Particle Colliders with Ultra-Short Bunches
LoI to Energy Frontier

Phil H. Bucksbaum, Gerald V. Dunne, Frederico Fiuza, Sebastian Meuren, Michael E. Peskin[a], David A. Reis, Greger Torgrimsson, Glen White, and Vitaly Yakimenko[b]

(Dated: 3 July 2020)

Abstract: In this LoI, we discuss a staged experimental strategy towards realizing a novel concept for electron linear colliders. We believe that there is a new design strategy for such colliders using very short electron bunches with very strong bunch-bunch interaction. This proposal leads to a number of inter-related studies described in accompanying LoIs: on the accelerator physics of the production of ultra-short electron bunches [1]; on the possibility of a $\gamma\gamma$ collider based on ee bunch collisions producing supercritical electromagnetic fields [2]; on the basic theory of QED in the regime of extreme background fields [3], and on the implications for astrophysics and plasma physics of the behavior of QED in such extreme environments [4]. In this LoI, we describe an experimental program with electron beams to validate these ideas.

I. INTRODUCTION

We have been exploring a new approach to the design of electron linear colliders based on the collision of very short and intense electron bunches. It is well appreciated that bunch collisions at linear colliders produce "beamstrahlung" radiation which acts, together with standard initial-state radiation, to broaden the spectrum of center of mass energies of the electron collisions. Currently proposed e^+e^- colliders such as ILC and CLIC attempt to mitigate this effect by colliding flat beams. We find it interesting to consider the opposite limit, in which beamstrahlung is emitted as synchrotron radiation in the extreme quantum regime, with the use of ultra-short bunches to suppress the low-energy part of the radiation spectrum. This strategy offers the potential of a gamma-gamma collider without the need for Compton backscattering. Because it is based on tightly focused round beams, this design would make efficient use of the beam power for luminosity. If these ideas are successful, they would scale naturally to very high energies, giving a strategy to achieve multi-10-TeV center of mass energies with gamma-gamma collisions. This strategy is discussed further in the accompanying LoI [2].

To validate these ideas, many issues must be studied. We need first to overcome the accelerator physics limitations to bunch compression and devise strategies for producing ultra-short bunches. We then need to understand how to compute beamstrahlung production in the extreme quantum limit, including quantum coherence effects that become important with short bunches. The basic QED theory needed here goes considerably beyond the current state of the art. Finally, we need to know how to simulate radiation and its back-reaction in extremely large background fields, well beyond the Schwinger critical field defined by $eE_c = m_e^2$. The theory and simulation questions outlined in this research program must also be addressed to compute the structure of the e^+e^- plasmas surrounding pulsars, magnetars, and other active astrophysical sources of radiation. These various issues are discussed further in the accompanying LoIs [1, 3, 4].

The development of these ideas requires a close interaction of theory, simulation, and experiment. We plan that the experimental input will come from a series of experiments at SLAC on bunch compression and electron-laser beam interactions. These are described in the next section.

a) mpeskin@slac.stanford.edu
b) yakimenk@slac.stanford.edu

II. EXPERIMENTAL R&D STRATEGY

We propose to carry out a set of experiments on beam physics of extreme compression and electron beam-laser interactions to improve confidence towards proposing a particle physics collider based on this novel short and round bunch paradigm. The first step in this program is planned for FACET-II – a frontier facility at SLAC that will be capable of producing collider-relevant beam intensities with bunch lengths on the order of 0.4 μm. In general, one expects that collective effects, which occur during the process of acceleration and longitudinal compression, will prohibit the compression of bunches to even smaller sizes. This program will investigate a number of strategies to mitigate these effects, discussed further in LoI [1]. In particular, it will extend our understanding and ability to model the process of compression, improve simulation codes through benchmarking into unprecedented parameter space, and provide experimental tests of mitigation techniques.

The approved E-320 experiment at FACET-II will study beamstrahlung radiation and pair production by colliding 13 GeV electron bunches with 20 TW laser pulses, reaching values of $\chi = E_*/E_c \sim 1$, where E_* is the electric field seen in the frame of the electron. In particular, it will demonstrate that energy losses can be mitigated by reducing the interaction time below the average radiation time. Furthermore, the formation length for photon radiation will be measured and the associated breakdown of the Local Constant Field Approximation (LCFA), which is used in all current codes, will be observed.

The next step in this program would involve reconnecting the FACET and LCLS linacs to provide an electron beam of energy 30 GeV. This facility would give the ability to test beam-quality preserving bunch compression schemes at higher energy, giving a quantitative understanding of the beam quality that is achievable. This will give the experience we need to scale the ideas about bunch compression to collider designs of 250 GeV and also to much higher center of mass energies.

Finally, we envision bringing the 30 GeV beam into collision with the beam of a multi-PW laser. Such a facility will produce QED cascades with pair multiplicities of order 10^2. This corresponds to $\chi \sim 30 - 100$, well into the regime of nonperturbative QED effects. This should lead to pair plasmas of density 10^{27} cm^{-3} with temperatures of order 100 MeV. Such conditions will stress-test codes describing QED plasmas, in particular, the algorithms for combining quantum and out-of-equilibrium dynamics. Plasmas with these parameters are encountered in the the magnetospheres of magnetars, and so this program allows tests of extreme astrophysical environments in the laboratory, as discussed in LoI [4]. They are also of strong interest to Fusion Energy Sciences. Moreover, the onset of radiative corrections will become important at this scale, in a way that will challenge the results of the theoretical studies discussed in LoI [3].

III. ADDITIONAL PARTICLE PHYSICS OPPORTUNITIES

The very high fields that these experiments will create offer other opportunities for particle physics exploration. A part of the current interest in new, weakly coupled particles is the search for axion-like particles (ALPs) that couple to electromagnetic fields through the operator $F\tilde{F}$ and dark photons that couple to electrons with millicharge strength. Possible detection methods include depletion of the beam energy into invisible particles and the decay of such BSM particles into known ones behind an absorber. It will be interesting to see if these two methods can provide sensitivity to couplings weaker than those currently probed [7].

References

[1] V. Yakimenko and G. White on behalf of the collaboration, Beam physics of extreme bunch compression, LoI to Accelerator frontier

[2] G. White and M. Peskin on behalf of the collaboration, Laser-less $\gamma\gamma$ collider, LoI to Energy frontier

[3] S. Meuren and G. Dunne on behalf of the collaboration, Probing fully NpQED regime, LoI to Theory frontier

[4] S. Meuren and F. Fiuza on behalf of the collaboration, Cascades, LoI to Cosmic frontier

[5] M. Peskin and V. Yakimenko on behalf of collaboration, Particle colliders with ultra-short bunches, LoI to Energy frontier

[6] S. Meuren on behalf of the E-320 Collaboration, Probing Strong-field QED at FACET-II (SLAC E-320).

[7] I. G. Irastorza and J. Redondo, Prog. Part. Nucl. Phys. **102**, 89 (2018) [arXiv:1801.08127 [hep-ph]].