Bright Electron and Positron Beams and High-Charge Electron Bunches for Beam-driven Structure-WakeField Accelerators

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Abstract: Beam-driven Structure-WakeField Accelerators (SWFAs) in support of TeV-class high-luminosity lepton colliders set challenging requirements on the particle sources. Both electron and positron sources must produce bright beams suitable for capture and acceleration in high-frequency accelerating structures. In addition, electron sources capable of producing high-charge drive electron bunches are crucial for the generation of wakefields with large accelerating gradients. This LOI outlines the requirements associated with these sources, identifies challenges and suggests possible research paths.

Introduction: Beam-driven wakefield accelerators relies on high-charge "drive" bunches [O(10–100 nC)] passing through slow-wave structures to excite electromagnetic wakefields [1]. The produced wakefields can be used to directly accelerate a trailing "main" bunch (CWA) or be out-coupled and guided to an optimized accelerating structure that accelerates a main bunch (TBA) in a parallel beamline. CWA offers a simpler configuration, where both the drive and main bunches are transported along the same beamline, while TBA decouples the dynamics of the drive and main bunches**.**

High-charge drive –electron bunch generation: In SWFA and PWFA-based colliders, the drive bunch exciting the wakefields is a high-charge electron beam with transverse emittance sufficient for transport through the structure(s). Producing such electron bunches relies on L-band photoinjectors and puts stringent demands on the associated photocathode and laser system especially when a high-repetition-rate is desired. Below we advocated three complementary paths for drive bunch research.

Laser and photocathode. To keep the photocathode-laser energy to sub-mJ level, the development of photocathodes with high-quantum-efficient (QE) and long lifetimes [O(week)] are needed. Also, photocathodes operating at wavelengths near available laser-media lasing range [typically in the infrared (IR) region of the spectrum] would be desirable to improve laser-to-electron wall-plug efficiency (by reducing the number of laser frequency conversion stages). Currently, Alkali-antimonide photocathodes are the most suited for high-charge bunches generation: CsK_2Sb operates with ~530-nm laser pulses and has an acceptable mean transverse energy (MTE) of ~200 meV [2] . Finally, improving the photocathode QE would be beneficial to further reduce the power requirement on the laser system and could be accomplished by, e.g., engineering the photocathode topology to enable plasmonic effects as demonstrated with metals [3].

Space-charge mitigation. The beam-dynamics associated with high-charge bunches is space-charge dominated during the bunch-formation process, initial acceleration, and transport to relativistic energy). Mitigating the impact of space-charge effects is critical to the generation of undisrupted beam distributions with reduced nonlinearities and improved emittances. Altering the photocathode topology was recently proposed as a way to alleviate the space-charge limit during the photoemission process [4] but a practical implementation and experimental validation remain unexplored. Likewise, shaping the laser distribution to linearize the space-charge fields offers a promising path to forming low-emittance high-charge bunches. The demonstrated blow-out regime [5-7] sets a stringent condition on the source size which ultimately limits the transverse emittance [8] and alternative methods proposed to directly generate uniformly-filled 3D electron bunch by proper shaping of the laser distribution [9-11] should be experimentally tested. Likewise, laser shaping may also be adapted to program the laser temporal distribution to ultimately produce shaped drive bunches required for efficient beam-driven acceleration (improvement of transformer ratio (TR) [12]); see example in Ref. [13,14]. Some of these laser-shaping techniques require precise control over the laser-pulse spectrum and would also benefit from photocathode operating close to the fundamental wavelength of the laser system.

RF-gun design & beam dynamics. The L-band RF guns typically employed to generate high-charge bunches provide a limited accelerating field on the cathode [typically O(50 MV/m)] with 3-5-MeV final energy at the RF-gun exit. RF guns operating at higher frequencies could provide higher-field to mitigate collective effects but the smaller RF wavelength limit the bunch duration. Lower-frequency (VHF) RF-gun could offer a viable path owing to the long RF wavelength as long as the bunch exit energy remains high-enough. For instance, numerical simulations indicate that a 200-MHz SRF gun with a 40-MV/m peak field [15,16] is capable of producing a preshaped 10-nC electron bunch with parameters suitable to ultimately support an enhanced TR of ~5 [13] in a SWFA [17]. These tradeoffs between RF-gun frequency choice and bunch quality should be studied quantitatively via precise numerical algorithms properly accounting for space charge effects during the emission process. The validity of the quasi-static models often employed to simulate the beam dynamics in photoinjectors should be investigated and validated against first-principle-physics algorithms (e.g. FDTD PIC algorithms).

Bright main electron and positron bunch production: Attaining high luminosity is contingent to the production of bright main bunches, which share many similarities with the drive bunch albeit at a lower charge and higher brightness. We identify three complementary research areas listed below.

Photocathodes and RF-gun selection. The electron bunch would benefit from low-MTE photocathode such as the one currently investigated by other groups [18,19] while high QE is not critical given the low charges (2-3 orders of magnitude smaller than for the drive bunch). An additional challenge associated with the main-bunch production regards the requirement for spin-polarization often realized using NEA GaAs photocathodes. The required ultra-high-vacuum (UHV) has, so far, prevented their prolonged operation in RF guns [20]. However, SRF guns could provide a path toward the reliable operation of spin-polarized photocathodes due to their excellent UHV levels sustained via cryo pumping. Ultimately, the 6D phase-space volume attainable in state-of-the-art photoinjectors combined with emittance-repartioning techniques could alleviate the need for an electron damping ring.

Bunch shaping and beam manipulations. Further improvements in the efficiency of an SWFA- and PWFA-based accelerators could be realized by shaping the main bunch current profile to load the wakefield generated by the drive bunch and significantly enhance the overall efficiency [21]. Controlling the bunch temporal distribution relies on similar laser-shaping techniques than the ones described above. Finally, the final beam distribution at the IP may be dominated by physics requirements (asymmetric "flat" beams [22] or ultrashort bunches [23] for bremsstrahlung mitigation). These requirements call for small 6D phase-space volumes. Given the low bunch charge and shorter laser pulse involved in the emission process, a path to enhanced brightness are high-frequency RF guns capable of sustaining 100's MV/m accelerating fields.

Positrons production. Conventional positron sources, based on Bremsstrahlung pair production using a high-energy electron beam impinging a thick target, typically produce beams with brightness orders of magnitudes smaller than attained in electron sources. The produced beam emittances are large and the source requires a complicated capture section [24]. Recently channeling-based positron source [25] with expected superior emittance quality was tested [26]. Likewise, thin target positron sources are expected to produce smaller beam emittance while also enabling the transfer of spin-polarization from the electron beam [27]. Finally, positron sources based on inverse-Compton scattering or based on undulator were also proposed and experimentally investigated [28,29]. None of these experiments has yet attempted to characterize the phase spaces distributions of the produced positron bunches. Finally, positron electrostatic traps [30] capable of trapping ~10^8 positrons have recently been demonstrated [31], the possible combination of such traps with advanced phase-space manipulations discussed in a companion LOI [32] could enable the generation of brighter positron bunches than presently available.

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