Snowmass2021 Letter of Interest:
The impact of high-field physics on plasma-based particle colliders

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Introduction. The next lepton collider will require center-of-mass energies on the order of several TeV, which represents a challenging energy frontier for conventional accelerator technology, given reasonable space and cost restrictions. For this reason, alternative high-gradient acceleration concepts are being developed [1]. Plasma-based acceleration schemes such as laser wakefield acceleration (LWFA) are particularly promising candidates due to their ability to achieve accelerating gradients in excess of 100 GV/m and hence may provide compact acceleration structures [2,3]. The recent demonstration of multi-GeV electron beams from cm-scale capillary discharge waveguides [4], as well as the proof-of-principle coupling of two accelerating structures [5], at Lawrence Berkeley National Laboratory has increased interest in laser-plasma accelerators as a promising technology to be considered for a compact, TeV-class, lepton linear collider [2].

One crucial aspect of a plasma-based lepton collider, that has however received relatively little attention, is the final focus and subsequent beam behavior at the interaction point (IP). A typical plasma-based collider will produce particle beams in a form of short tightly focused bunches of high density, surrounded by strong electromagnetic (EM) fields [6]. Operating at center-of-mass energies of hundreds of GeV to several TeV, the mean field strength in the beam rest frame will, in the neighborhood of the IP, exceed the critical field of quantum electrodynamics by a significant factor, parameterized by the beamstrahlung parameter $\chi \gg 1$. The combination of high fields and high density will cause significant variability of particle orbits at the IP and, consequently, the patterns of beamstrahlung and electron-positron pair production by emitted photons, will differ significantly from those predicted for conventional collider designs [7–11]. The physics associated with high-field phenomena in this *deep quantum regime* is at present poorly understood and requires new theoretical developments. The theory addressing them, Strong Field Quantum Electrodynamics (SFQED), thus needs to be updated or generalized.

SFQED theory and simulations. Ideally, SFQED, should reach the same status as its weak-field counterpart, QED, which for decades has served as a paradigm for ultra-precise agreement between theory and experiment. However, this agreement has only been achieved in a perturbative setting at low particle

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numbers. When electrons, positrons, and photons start to interact with sufficiently strong EM fields, new phenomena (both at a single particle and collective level) start to manifest themselves. They are relevant for a diverse range of conditions and physical scenarios such as the early universe, extreme astrophysical objects, the extension of color-kinematic duality beyond flat space-times [13, 14], the physics of future high-intensity laser driven relativistic plasmas, and, in particular, plasma based lepton linear colliders of TeV class. Over the last three decades or so, a combination of SFQED theory, simulation, and experiments have produced a wealth of results that have considerably improved our understanding of high-field phenomena, mostly in the domain of laser plasma interactions [15–19]. Many of the developments in SFQED have been driven by progress in laser technology [12], which has led to EM fields strong enough to realize a genuine SFQED environment for charged probes interacting with them [20–22]. Ultra-relativistic lepton beams can provide a similar environment, which has stimulated renewed interest in SFQED studies of beam-beam interactions in conventional [27] and plasma-based colliders [28].

Theory developments in the non-perturbative regime. Future research needs to address a number of remaining topics in connection with the design of proposed TeV-scale lepton colliders at which the final focus and IP designs will be strongly affected by SFQED effects [27, 28]. These topics are tied to the theoretical methods used for calculations in strong external fields, and the limitations thereof. Studies will need to go beyond (i) simple approximations of the geometry of strong fields, (ii) limited 'locally constant field' approximations used in numerical simulations, and (iii) the external field approximation itself. Going beyond these 'theoretical frontiers' is challenging since it is these very approximations which enable the analytical treatment of SFQED processes. Approximations (i) and (iii), in particular, allow for a *semi-non-perturbative* approach in which scattering amplitudes may be calculated to all orders in the strong background field, at any given order in the fine structure constant. These studies would also require a coordinated experimental effort at multi-beam high intensity laser facilities to verify the theory developments. Moreover, with the increase of EM field strength, it has been conjectured that interactions enter a new regime where the semi-non-perturbative expansion of SFQED breaks down as higher and higher order loop processes become important [23–26]. This regime may be reached in future beam-beam interactions [27] and will influence the design of TeV-scale lepton colliders; as such, a new non-perturbative formulation (an exact theory of the interaction with the radiation field) may be required in order to understand and control non-perturbative effects, and thus properly analyze beamstrahlung, cascades, and beam disruption at the IP of future colliders.

SFQED at a plasma based lepton collider. A plasma based collider is envisioned to have two multi-stage LWFA arms, one for electrons and the other for positrons [1], with each stage powered by a separate laser pulse. Such a facility can easily be made multi-purpose with minimal adjustments to the collider configuration, allowing for more general studies at the same location: a subset of multiple laser pulses, corresponding to one LWFA arm, may be used to accelerate electrons (or positrons) while the remaining pulses can be rerouted and brought into collision at the IP [19, 29, 30]. This would provide a configuration for the study of e-beam laser interactions and SFQED phenomena such as high-multiplicity cascades, spin-polarized high energy lepton beams [31], high energy photon sources, and prototype $\gamma\gamma$ colliders. Another configuration could bring all the lasers to the IP, providing the highest intensity for experiments involving different fixed plasma targets or the study of nonlinear vacuum polarization, relevant for different astrophysical phenomena.

Summary. Realizing a plasma based lepton collider represents a significant challenge on many frontiers. In particular, extensive R&D is required for the design of its final focus and IP. From a theoretical perspective, this requires taking the effects of SFQED into account. A dedicated research program including interdisciplinary and international collaboration is needed to (i) develop new approaches for theoretical and numerical studies of high field phenomena, (ii) design a new class of ultra-high intensity laser experiments analyzing the outlined development of the SFQED theory in preparation of future collider studies, and (iii) explore compact set-ups for transporting electron and positron beams to the IP. These three elements should be regarded as essential ingredients for plasma based accelerator research aiming to realize future compact colliders.

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