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Simulations on Pair Creation from Beam-Beam Interaction in Linear Colliders*

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Abstract

It has been recognized that e^+e^- pair creation during the collision of intense beams in linear colliders will cause potential background problems for high energy experiments. Detailed knowledge of the angular-momentum spectrum of these low energy pairs is essential to the design of the interaction region. In this paper, we modify the computer code ABEL(Analysis of Beam-beam Effects in Linear colliders) to include the pair creation processes, using the equivalent photon approximation. Special care has been taken on the non-local nature of the virtual photon exchanges. The simulation results are then compared with known analytic formulas, and applied to the next generation colliders such as JLC.

I. INTRODUCTION

In future linear colliders, low energy e^+e^- pairs created during the beam crossing would cause background problems for the detectors. At the next generation of colliders, most such pairs will be made by *incoherent* processes, from the interactrion of individual particles (e^+, e^- or beamstrahlung γ) in the two beams. This problem was first identified by Zolotarev *et al.*[1]. At energies where the beamstrahlung parameter Υ is ≥ 1, the *coherent* production of a pair from a beamstrahlung photon interacting with the field of the oncoming beam becomes dominant, as first noted by Chen[2]. The seriousness of this problem lies in the transverse momenta that the pair particles carry when leaving the interaction point(IP) with large angles. One source of transverse momentum is from the kick by the field of the oncoming beam, which results in an outgoing angle $\theta \propto 1/\sqrt{x}$, where x is the fractional energy of the particle relative to the initial beam particle energy[3]. The second source comes from the inherent scattering angles of these pairs, which may already be large when they are created. This issue was first studied in Ref.1.

In this paper we modify the ABEL[4] to include the incoherent pair creation processes using the equivalent photon approximation in the same way as Ref.1. By this simulation we can correctly take account of both the kicks and the inherent angles of the pairs. The geometric reduction is also implemented in the ABEL. The simulation results are compared with the analytic calculations with the parameters of JLC as an example of the next generation linear colliders.

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II. THE ANALYTIC FORMULAS

We consider three incoherent pair creation processes, which are so-called Breit-Wheeler (BW: $\gamma\gamma \rightarrow e^+e^-$), Bethe-Heitler (BH: $e^\pm\gamma \rightarrow e^\pm e^+e^-$) and Landau-Lifshits (LL: $e^+e^- \rightarrow e^+e^-e^+e^-$) processes. In the calculations of these cross sections the basic kernal is the same using the equivalent photon approximation. For the BW process both photons are real beamstrahlung photons; for the BH process one is real and the other one is virtual; for the LL process both photons are virtual. The partial cross sections with transverse momentum (devided by γm) and outcoming angle $\theta_o \leq \theta \leq \pi-\theta_o$ are calculated by the convolution of two photon energy spectra, $n_a(y_1), n_b(y_2)$, and the differential cross section for $\gamma\gamma \rightarrow e^+e^-$, $\sigma_{\gamma\gamma}(y_1, y_2, c)$, as below.

$$\sigma(x_{\perp o}, c_o) = g \int_{-c_o}^{c_o}\int_{y_-}^{1}\int_{y_b}^{1} dc dy_2 dy_1 n_a(y_1) n_b(y_2) \sigma_{\gamma\gamma}(y_1, y_2, c), \tag{1}$$

where y_i and c are fractional photon energy and $c = \cos\theta$, respectively and g=1/4 for the BW process and 1 for both BH and LL processes. The fractional energy x of the outcoming positron(or electron) to its angle θ is expressed by

$$x = \frac{2y_1y_2}{y_1(1-c)+y_2(1+c)} \tag{2}$$

As denoted in Eq.(1), the integration regions of two photon energies are

$$1 \geq y_1 \geq y_b = \frac{y_2y_+}{y_2-y_-}, \quad 1 \geq y_2 \geq y_-, \tag{3}$$

$$y_\pm = \frac{x_o}{2}(1 \pm c) = \frac{x_{\perp o}}{2}\sqrt{\frac{1\pm c}{1\mp c}}, \tag{4}$$

where x_o and $x_{\perp o}$ are the minimum energy and the minimum transeverse energy. These lower bounds are very important for the calculations because the dominant contribution comes from them. The virtual and the beamstrahlung photon spectra are given by

$$n_v(y) = \frac{2\alpha}{\pi}\frac{1}{y}\ln(\frac{1}{y}) \quad \text{and} \tag{5}$$

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$$n_b(y) = \frac{1}{\pi}\Gamma(\frac{2}{3})(\frac{\alpha\sigma_z}{\gamma\lambda_e})(3\Upsilon)^{2/3}y^{-2/3} \equiv Ay^{-2/3}, \quad (6)$$

respectively, where σ_z is the beam bunch length and λ_e is the electron Compton wavelength. Finally $\sigma_{\gamma\gamma}(y_1, y_2, c)$ is calculated by neglecting the obviously small terms $<O(\gamma^{-2})$.

$$\sigma_{\gamma\gamma}(y_1, y_2, c) = \frac{\pi r_e^2}{\gamma^2 y_1 y_2}\frac{1}{1-c^2}\left\{\frac{y_1^2(1-c)^2 + y_2^2(1+c)^2}{[y_1(1-c) + y_2(1+c)]^2}\right\} \quad (7)$$

$$\simeq \frac{\pi r_e^2}{\gamma^2 y_1 y_2}\frac{1}{1-c^2}, \quad (8)$$

where r_e is the classical electron radius. The last approximation of Eq.(8) is made due to the fact that the factor in the parenthesis (Eq.(7)) is a slowly varying function ranging from 1/2 to 1. Our estimates are therefore upper bounds, which are too big by less than a factor of 2. As we do not use this last approximation in the ABEL, this effect wil be discussed in the subsequent section. The resultant partial cross sections are[5]

$$\sigma_{BW} = 2.42\frac{r_e^2}{\gamma^2}A^2(\frac{2}{x_{\perp o}})^{\frac{4}{3}}\ln\frac{1}{\tau_o} \quad (9)$$

$$\sigma_{BH} = 5.40\frac{\alpha r_e^2}{\gamma^2}A(\frac{2}{x_{\perp o}})^{\frac{5}{3}}(\tau_o^{-\frac{1}{3}} - \tau_o^{\frac{1}{3}})(-\ln\frac{x_{\perp o}\tau_o}{2} - 0.20) \quad (10)$$

$$\sigma_{LL} = 1.27\frac{\alpha^2 r_e^2}{\gamma^2}(\frac{2}{x_{\perp o}})^2\ln\frac{1}{\tau_o}(\ln\frac{x_{\perp o}}{2\tau_o}\ln\frac{x_{\perp o}\tau_o}{2} + 3\ln\frac{x_{\perp o}}{2} + 4.44) \quad (11)$$

where $\tau_o = \tan(\theta_o/2)$. The above expressions account for only one of the two particles(say positron) in the pair. To count electron as well, we must multiply each one by 2.

III. THE ABEL SIMULATION

In the ABEL the beam bunches are described by ensembles of macro-particles. The number of macro-particles is typically 10^3 to 10^5. The whole process is divided into time slices. At each time step the bunches are further divided into longitudinal slices. For the modification of the ABEL the pairs are created in the collision between the macro-particles and the beamstrahlung photons in each logitudinal slice. There is no pair creation between the different slices, that is the incoherent pair creation processes are "local" in longitudinal direction. Then the created particles(e^+ or e^-) are tracked in the Coulomb potential which is produced by the oncoming beam. As the transverse momenta of these particles are affected by the kicks in the tracking, the partial cross sections for the processes in the ABEL are given with (x_o, θ_o) instead of $(x_{\perp o}, \theta_o)$, and there are no integrations over the beamstrahlung photon energy spectra for the BW and BH processes. Here we set θ_o=0.1 and $x_o = 10^{-5}$(5 MeV at E_{beam}=500 GeV).

$$\sigma_{BW}(y_1, y_2) = 6.28\frac{r_e^2}{\gamma^2}\frac{1}{y_1 y_2}ln\frac{1}{\tau_o} \quad (12)$$

$$\sigma_{BH}(y_1) = 4\frac{\alpha r_e^2}{\gamma^2}\frac{1}{y_1}\left\{2\ln\frac{1}{\tau_o}\{1 - \frac{1}{x_o}(\ln\frac{x_o}{2} + 1)\} + (\frac{1}{y_1} - \frac{1}{x_o})\{\frac{\ln(1-c_o)}{1-c_o} + \frac{2c_o}{1-c_o^2}(\ln\frac{x_o}{2} + 2)\}\right\} \quad (13)$$

$$\sigma_{LL} = 1.27\frac{\alpha^2 r_e^2}{\gamma^2}(\frac{2}{x_o})^2\left\{(\ln\frac{x_o}{2}+1)\{(\ln\frac{x_o}{2}+\frac{2}{3})(\frac{c_o}{1-c_o^2}+\ln\tau_o) + \frac{c_o\{1+\ln(1-c_o^2)\}}{1-c_o^2}\}\right\}, \quad (14)$$

where y_1, y_2 are the beamstrahlung photon energies. The energy and inherent angle of the outgoing particle are calculated by Eq.(2) and (7), respectively, with y_1, y_2 satisfying the boundary conditions of Eq.(3). For the virtual photon energy, we use the distribution of Eq.(5). The transverse momentum is calculated by the energy and the final scattering angle after the kicks.

Geometric Reduction

The finite impact parameter of the interactions in these processes comes from the transverse energy($q_\perp$) of the virtual photon. The distribution of $y_\perp(\equiv q_\perp/\gamma m)$ is[6]

$$n_v(y_\perp) = \frac{y_\perp^2\, dy_\perp^2}{(y_\perp^2 + y^2/\gamma^2)^2}. \quad (15)$$

As clearly seen in the above equation, for a given equivalent photon energy y, the dominant contribution to the cross section comes from the region of small transverse momentum $y_\perp \sim y/\gamma$. In the ABEL every virtual photon has finite transverse energy($y_\perp$) according to Eq.(15). To take account of this non-local nature of virtual photon interaction, we first calculate the probability of the pair creation which is proportional to the local intensities of two beams (macro-particles or beamstrahlung photons) at a point. Defining the impact parameter(ρ) as $1/y_\perp\gamma$m,we get the non-local intensities of two beams separating by ρ in each other. Then the reduction factor can be obtained by the ratio of "non-local" intensities/ "local" ones. If the separation is far beyond the beam (transverse) size, the pair creations will be suppressed largely‡. The ABEL creates the pairs at the position separated by ρ from the beam position and even outside the beam size.

IV. NUMERICAL COMPARISON

For the numerical comparison between the analytic calculation and the ABEL, we estimate the yields from a 1 TeV linear collider, JLC[7], where $\gamma = 10^6, \sigma_x/\sigma_y = 230/1.4$nm, $\sigma_z = 76\mu$m, $\Upsilon_{max} = 1.12$ (we use Υ=0.39 in the analytic calculation), luminosity $L = 3.6 \times 10^{31}$/cm^2/ bunch train (10 bunches per train) and 200Hz rf pulse rate. Figure 1 shows the yields per bunch crossing calculated

‡This *geometric reduction* effect was first observed at Novosibirsk[9], and subsequently developed theoretically by several authors[8,10].

by the partial cross sections of Eq.(9),(10),(11) and their sum as a function of $p_{\perp o} = \gamma m x_{\perp o}$ at $\theta_o = 0.1$ together with the results of the ABEL which are plotted with error bars. The yields of the analytic calculations are already multiplied by 2 for e^+ and e^-. In this figure the effect of the kicks, "correct" angular distribution (Eq.(7)) and non-local interaction in the ABEL are switched off just for the comparison. The agreement for the LL and BW processes is excellent. For the BH process the analytic calculation predicts 30% more yields than that of the ABEL, however its agreement is still good because the beamstrahlung spectrum in the analytic formulas is only approximation.

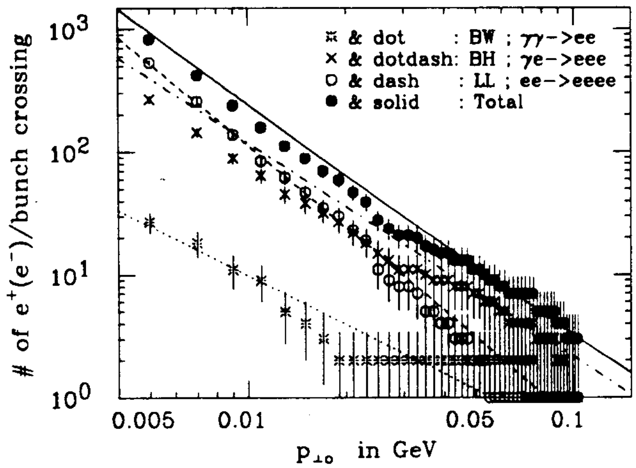

Fig. 1 Comparison between the analytic calculation and the ABEL.

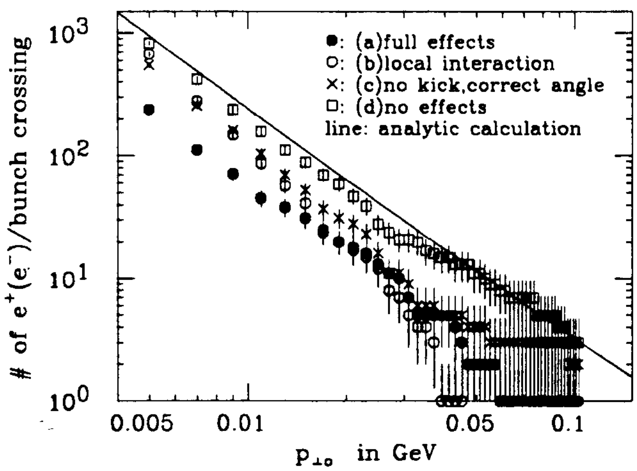

Fig. 2 The ABEL simulation results with the various effects of (a)-(d) which are explained in the text.

In addition to the large inherent angles of the pair creations, the ABEL implements the kicks, "correct" angular distribution (Eq.(7)) and the geometric reduction as described in the previous section. To see these individual effects in detail, we simulated the pairs under the four kinds of conditions, that is (a) all effects are included, (b) no geometric reduction whereas the other effects are considered, (c) only "correct" angular distribution is taken account into and (d) with no effects as described in the above comparison with the analytic calculations. The results are shown in Fig.2, where the total yields summed over the three processes are plotted in the same way as Fig.1. As clearly seen in this figure, two effects are apparent. First one is "correct" angular distribution, which reduce the yields by 35%. This effects are expected because the angular distribution of Eq.(7) has more forward-backward peaking than that of Eq.(8) which has been used in the analytic calculations. The second one is the geometric reduction. The reduction ranges from 60 to 50% for the minimum transverse momentum from 5 to 10 MeV, respectively. These values are consistent with the analytic calculation by G. L. Kotkin *et al.*[8].

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