LBNL-42286

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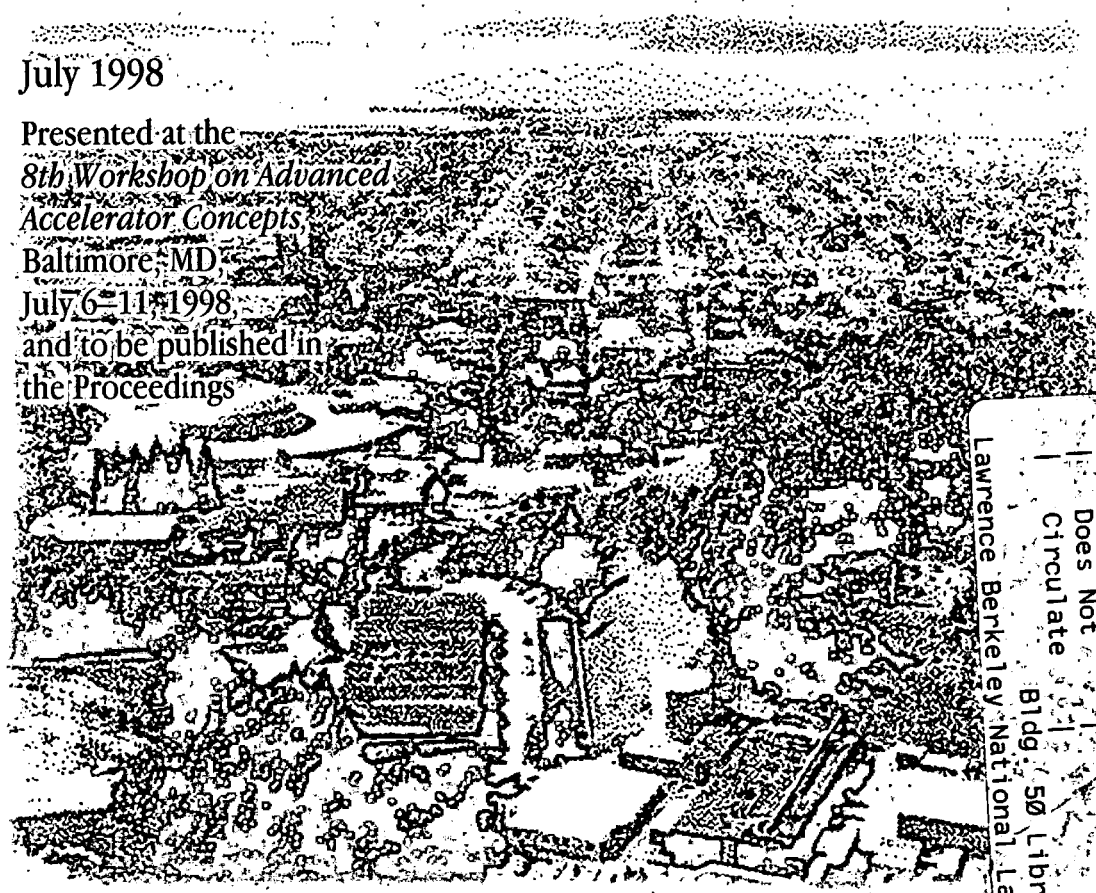
July 1998

Presented at the *8th Workshop on Advanced Accelerator Concepts*, Baltimore, MD, July 6–11, 1998, and to be published in the Proceedings



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LBNL-42286
UC-414
CBP Note-271

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To be Published in the Proceedings of
The 8th Workshop on Advanced Accelerator Concepts
July 6-11, 1998, Baltimore, USA.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, of the U.S. Department of Energy under contract No.DE-AC03-76SF00098.

Quantum Suppression of Beamstrahlung for Future e^+e^- Linear Colliders: an Evaluation of QED Backgrounds

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Abstract. Beamstrahlung at interaction point may present severe limitations on linear collider performance. The approach to reduce this effect adopted for all current designs at 0.5 TeV range in center-of-mass energy will become more difficult and less effective at higher energy. We discuss the feasibility of an alternative approach, based on an effect known as quantum suppression of beamstrahlung, for future linear colliders at multi-TeV energy.

I INTRODUCTION

One of the most important constraints on the performance of an e^+e^- linear collider is that imposed by the QED processes [1], in particular beamstrahlung [2–8], at the Interaction Point (IP). Beamstrahlung is the synchrotron radiation produced by particles of one beam as they pass through the electric and magnetic fields of the oncoming beam. The fields can be so strong due to extremely high charge density that colliding particles may lose significant amount of their energy, causing severe luminosity degradation. The photons generated by beamstrahlung may also turn to copious e^+e^- pairs, or even hadrons through QCD processes, causing troublesome background problem to the detector and hence the particle physics under study. Therefore a crucial task to assess the potential of future linear colliders is to identify the operation regimes and approaches for beamstrahlung suppression with which the impact of these deleterious effects on collider performance can be minimized, taking into account other collider constraints, of course.

To suppress beamstrahlung, the so-called flat-beam approach has been adopted for all current designs of linear collider at 0.5 TeV c.m. energy range [9]. However, this approach will become more difficult technically and less effective at higher energy, as will be explained later. In addition, several other

methods have been proposed. Charge compensation method [10,11] requires the mixing of beams of opposite charge to neutralize the beam fields before collision. But, due to a beam instability, imperfection in mixing could cause luminosity degradation. The beam fields may also be reduced by the return current in a plasma [12] introduced at the IP. The problem of concern in this case is the hadronic backgrounds due to collisions of beams with dense plasma ions. Instead of colliding charged particle beams, one may also convert them into photon beams to make a $\gamma\gamma$ collider [13]. However, it seems unlikely that a $\gamma\gamma$ collider could scale more favorably to higher energy than its e^+e^- counterpart due to other types of technical constraints. Apart from that, $\gamma\gamma$ collision is not meant to be a substitute for e^+e^- annihilation in terms of physics discovery potential [14]. Regardless of the variety, the working philosophy behind all these methods is the same that is to reduce or eliminate if possible the strong beam fields. Nevertheless, there is an exception.

In this paper, we discuss an effect known as Quantum Suppression of Beamstrahlung (QSB). Unlike all other approaches, QSB is effective only when the beam field is sufficiently strong. In that regard, it is compatible with the ever-increasing beam density required of a linear collider at higher energy, thus deserves a careful investigation. A brief description of beamstrahlung and the rational behind the interest in QSB are given in Section II. Monte-Carlo IP simulation for a 5 TeV collider case is presented in Section III to illustrate the main characteristics of QSB and in particular to evaluate the collision induced QED backgrounds. This then leads to a discussion in Section IV of major issue and uncertainty involved in establishing QSB as a feasible IP approach for linear colliders at higher energy.

II BEAMSTRAHLUNG

Beamstrahlung can be classified into three regimes [1] according to the magnitude of the beamstrahlung parameter, $\Upsilon = \gamma B/B_c$, where $\gamma = E_b/mc^2$, E_b is the beam energy, B the beam field and B_c the Schwinger critical field. The three regimes are, respectively, the classical regime if $\Upsilon \ll 1$, the extreme or strong or deep quantum regime if $\Upsilon \gg 1$, and in between the transition regime. In the classical regime, beamstrahlung can be calculated with the usual synchrotron radiation formula derived from classical electrodynamics. Alternatively, the beamstrahlung parameter in this regime may be expressed as $\Upsilon = 2\epsilon_c/3E_b$ in terms of a classical quantity known as critical photon energy, ϵ_c. The classical theory is valid only if the energy of the radiated photon, characterized by ϵ_c, is much less than the kinetic energy of the radiating particle. This condition corresponds to $\Upsilon \ll 1$.

So far all the designs of linear colliders at 0.5 TeV range have managed to stay in the regime with $\Upsilon < 1$ [9], where beamstrahlung and its deleterious effects can be reduced by having smaller Υ. Therefore reducing Υ by reducing

the beam field, has been adopted as a guideline and that is made possible by taking the flat-beam approach. However, as we know the required luminosity for a collider has to rise as the square of its energy, thus to keep wall plug power under control the beams have to be focused to smaller size with higher charge density. This will unavoidably raise Υ and put a linear collider into the deep quantum regime. As a result, the flat-beam approach will become more difficult and less effective at higher energy. More difficult for technical reason, as the flat-beam approach requires beam size in one transverse direction to be much smaller (for given beam area), thus pushing the limit for tight beam positioning control at higher energy. For current designs at 0.5 TeV, vertical beam size is already down to a few nanometers. Less effective for physical reason, as it has been shown [3] the dependence of spread in luminosity spectrum on beam shape is very week in the deep quantum regime.

Question then arises: what would be the approach to suppress beamstrahlung at higher energy if a linear collider will be unavoidably pushed into the deep quantum regime ? Fortunately, the very nature itself offers help. As Υ increases due to either stronger fields or higher beam energy, the radiated photons become more energetic. Quantum theory has to be used to take into account radiation recoil and the fact that photon spectrum beyond the particle energy is kinetically forbidden. A full quantum treatment of synchrotron radiation was given by Sokolov et al. [15] for arbitrary value of Υ in a constant field. This result was later applied to and extended for the study of beamstrahlung [2–8].

According to the quantum theory, beamstrahlung scales differently in the regimes $\Upsilon \ll 1$ and $\Upsilon \gg 1$. It was shown [2] that advantage may be taken of this behavior in the deep quantum regime to extend collider energy to multi-TeV without excessive beamstrahlung. It was also made clear that the beam parameters required to take advantage of this effect, such as very short bunch or small emittance, are not readily achievable, and the flat-beam approach is a much better choice at 0.5 TeV energy range.

However, one should not forget that 0.5 TeV is only a near term goal for linear collider development, very much limited by the current technologies. Considering competitions from hadron or even muon colliders, it would be much more compelling for linear collider to go beyond that energy. Recently, high energy physics community has been emphasizing the importance of higher energy reach (up to 5 TeV) for a linear collider [16]. There is also a need to explore drastically different collider parameter regime that might potentially be reached with the advanced acceleration techniques currently under active investigation [17]. It is now becoming increasingly important to search for more feasible IP approaches at higher energy.

In particular, possibility of employing quantum suppression as an IP approach was explored over a wide range of beam parameters at 5 TeV by Xie et al [18]. It was shown in this study that when major accelerator and IP constraints are taken into account, it becomes increasingly necessary to operate

linear colliders in high Υ regime and use to our advantage the quantum effect to suppress beamstrahlung. Monte-Carlo simulation was performed to study luminosity spectrum. The results were surprisingly encouraging. To carry this study a step further, in this paper we present a detailed evaluation of QED backgrounds for a representative case of collider parameters in high Υ regime. The analysis of hadronic backgrounds due to QCD processes will be presented in a companion paper [19] in these proceedings.

What is quantum suppression and how could it be realized in a linear collider ? Before going to the simulation next let's address this question by giving at least one scenario where QSB could manifest itself in a linear collider. Consider a case when all beam parameters are fixed except bunch length. As bunch length decreases, beam density hence the beam field and Υ increase, radiative energy loss per unit time will also increase either in the deep quantum regime or classical regime. However when multiplied by bunch length, radiative energy loss per bunch crossing decreases in the deep quantum regime while still increases in the classical regime. This effect thus may be called the quantum suppression of beamstrahlung. The QSB so defined calls for short bunch length. This is again compatible with the trend of reducing the wavelength of acceleration field from current microwave accelerators to future laser-driven accelerators.

III SIMULATION IN HIGH Υ REGIME

We now present full-blown IP simulations using CAIN developed by Yokoya and co-workers [20]. CAIN is capable of handling all major electromagnetic and QED processes occurred at the IP, including disruption, beamstrahlung, bremsstrahlung, coherent and incoherent pair creation. It is a Monte-Carlo code which follows beam particles, photons and pairs in six-dimensional phase space, as well as their spins and polarization. In comparison, previous studies of beamstrahlung in the deep quantum regime [2–8] were concentrated mainly on obtaining analytical and semi-analytical results to understand the physics, thus were limited to treating only simple, idealistic models. In these early studies, either disruption or multiple beamstrahlung or both were neglected, and none was able to treat simultaneously pair production and give angular-momentum distributions. However this information is essential to background analysis and overall assessment of collider performance, especially in high Υ regime. Beam parameters used in simulation are given in Table 1, which are taken from the CASE II by Xie et al [18], along with their definitions.

Figure 1 shows the luminosity spectrum for e^+e^- and $\gamma\gamma$ collisions. For e^+e^- case the spectrum is characterized by an outstanding core at full energy and a very broad tail two orders of magnitude below the peak. Seen from Table 3, the core itself within 1% of full energy accounts for 65% of the geometrical luminosity, even though on average the beam loses 26% of its energy

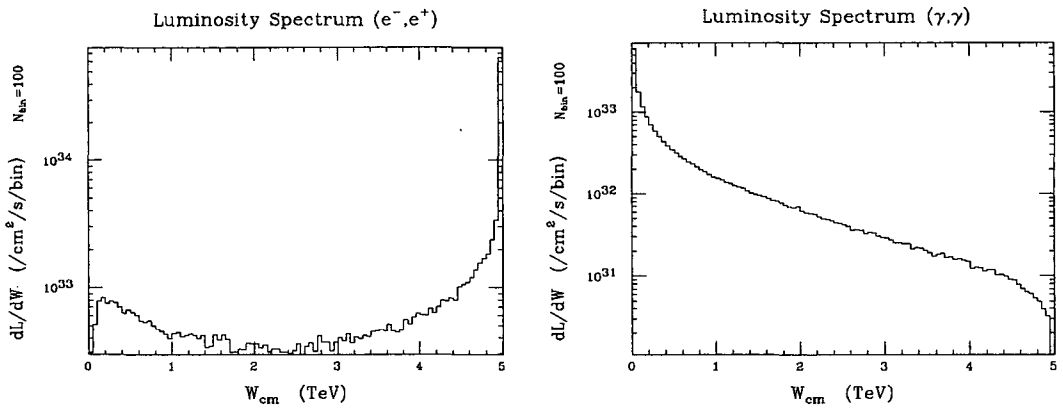

FIGURE 1. Luminosity spectrum for e^+e^- (left) and $\gamma\gamma$ (right) with 100 bins.

and has a rms energy spread of 36%. The sharpness and high peak value of the core is surprisingly encouraging. Upon careful examination, it is found that nearly half of the primary particles went through beam crossing without having enough probability to suffer energy loss through any QED process, even though their trajectories are bent significantly by the beam field. Because of quantum suppression, number of beamstrahlung photons defined in terms of n_γ is even lower than most of the designs at 0.5 TeV [9]. Although cross sections for background events are generally higher at lower energy, this effect is significantly suppressed. The products from most collisions in the low energy region are highly boosted due to the asymmetry in energy of the collision partners, thus are confined mostly within small angular cones along the beam pipe.

Angle spectrum and angle-energy distribution of the photons are given in Figure 2. In the right plot we see features of two distinct distributions. The

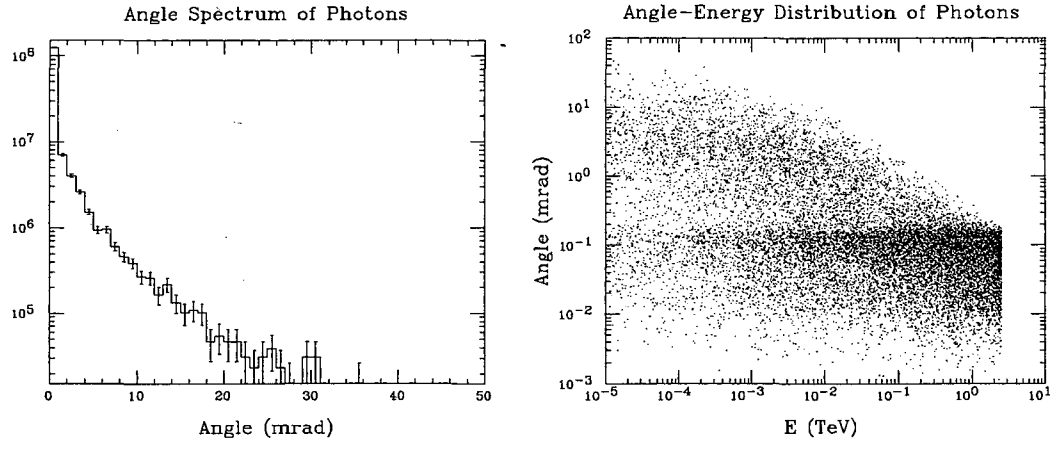

FIGURE 2. Angle spectrum of photons with bin size of 1 mrad (left). Scatter plot of photons in angle-energy space (right).

photons generated by primary particles at full energy occupy the band below 0.2 mrad, roughly. This number corresponds to the characteristic disruption angle of primary particles given by $\theta_d = D_y\sigma_y/\sigma_z$. The photons with angle larger than 0.2 mrad are generated either through secondary beamstrahlung or by pair particles to be discussed later. The angle-energy correlation, shown more remarkably above the lower band, is due to the fact that the lower the energy of the radiating particle, the larger the angle it is deflected by the beam field, and the larger the angle of the radiated photon.

Table 1. Beam Parameters Used for Simulation.

P_b(MW)	$N(10^8)$	f_c(kHz)	ε_y(nm)	$\beta_y(\mu$m)	σ_y(nm)	$\sigma_z(\mu$m)
20	1.6	156	25	62	0.56	1

Table 2. Results Given By the Formulas.

Υ	D_y	n_γ	δ_E	n_b	n_v	$\mathcal{L}_g(10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1})$
631	0.29	0.72	0.2	0.094	0.026	1

Table 3. Results Given By CAIN Simulations.

n_γ	δ_E	σ_e/E_b	n_b	$\mathcal{L}/\mathcal{L}_g(\mathrm{W_{cm}} \in 1\%)$	$\mathcal{L}/\mathcal{L}_g(\mathrm{W_{cm}} \in 10\%)$
0.97	0.26	0.36	0.12	0.65	0.80

Another major source of backgrounds at high Υ is the copious coherent e^+e^- pairs created by beamstrahlung photons traveling in the strong field of the opposing beam [1,21]. In high Υ regime, coherent pair partners are more likely to share the photon energy asymmetrically, giving rise to particles with significantly lower energy. These low energy pair particles, if deflected to large enough angle, may enter the detector and cause background or even damage problems. The pair partner with the same sign as the co-moving beam sees a focusing field, while the opposite sign pair partner sees a defocusing field of the opposing beam. As a result, the angle characteristics can be quite different for different pair partners. Angle-energy distributions of coherent pairs together with beam particles are shown in Figure 3 (left). The beam particles are concentrated mostly in the area near full energy. Notice the split of two bands in the lower energy region. The band with larger angle corresponds to the opposite sign pair partners. The band with smaller angle corresponds to the same sign pair partners and beam particles. Deflection angle for opposite sign pair particle is up to 100 mrad for energy as low as several hundred MeV.

Because of the angle-energy correlation, the number of detector hits by the charged particles may be further reduced with a solenoid magnetic field along the beam pass. In this situation, rather than particle energy, a more relevant variable is transverse momentum, P_t, which determines radius of the helical orbit in given solenoid field. Angle-P_t distributions of coherent pairs and beam particles are shown in Figure 3 (right). Here again the band with larger angle corresponds to the opposite sign pair partners. On this plot, only those particles in the top right corner with large enough angle and P_t will fall outside of a given forward cone and have a chance of hitting the detector directly. The detector planned for NLC has a half angle of 100 mrad [22], seemingly large enough to swallow all coherent pairs and photons in our case. More definitive assessment on these backgrounds requires enhancement in simulation statistics especially for the particles distributed in the low energy, large angle tails. It is also necessary to know more details about masking scheme and design of the Interaction Region (IR).

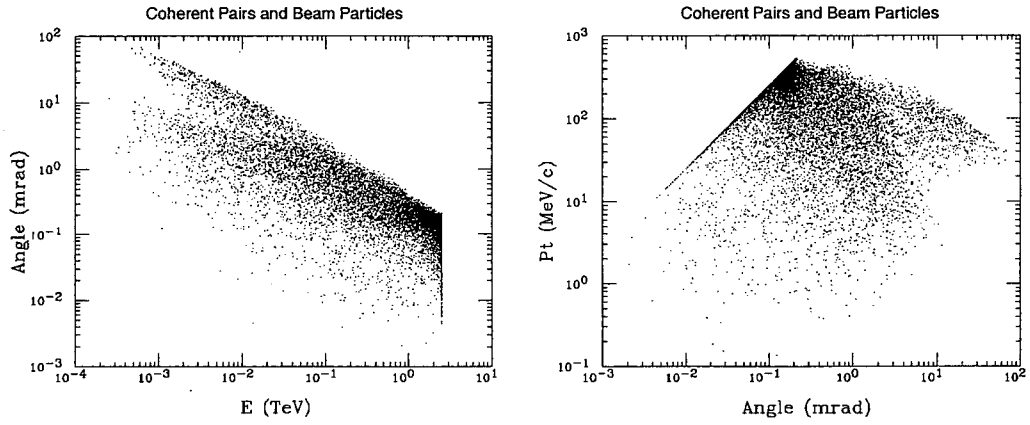

FIGURE 3. Coherent pairs and beam particles in angle-E (left) and angle-P_t space (right).

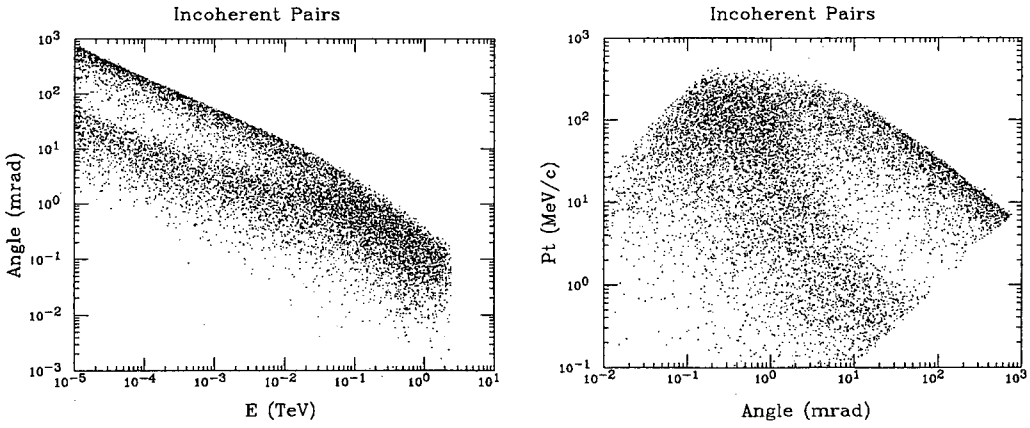

FIGURE 4. Incoherent pairs in angle-E (left) and angle-P_t space (right).

Coherent pairs can also be produced from virtual photons (as opposed to real photons from beamstrahlung) through a process known as trident cascade. Current version of CAIN does not include this process, but its production rate can be estimated with a simple formula [1,21]. Seen from Table 2 and Table 3 for our case the number of pairs per primary particle due to virtual photon process, n_v, is somewhat lower than the real photon pair production, n_b. Recently Thompson and Chen [23] have checked this process in more detail for our parameter set and found it does not seem to cause extra problem.

In addition to coherent pairs produced in collective beam field, incoherent pairs can also be created through individual particle-particle scattering processes. The following processes are included in the simulation: Breit-Wheeler: $(\gamma + \gamma \longrightarrow e^+ + e^-)$; Bethe-Heitler: $(\gamma + e^\pm \longrightarrow e^\pm + e^+ + e^-)$; and Landau-Lifshitz: $(e^+ + e^- \longrightarrow e^+ + e^- + e^+ + e^-)$. Figure 4 shows the scatter plot of incoherent pairs (without beam particles) in angle-energy space (left) and in angle-P_t space (right). The simulation used a 10 MeV cut on pair member energy. The two bands seen in the left plot corresponds to the opposite sign partners in the larger angle region and the same sign partners in the smaller angle region. Similarly, in the right plot the band with larger angle on the right corresponds to opposite sign partners. Comparing with the coherent pair distribution, incoherent pairs spread much more to the lower energy region and thus are deflected to larger angles. However the total number of incoherent pairs, about 5 thousands for our case, is more than 3 orders of magnitude below that of the coherent pairs. In fact each macro-particle in this Figure corresponds to a real pair particle. With angle and P_t cuts similar to NLC case [22] the situation here does not seem to be much worse than the 0.5 TeV machine.

IV MAJOR ISSUE AND UNCERTAINTY

A major issue involved in establishing QSB as a feasible IP approach is the assessment of various sources of backgrounds. We have shown in the preceding section that it seems collision products from QED processes could all be confined within a cone of reasonable opening angle along the beam path. However, the detector may still be affected by secondary particles generated by the spent beam hitting other components such as quadrupole magnets within the forward cone. In addition, the spent beam may induce damage or even radioactivation on these components. A detailed analysis of these issues requires more specific detector design and realistic detector environment simulation, which is beyond the scope of this paper. It is hoped the situation could somehow be managed with appropriate masking scheme and IR design.

Collisions of beamstrahlung photons can also produce hadrons through QCD processes, giving rise to yet another source of backgrounds. Conceptually, the hadronic interaction between two colliding photons can be sepa-

rated into two parts: the soft and hard scattering depending on the energy and transverse momentum involved. Cross section for the hard scattering can be calculated in part with perturbative QCD as in the minijet model [24], while the soft part is nonperturbative in nature and has to be treated with different model. For detector background consideration, the hard part is more serious as it could generate hadronic jets with higher transverse momentum. However, current theory on γ-γ minijet is subject to significant uncertainty.

Generally speaking, the uncertainty is due to inherent difficulty in nonperturbative QCD calculations. In particular, it comes from two major sources. First of all, as the hard scattering between two photons occurs among their respective partonic constituents, the knowledge of parton distribution of a photon or photon structure function is required. The photon structure function is available only in the form of parametrizations that are empirical and model dependent. Secondly, the minijet cross section is infrared divergent, thus a cutoff at low transverse momentum is necessary. As the transition between the hard and soft scattering is not well defined, this cutoff has to be determined also empirically for each parametrization used. So far experimental data on process $\gamma\gamma \rightarrow$ *hadrons* is available only up to 100 GeV. As a result, when extrapolating to multi-TeV, predictions for minijet cross section based on different parametrization are in nowhere near converging.

Nevertheless, the situation can still be improved with plausible arguments, phenomenological considerations and empirical scaling laws. Taking such an approach, recently Ohgaki et al. [19] have made an attempt to reach a more realistic, upper bound estimation of minijet cross section at higher energy. With such a recipes for the cross sections, a complete case study was conducted to evaluate hadronic backgrounds for our parameter set. Monte-Carlo simulations were carried out in steps from beam-beam interaction to hadronic event generation, from minijets fragmentation to detector selection performance. It was shown that both background event rate and energy deposits on detector per bunch crossing are quite small.

Last but not least, backgrounds due to standard model processes, such as W pair production in two-photon collisions, may also have to be dealt with for exploration of physics beyond the standard model.

Constrained by the sheer size and cost of a modern collider, scaling of current technology and approach to higher energy is becoming prohibitive. Thus more than ever before, the future of high energy colliders will depend critically on innovative concepts and techniques, and more important on the successful integration of these concepts and techniques into a collider system, from acceleration to collision, to detection, and all the way to the origination of a discovery experiment. Should the approach of quantum suppression of beamstrahlung be proven acceptable for high energy physics community and viable technically, it will make a strong scientific case with potentially significant strategic value for the future developments of high energy physics and accelerator technology.

ACKNOWLEDGMENTS

I wish to extend many thanks to K. Yokoya for help on understanding and using the simulation code CAIN; to J. Siegrist for making available the computer facility with which the simulations for this paper were performed; to S. Chattopadhyay, J. Siegrist and B. Barletta for program support; and to K. Yokoya, T. Tajima, S. Chattopadhyay, T. Ohgaki, H. Murayama, K.-J. Kim, J. Siegrist and P. Chen for helpful comments and discussions. This work was supported by the U.S. Department of Energy under contract No.DE-AC03-76SF00098.

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Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098