth, the ultralow emittance combined with femtosecond-level bunch duration - corresponding to multi kA currents- in principle allows for extreme charge densities. The resulting collective, Lorentz-boosted unipolar electric field distribution is a unique modality, which makes them highly attractive e.g. to QED studies [8].

Fifth, the potential availability of intense hard x-ray or γ-ray beams, derived from ultrabright electrons produced by integrated plasma photocathode wakefield accelerators via novel and/or improved mechanisms [9], could enable novel constellations for particle and photon colliders as outlined in the UK-XFEL Science Case [10].

Finally, efforts to use plasma also as collective diagnostics of low emittance and/or high brightness beams e.g. via the plasma afterglow [11] mechanism, and for symmetric focusing of such beams via plasma lenses [12-14], are highly synergistic with plasma photocathodes.

Such an emerging ecosystem of plasma- and laser-based building blocks, also being attractive to radiofrequency-based accelerator concepts, adds momentum for R&D towards the next generation of collider and HEP applications.

Status and R&D of plasma photoguns The first experimental proof-of-concept demonstration of downramp injection in PWFA [15] as well as the plasma photocathode [16] was realized in the "E-210: Trojan Horse" experiment at SLAC FACET. The plasma photocathode was realized in 90°-geometry but can be implemented with arbitrary geometry [3]. Broader plasma channels and operation at lower plasma densities, sharper and innovative laser focusing techniques, improved stability of incoming beams, and collinear geometry are among experimental goals of the "E-310: Trojan Horse-II" experiment at SLAC FACET-II. Simulations predict the generation of controllable electron beams with normalized emittance towards the nm rad level, and linac-level energy spreads [4]. Related experiments e.g. on plasma afterglow diagnostics and plasma focusing are crucial in order to achieve these goals, and exploitation for applications.

Summary Plasma wakefield accelerators offer attractive features for acceleration of electron beams, but also for their generation inside the plasma via the plasma photocathode process. First steps towards controlled generation of electron beams with nm rad scale emittance have been promising - next steps aim at exploiting the full potential of the method. The prospects of ultralow emittance and ultrahigh brightness electron beams as key performance parameters align and unite the goals of HEP, strong-field QED and brilliant light sources towards cutting-edge research facilities and raise substantial capabilities for next-generation R&D.

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