# Beam Physics Challenges & Research Opportunities for Structure-based Wakefield Accelerators

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**Abstract**: Structure-wakefield accelerators (SWFAs) have the potential to support TeV-class high-luminosity lepton colliders. SWFAs can be configured in either two-beam acceleration (TBA) or collinear wakefield acceleration (CWA). Enabling high-gradient, efficient SWFAs to produce TeV-class high-quality beams depends on precise control of the beam distribution. This LOI identifies critical beam-dynamics research opportunities relevant to beam-driven wakefield accelerators.

**Introduction:** Beam-driven wakefield accelerators rely on high-charge "drive" bunches [O(10–100 nC)] passing through slow-wave structures (SWSs) to excite electromagnetic wakefields [1]. The produced wakefields can be directly used to accelerate a delayed "main" bunch (CWA) or be out-coupled and guided to an optimized accelerating structure that accelerates the 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; the TBA scheme decouples the drive and bunch beam dynamics at the expense of increased complexity (e.g., two parallel beamlines are required). The beam dynamics associated with the simultaneous transport of the accelerating main bunch and decelerating drive bunch is one of major challenges in CWA.

**Drive bunches:** For a given SWS, precise control of the drive-bunch distribution is critical to maximizing the SWFA efficiency and accelerating field for both TBA and CWA. In CWA (both SWFA and plasma wakefield acceleration [PWFA]) a shaped high-charge drive bunch can significantly enhance the transformer ratio while also enabling large accelerating fields [2]. This area of research has developed significantly over the last decade as a variety of temporal-shaping techniques have been proposed (e.g., the possible use of laser shaping, transverse-to-longitudinal phase space exchangers, or exploiting nonlinear correlations introduced in the longitudinal phase space using nonlinear longitudinal dispersion, multifrequency linear accelerators, or controlling collective effects; see [3]).

Some techniques can shape the beam with sub-picosecond resolution consistent with the use of SWS operating in the THz regime, as required for a GV/m accelerating field. In addition, a possible path to increasing the transformer ratio involves the use of multi-channel SWSs where the drive and main bunches are transversely offset but propagate in the same accelerator beamline [4]. This latter path of CWA utilizes a transversely shaped drive bunch (e.g., an annular [5] or segmented bunches). Generating these various bunch distributions involves precise phase-space manipulation discussed in a companion LOI [3], while also relying on a precise analytical understanding and high-fidelity modelling of collective effects. For instance, the bunch shape and charge involved will most likely require more elaborate models (for, e.g., coherent synchrotron radiation [CSR]) [6]. Likewise, understanding and optimizing the drive-bunch beam dynamics during its deceleration in the SWS is critical. An important aspect regards the interplay between the imposed external periodic focusing and transverse wakefield experienced by the

bunch as it propagates off-axis in the SWS. This interplay can be detrimental to the bunch, resulting in a short-range beam-break-up (BBU) instability where the imparted time-dependent deflecting force eventually yields beam loss [7]. Understanding the mitigation of this instability will be essential to improving the efficiency of CWA. Some early mitigation schemes include the dynamical control of the wakefield-induced correlated energy spread via a precise shaping of the current distribution. Most of these investigations also apply to TBA; the main difference is that the TBA excitation mode (train of bunches with modulated charge [8] and with repetition frequencies up to THz) is prone to a "long-range" BBU instability.

**Main bunches:** Attaining a high luminosity requires the production and transport of bright main bunches, which share many similarities with the drive bunch (albeit at a lower charge and higher brightness). Further improvements in the efficiency of an SWFA-based accelerator are limited by beam loading. Consequently, shaping the main bunch current profile to load the produced wakefield would significantly enhance the overall efficiency [9] for both SWFA and PWFA. Likewise, main-bunch shaping could also produce lower correlated energy spread across the main bunch, which could improve the beam quality during acceleration. Finally, the final beam distribution at the IP may be dominated by physics requirements (asymmetric "flat" beams [10] or ultrashort bunches [11] for bremsstrahlung mitigation). These requirements affect the acceleration process (i.e., producing shaped short main bunches would require shaping with unprecedented temporal precision).

An important factor for the main bunch is timing with respect to the drive bunch's electromagnetic field. The required synchronization level is expected to be a small fraction of the fundamental-mode wavelength (i.e., sub-100-fs for fields in the THz regime). This requirement will also necessitate the development of novel beam diagnostics [12]. Finally, the production of a positron bunch with the required emittance presents a significant challenge for any high-frequency accelerators. If a conventional adiabatic matching capture [13] is employed, the positron beam would have to be cooled and compressed before injection in the SWFA. Alternative positron production techniques capable of producing low-emittance ultrashort pulse should be actively explored.

**Need for integrated studies:** Significant progress has been made in precise control of the electron-beam distribution: several shaping methods have been developed and experimentally demonstrated [14, 15]. Likewise, an analytical theory of the BBU instability has been formulated [16] and mitigation techniques developed [17], and numerical-simulations validation is underway (i.e., tapered external-focusing configurations were devised) [18]. An important step toward the realization of an SWFA-based collider is the development of an integrated experiment where shaped drive bunches supporting enhanced transformer ratios are propagated in a meter-scale SWFA module to explore the onset of the BBU instabilities while also supporting the development of associated beam diagnostics and correction techniques. The injection of a main bunch could also support investigations on transverse-emittance dilution during the acceleration process, along with the exploration of main-bunch shaping for wakefield loading. Similar integrated experiments for a TBA scheme should also be initiated using, for example, a modulated bunch-train for efficient peak-power generation. Although these experiments would most likely focus on modest sub-GeV energy gain [19,20], they could demonstrate the maturity of the TBA and CWA techniques for their possible inclusion in larger facilities (e.g., compact X-ray free-electron lasers [21]), before the possible deployment of a full-fledged linear-collider concept [22, 23].

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