Short-Bunch Paradigm Laserless $\gamma\gamma$ Collider LoI to Energy Frontier

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Abstract. We propose to investigate a new paradigm for a $\gamma\gamma$ collider based on an e^-e^- collider with extremely short, cylindrical bunches and strong beam-beam interaction. In this regime, the beams emit beamstrahlung in the extreme quantum limit, producing a hard photon spectrum that, in principle, can be useful for physics. We plan to investigate this idea for applications to low-energy $\gamma\gamma$ collisions, a $\gamma\gamma$ Higgs factory, and a 30 TeV $\gamma\gamma$ frontier collider.

I. INTRODUCTION

In the study of future linear electron colliders, much attention has been given to the option of converting the electron beams to photons to create a dedicated $\gamma\gamma$ collider [1]. The conversion of an e^+e^- collider to a $\gamma\gamma$ collider has been considered for GLC/JLC [2, 3], NLC [4], TESLA [5], ILC [6], and CLIC [7]. The physics available to a $\gamma\gamma$ collider has many unique features. In particular, the 125 GeV Higgs boson appears as a resonance in $\gamma\gamma$ collisions, enabling a measurement of the its partial width into $\gamma\gamma$. This is a uniquely interesting aspect of the Higgs boson profile, since this quantity is especially sensitive to physics beyond the Standard Model. In addition, the relatively low ee CM energy needed (below 160 GeV) might allow this program to be the first stage of an accelerator based on a new technology. Physics possibilities at even lower energies, for example accessible with current FEL accelerator technology, have been discussed in [8, 9]. In e^+e^- colliders at very high energies, above 3 TeV, it is almost unavoidable that the strong beam-beam interaction and associated beamstrahlung will severely distort the e^+e^- luminosity spectrum, frustrating the ability to achieve collisions at the highest energies, and also severely disrupt the bunches themselves, complicating the interaction region design [10]. Also, in particular with plasma wakefield technology, it is not obvious that positrons can be accelerated to high energy. Even if this is technically feasible, producing and accelerating positrons will almost certainly increase the costs significantly. A solution to these problems might be to consider a $\gamma\gamma$ collider based on an e^-e^- accelerator as the primary electromagnetic collider for the multi-10 TeV energy frontier.

Such a collider necessitates entirely new concepts to achieve the required high-brightness γ beams. Existing approaches based on Compton-backscattering from laser sources presents severe limitations in their ability to scale to higher COM energies associated with nonlinear QED effects. Blankenbecler and Drell [11] suggested beamstrahlung as an alternative source for high-energy gamma photons. This approach also needs to be revisited under strong-field QED conditions. Counterintuitively, very dense beams could mitigate beamstrahlung disruption, leading to much higher luminosity. The idea becomes particularly attractive in the extreme quantum regime $\chi = E^*/E_{\text{cr}} \gg 1$, where E^* denotes the rest-frame electric field produced during a beam-beam collision and $E_{\text{cr}} \sim 10^{18}$ V/m is the QED critical (Schwinger) field. In this limit the beamstrahlung spectrum exhibits a pronounced peak close to the energy of the incoming lepton. It is important also to limit the production of low-energy photons in beamstrahlung, since these will degrade the e^- energy spectrum and also lead to backgrounds from low-energy pair production. To do this, we plan to utilize very short bunches, observing that the radiation of low-energy photons will be suppressed when the bunch length becomes less than their formation length. We envision that this strategy for creating a $\gamma\gamma$ collider will be scaleable to multi-10 TeV energies.

II. OUTLINE OF POTENTIAL RESEARCH PROGRAM

Currently proposed linear colliders are designed to minimize beamstrahlung by using flat and relatively long bunches [10]. We propose to explore the opposite regime, with dense, cylindrical, and

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very short electron bunches. It was noted in the early papers on beam-beam interactions [11] that, by maximizing beamstrahlung radiation in this way, a high luminosity in $\gamma\gamma$ would be generated within the intense EM fields of the colliding particle bunches. At the time, a machine capable of generating the required short bunch lengths was not considered feasible. Recent progress in electron bunch compression techniques has led to the realization [12] that electron bunches with bunch lengths below 100 nm, together with transverse emittances capable of < 10 nm round spot sizes at collision, may be feasible. The accelerator physics of this parameter region is the subject of an accompanying LoI [13].

Note that the new paradigm requires a major re-design of the final focusing system with respect to the traditional approach. Ideally, the transition region between zero and highly supercritical rest-frame electromagnetic field should be much shorter than the average radiation length, such that all photons are emitted in the strong-field region, where the spectrum favors hard emissions. Otherwise, the electrons lose all their energy during the ramp-up of the field, and due to their degraded Lorentz factor the extreme quantum limit is not achievable.

Preliminary simulations of beam-beam collisions with these parameters indicate that $\gamma\gamma$ luminosities in excess of equivalent e^+e^- collision luminosities are possible (for equivalent beam power loads). Unlike the case of a $\gamma\gamma$ collider based on laser Compton backscattering, the $\gamma\gamma$ luminosity extends up to the full center-of-mass collision energy ($2E_{beam}$). As an example: considering the aforementioned beam parameters with a 250 GeV center-of-mass collision energy and electron bunch charge of 1.4 nC, the $\gamma\gamma$ luminosity is $\sim 6 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ per bunch crossing, 100× higher than previously considered $\gamma\gamma$ collider designs.

There are a number of open questions requiring further study to more fully evaluate the feasibility of this approach. These include:

What is the complete picture of the beam-beam interaction? The beam parameters proposed produce interacting fields of sufficient strength that existing, perturbative, treatments of QED break down [12]. At extreme particle/photon densities coherence effects might become relevant, such that more than two high-energy particles/photons can participate in a hard scattering event. Also, existing PIC-style codes which model the beam-beam interaction have known deficiencies in this regime. Most importantly, these codes depend on the so-called Local Constant-Field Approximation (LCFA), which is not applicable for very short bunches. This is a known issue for PIC codes and is the subject of ongoing development [14]. These and other topics of study are outlined in an associated LoI [15]. It is crucial to have a reliable calculation of the $\gamma\gamma$ luminosity as a function of $\sqrt{s_{\gamma\gamma}}$. This must be understood both for the highest energy photons, to asses the particle physics potential, and also for lower-energy photons, to understand the background conditions. These theoretical studies also link to the subject of an accompanying LoI [16] on the nature of the e^+e^- plasma formed by strong beam-laser interactions and the applications of that study to high-energy astrophysics.

Can we design an accelerator capable of delivering the required beam parameters? A number of beam physics issues need to be resolved to understand the limitations of bunch compression while preserving transverse emittance. For example, emittance dilution due to coherent sychrotron radiation (CSR) in bunch compressor bends is a known issue. Mitigation strategies exist but require further development of CSR theory and experimental tests of CSR-compensating bunch compressor designs. These and other accelerator design issues are addressed in an accompanying LoI [17].

How should one design a detector for this short-bunch-paradigm $\gamma\gamma$ collider? Unlike conventional $\gamma\gamma$ collider concepts, there is no need to transport a high-power laser beam to the collision region. However, other difficulties of the $\gamma\gamma$ collider idea, including the large backgrounds from low-energy $\gamma\gamma$ and γe collisions, become even more problematic. The post-collision e^- bunches will have a large spread in energy and transverse momentum, requiring a large crossing angle to extract them cleanly. The extremely compressed, Mega-Ampere scale peak currents of these beams cannot traverse a strong detector solenoid field with these large crossing angles. This requires a fundamental redesign of the detector beam extraction system. For the Higgs factory application, the layout of the vertex detector must be reconsidered. At multi-10 TeV energies, the structure of collision events will also be different from those at current energies, so a complete re-thinking of the detector design will be needed.

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