Comparison of Photon Colliders Based on e^-e^- and e^+e^- Beams

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At photon colliders ($\gamma\gamma$,γe) high energy photons are produced by Compton scattering of laser light off the high energy electrons (or positrons) at a linear collider. At first sight, photon colliders based on e^+e^- or e^-e^- primary beams have similar properties and therefore for convenience one can use e^+e^- beams both for e^+e^- and $\gamma\gamma$, γe modes of operation. Below we compare these options and show that e^-e^- beams are much better (mandatory) because in the e^+e^- case low energy background $\gamma\gamma \to$ hadrons is much higher and e^+e^- annihilation reactions present a very serious background for $\gamma\gamma$ processes.

1. INTRODUCTION

A photon collider is a very natural supplement to e^+e^- linear colliders. Using Compton scattering of laser photons off high energy electron (positron) beams one can obtain colliding $\gamma\gamma$, γe beams with the energy and luminosity close to those in e^+e^- collisions [1–4]. It is usually assumed that photon colliders are based on e^-e^- beams because production of electrons with a high degree of polarization is much easier. There are several other arguments in favor of e^-e^- beams that were known to photon collider experts but not emphasized because there was no such need.

Recently, designers of the interaction region raised the question about using e^+e^- beams for the photon collider at the ILC because some schemes of the final focus do not allow easy switching between e^+e^- and e^-e^- modes and the disruption angles with e^+e^- beams should be smaller, which would make beam removal somewhat easier.

Below I present strong arguments in favor of using e^-e^- beams. In summary,

- the study of e^-e^- interactions is a part of the ILC physics program, and so e^-e^- beams are necessary in any case;
- a photon collider based on e^-e^- beams is much better due to larger luminosity and much lower backgrounds from e^+e^- annihilation and low energy $\gamma\gamma \to$ hadrons reactions.

2. LUMINOSITY

If both e^+ and e^- beams are prepared in the same damping rings, then their emittances and the geometric (without beam collision effects) e^+e^- and e^-e^- luminosities are equal. The $\gamma\gamma$ luminosity in the high energy part of the luminosity spectrum, which presents the main interest for physics, is simply proportional to the geometric luminosity. However, there is some difference in the degree of the polarization: for electrons $2\lambda_{e^-} = 85$ % [5] (determined by photo-guns), for positrons $2\lambda_{e^+} \sim 50\%$ [6] (determined by the positron production scheme based on the process of e^+e^- pair production by polarized photons), where λ_e is the helicity ($|\lambda_e < 1/2|$). The $\gamma\gamma$ luminosity at the high energy peak of the luminosity spectrum is just proportional to the product of photon spectra [3]

$$\left(\frac{dL}{dW_{\gamma\gamma}}\right)_{peak} \propto \left[x+1+\frac{1}{x+1} - 2P_c\lambda_i\frac{x(x+2)}{(x+1}\right]\left[x+1+\frac{1}{x+1} - 2P_c\lambda_j\frac{x(x+2)}{(x+1}\right], \qquad (1)$$

where $x = 4E_0\omega_0/m_e^2c^4$, E_0 is the electron beam energy, ω_0 the laser photon energy and P_c is the helicity of laser photons.

For the optimum of $x = 4.8$ (the threshold for e^+e^- pair production at the conversion region) and $P_c = -1$ (gives maximum luminosity in the high energy peak), we get

$$\left(\frac{dL}{dW_{\gamma\gamma}}\right)_{e^+e^-} \Big/ \left(\frac{dL}{dW_{\gamma\gamma}}\right)_{e^-e^-} \sim 0.82 \quad \text{for} \quad 2\lambda_{e^+} = 0.5$$

$$0.58 \quad \text{for unpolarized } e^+. \qquad (2)$$

The reduction of the high energy $\gamma\gamma$ luminosity for the e^+e^- case is quite noticeable. However, more informative is the comparison of $\gamma\gamma$ luminosity spectra. The $\gamma\gamma$ luminosity spectra for the TESLA TDR beams parameters at $2E_0 = 500$ GeV in the e^+e^- and e^-e^- cases obtained by the simulation code [4, 7] are presented in Fig. 1. The main results are summarized in Table I.

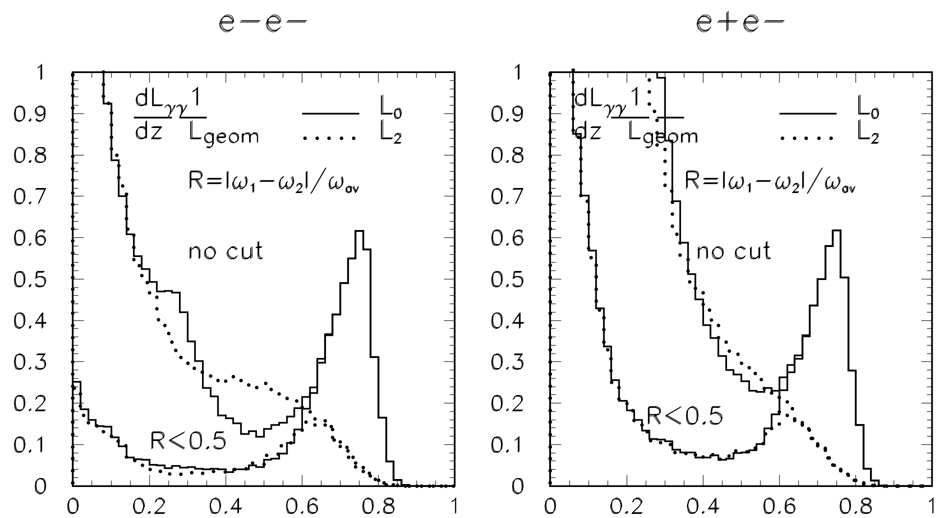

Figure 1: $\gamma\gamma$ luminosity spectra for e^+e^- and e^-e^- initial colliding beams with and without a cut on the longitudinal momentum; $2\lambda P_c = -0.85$ for both beams; indices 0, 2 are total helicities of colliding photons.

Table I: Beam parameters and luminosities at the photon collider based on e^+e^- and e^-e^- beams, $2E_0 = 500$ GeV, the transverse beam emittances are the same as in the TESLA TDR [4]

	e^-e^-	e^+e^-
$N/10^{10}$	2	2
σ_z, mm	0.3	0.3
σ_x, nm	88	88
σ_y, nm	4.3	4.3
$L_{\rm geom}, 10^{35}$	1.2	1.2
$L_{\gamma\gamma}(z > 0.65)/L_{\rm geom}$	0.1	0.1
$L_{\gamma\gamma}(tot)/L_{\rm geom}$	0.92	5.6
$L_{e^-e^-}/L_{\rm geom}$	0.006	—
$L_{e^+e^-}(z > 0.65)/L_{\rm geom}$	—	0.062
$L_{e^+e^-}(tot)/L_{\rm geom}$	—	0.24

We see that the $\gamma\gamma$ luminosities in the high energy peak are equal for e^-e^- and e^+e^- because we assumed similar e^+ and e^- properties, including polarizations. It is about 10% of the geometric luminosity. However, there are two serious disadvantages of e^+e^- beams:

- The total (mainly low energy) $\gamma\gamma$ luminosity with e^+e^- beams is larger than with e^-e^- beam by a factor of 6. The corresponding number of $\gamma\gamma \to$ hadron reactions per one beam collision with e^+e^- beams will be about ten per bunch crossing!
- In the case of e^+e^- beams, $L(e^+e^-))$ and $L(\gamma\gamma)$ in the high energy region are comparable, and so it will be difficult to separate e^+e^- and $\gamma\gamma$ reactions due to similar final states.

3. LUMINOSITY MEASUREMENT

The primary calibration processes for $\gamma\gamma$ collisions are $\gamma\gamma \to e^+e^-$ or $\mu^+\mu^-$. At the photon collider with e^+e^- beams similar final states will be produced in e^+e^- annihilation. The residual e^+e^- luminosity is comparable to the high energy $\gamma\gamma$ luminosity, so the number of pairs produced in e^+e^- and $\gamma\gamma$ reactions will also be similar. It is possible, but very difficult, to extract the $\gamma\gamma$ luminosity using differences in the angular distributions of pairs in e^-e^- and $\gamma\gamma$ processes.

Note that at the photon collider with e^-e^- beams the e^+e^- luminosity is also non-zero due to positron production at the conversion region (Sect. 5) and at the interaction region (coherent pair creation [4]), but it will be much smaller than in the case of e^+e^- beams.

4. PHYSICS BACKGROUNDS

At a photon collider based on e^+e^- beams, the residual e^+e^- luminosity leads to a high rate of annihilation reactions $e^+e^- \to X$, which look very similar to $\gamma\gamma \to X$ and present a serious problem for analysis of two-photon processes.

Such a problem exists for study of charged pair production in $\gamma\gamma$ collisions. Only a combined analysis of e^+e^- and $\gamma\gamma$ reactions by fitting their angular distributions allows to separate these processes at the price of a significant loss of the statistical accuracy.

For $\gamma\gamma \to H \to b\bar{b}$ (the main decay mode for the light Higgs boson), the most serious background at a e^-e^- photon collider is the QED process $\gamma\gamma \to b\bar{b}$, which can be suppressed by a proper choice of photon polarizations. Indeed, $\sigma(\gamma\gamma \to H) \propto 1 + \lambda_{\gamma,1}\lambda_{\gamma,2}$, while $\sigma(\gamma\gamma \to b\bar{b}) \propto 1 - \lambda_1\lambda_2$, where photon helicities λ_i are close to 100% in the high energy part of the luminosity spectrum.

At a e^+e^- based photon collider, additional background for the Higgs arises from the reaction $e^+e^- \to b\bar{b}$. It is not suppressed by the beam polarizations because $\sigma_{e^+e^-} \propto (1 - \lambda_e\lambda_{e^+}) \sim (1 - 0.8 \cdot 0.6) \sim 0.5$ and $\sigma(e^+e^- \to b\bar{b}) \sim \sigma(\gamma\gamma \to b\bar{b})$.

Note that at the photon collider the horizontal beam size should be as small as possible, which causes large beamstrahlung losses for initial charged particles during beam collisions. As a result, for the photon collider with e^+e^- beams the residual e^+e^- luminosity spectrum is very broad and overlaps with the $\gamma\gamma$ luminosity spectrum.

5. DISRUPTION ANGLES

At a photon collider with e^-e^- initial beams, the maximum disruption angle is about 10–12 mrad [4]. Large angles are caused by the repulsion of the low energy (after multiple Compton scattering) electrons off the opposing electron beam. One can expect that for e^+e^- initial beams, the disruption angles are much smaller because particles attract to the opposing beam. However, even here e^+e^- beams have no preferences due to the following reason.

In the $e \to \gamma$ conversion region, a high energy photon can produce a e^+e^- pair in collision with a laser photon. The threshold for this process is $x = 4.8$ [2, 4]. For $2E_0 = 500$ GeV and a laser wavelength of $\lambda = 1.06\ \mu$m, $x \approx 4.5$, just somewhat below the threshold. For higher energies (above the threshold), this process has a cross section comparable to the Compton one. As a result, after the conversion region the beam will contain particles of both signs. Moreover, even at the parameter x several times below the threshold value of $x = 4.8$, the high energy photon at the conversion region can with a rather high probability produce a e^+e^- pair in a collision with several laser photons. So, the disrupted beams contain particles of both signs, so the maximum disruption angles at e^+e^- and e^-e^-–based photon colliders are approximately equal.

6. CONCLUSION

Comparison of photon colliders based on e^+e^- and e^-e^- beams shows that

- the $\gamma\gamma$ luminosity (in the high energy region) in the case of e^+e^- beams will be smaller by a factor of 1.2–1.8 depending on the polarization degree of positrons;
- the low energy $\gamma\gamma$ luminosity with e^+e^- beams is greater by a factor of 6 for considered beam parameters. The corresponding hadronic background (about 10 events per bunch crossing) leads to degradation of the energy and mass resolutions for most physics processes;
- at a photon collider with e^+e^- beams, the residual e^+e^- luminosity is comparable to the $\gamma\gamma$ luminosity and reactions look very similar. This causes a very serious problem for distinguishing $\gamma\gamma$ reactions and worsens the statistical accuracy. Due to the same problem, it is difficult to measure the $\gamma\gamma$ luminosity spectrum using e^+e^- or $\mu^+\mu^-$ pairs.
- the maximum disruption angles at a photon collider with e^+e^- and e^-e^- beams are similar due to intensive e^+e^- pair production in the conversion region.

In summary, a photon collider with e^-e^- initial beams has many advantages compared to that based on e^+e^- beams. I would put it even stronger: e^+e^- beams are absolutely unsuitable for photon colliders due to very serious problems with identification of $\gamma\gamma$ and e^+e^- reactions.

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