Photon Colliders at Multi-TeV Energies

Valery Telnov*
Institute of Nuclear Physics, 630090 Novosibirsk, Russia†

High energy photon colliders ($\gamma\gamma$, γe) based on backward Compton scattering of laser light are very natural supplement to e^+e^- linear colliders and can significantly enrich the physics program. The region below about one TeV is very convenient from a technical point of view. In the multi-TeV energy region the situation is more complicated due laser problems and beam–beam collisions effects. These problems and possible solutions are discussed in this paper.

1. Introduction

In the energy region below one TeV e^+e^- linear colliders are the best machines for study of elementary particles; they can have a sufficient luminosity, good monochromaticity, and rather low backgrounds. At multi-TeV linear colliders, such as CLIC [1], all problems are much more severe due to collisions effects.

Photon colliders [2, 3, 4, 5, 6] are based on the Compton scattering of laser light on high energy electrons. The region below about one 0.5–1 TeV is very convenient from a technical point of view: wave length of the laser should be about 1 μm, i.e. in the region of most powerful solid state lasers, collision effects do not restrict the $\gamma\gamma$ luminosity. In the multi-TeV energy region the situation is more complicated: the collision effects (coherent pair e^+e^- pair creation in $\gamma\gamma$ collisions) restrict the luminosity. The optimum laser wavelength increases proportionally with the energy. In addition, due to nonlinear effects in the Compton scattering, the required laser flash energy increases. Problems of multi-TeV photon colliders and possible solutions has been analyzed in detail recently [7]. In this paper, previous results are discussed and possible parameters of the photon collider at CLIC are given.

2. Conversion of electrons to high energy photons

2.1. Laser wave length

The maximum energy of the Compton scattered photons is [3]

$$\omega_m = \frac{x}{x+1}E_0; \qquad x \approx \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3\left[\frac{E_0}{\text{TeV}}\right]\left[\frac{\omega_0}{eV}\right], \tag{1}$$

where E_0 is the electron energy, ω_0 the energy of the laser photon. The cross section depends on the longitudinal electron polarization λ_e ($|\lambda_e| \leq 1/2$) and the circular polarization of laser photons P_c. Cross sections, typical spectra and polarizations are shown in Figure 1 [5, 7].

With an increase in x the energy of the back-scattered photons grows and the energy spectrum becomes narrower, however, at $x > 4.8$ the high energy photons may be lost due to creation of e^+e^- pairs in the collisions with laser photons [3, 5]. Dependence of the maximum conversion coefficient on x is shown in Figure 1-right. For $x < 4.8$, $k_{max} = 1$ (in principle), though it would be more reasonable to assume the thickness of the laser target to be equal to one collision length, this gives $k_{\max} = 0.632$. For $x = 50$ ($E_0 = 2.5$ TeV, $\lambda = 1\mu$m) $k_{\max}$ is equal to 0.42 (0.19) for $2\lambda_e P_c = 1(-1)$, respectively. The $\gamma\gamma$ luminosity is proportional to k^2, therefore, at $x = 50$ it will be lower than at $x < 4.8$ by a factor of 2.2 (11.4), for the two cases, respectively.

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*e-mail:telnov@inp.nsk.su
†DESY, Notkestr. 85, D-22603 Hamburg, Germany

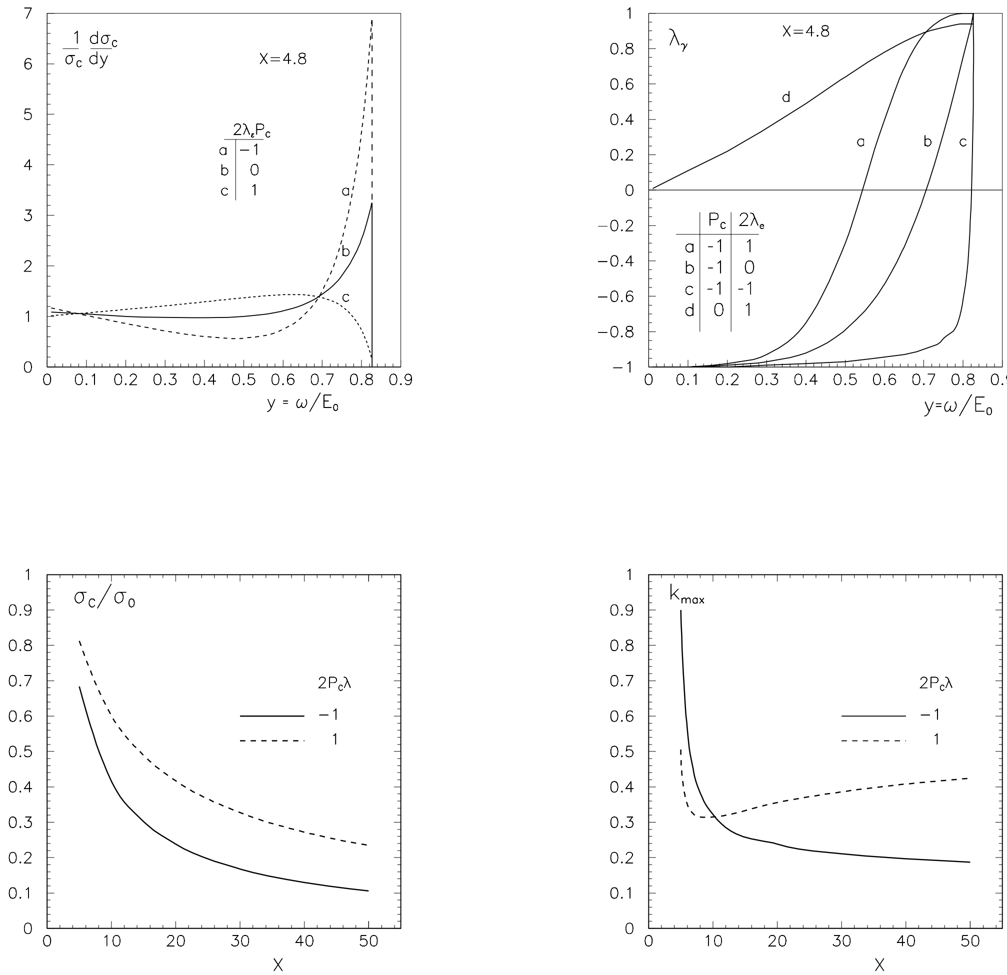

Figure 1: From left to right: 1) spectra of Compton scattered photons; 2) helicity of scattered photons; 3)Compton cross section vs x in the case of linear Compton scattering; 4) maximum conversion coefficient (due to e^+e^- pairs) versus x.

So, there are two possibilities for multi-TeV photon colliders:
1) $x \sim 4.8$ ($\lambda \sim 4E_0$[TeV]μm), $2\lambda_e P_c = -1$; 2) $\lambda \sim 1\mu$m, $2\lambda_e P_c = 1$, $L_{\gamma\gamma} \sim 0.4 L_{\gamma\gamma}(x = 4.8)$.

2.2. Nonlinear effects in Compton scattering

In strong field in the laser wave the electron (or high energy photon) can interact simultaneously with several laser photons. The characteristic parameter

$$\xi^2 = e^2\overline{B^2}\hbar^2/(m^2c^2\omega_0^2) = 2n_\gamma r_e^2 \lambda/\alpha, \qquad (2)$$

where n_γ is the density of laser photons. At $\xi^2 \ll 1$ the electron scatters on one laser photon. Nonlinear Compton scattering was considered in detail in [8]. With grows of ξ^2 the spectrum becomes wider and is shifted to lower energies. For $x = 4.8$ and $2\lambda_e P_c = -1$ the shape of the luminosity spectra are still acceptable up to $\xi^2 \sim 0.5$. For $x = 50$ and $2\lambda_e P_c = 1$ the spectrum does not change too much up to $\xi^2 < 3$. However, at large ξ^2 and large x the linear theory of e^+e^- production in collisions between laser and high energy photons used above may be not valid due to coherent effects [5, 9]. The parameter characterizing coherent pair creation $\Upsilon \sim 0.5x\xi$ is equal 75 for the last example, much above the threshold for this effects $\Upsilon \sim 1$. For $\xi < 1$ the formation length is shorter than the wave length therefore coherent pair creation is suppressed even for large Υ. From these we conclude that in all cases $\xi^2 < 0.3 - 0.5$ is needed.

2.3. Laser flash energy

The laser flash energy required for $e \to \gamma$ conversion is determined by diffraction properties of the laser beam and by the nonlinear effects (maximum density of photons). If laser optics is situated outside the laser beam then according to [7] it is equal to

$$A[J] \approx 20p\left(\frac{\sigma_0}{\sigma_c}\right) l_e \left[1 + p\frac{150\lambda\sigma_0}{\xi^2 l_e \sigma_c}\right], \tag{3}$$

where $p \approx 1$ is the number of collisions length, $l_e = 2\sigma_z$ is the length of the electron bunch, all length are expressed in cm. The first term is due to diffraction of a laser beam, the second term is due to the nonlinear effects. With the increase of the electron beam energy the second term becomes more important for two reasons: 1) if x = const, then $\lambda \propto E_0$; 2) if λ = const, then $x \propto E_0$ and the ratio σ_c/σ_0 decreases. The required flash energy and contribution of each term for three cases are given in Table I.

Table I Laser flash energies for three sets of parameters.

	a	b	c
$2E_0$, GeV	500	5000	5000
$2P_c\lambda_e$	-1	-1	1
λ, μm	1	10	1
ξ^2	0.3	0.3	0.5
σ_c/σ_0	0.66	0.66	0.21
l_e, μm	600	200	200
p	1	1	0.75 (close to opt.)
A, J	1.8(1+1.25)=4	0.6(1+37)=23	1.42(1+5.3)=9

Note that in the case c) the luminosity is lower by a factor of 2.3 than in the case b) due to e^+e^- production. So, in both cases b) and c), the flash energy is much larger than for sub-TeV photon collider.

2.4. Conversion region with a “traveling laser focus”

Above we considered the “usual” method of laser beam focusing. In order to get a high conversion probability at a fixed value of the parameter ξ^2, the length of the laser target and the diameter of the laser beam should be large enough, as result most of laser photons do not cross the electron beam. This is the reason why the required flash energy grows with the increase of the laser wave length.

Fortunately, there is a way to overcome this problem, that is *traveling laser focus* [7]. In this scheme, the laser focus follows the electron beam. Detail consideration of this approach is given in [7]. The required flash energy for the case b) from Table I $A \sim 0.8$ J that 30 times smaller than with conventional focusing and about 1.8 J for the case c). So, the traveling focus is a very attractive solution for multi-TeV photon colliders.

3. Collision effects

Though photons are neutral there is one collision effects restricting the $\gamma\gamma$ luminosity, that is coherent pair creation—conversion of high energy photons into e^+e^- pairs in the field of the

Table II Possible parameters of the photon collieder at CLIC. Parameters of electron beams are the same as for e^+e^- collisions

$2E_0$ GeV	3000
$\lambda_L[\mu m]/x$	4.4/6.5
$t_L[\lambda_{scat}]$	1.
$N/10^{10}$	0.4
σ_z [mm]	0.03
$f_{rep} \times n_b$ [kHz]	15.4
$\gamma\epsilon_{x/y}/10^{-6}$ [m·rad]	0.68/0.02
$\beta_{x/y}$ [mm] at IP	8/0.15
$\sigma_{x/y}$ [nm]	43/1
b [mm]	3
L_{ee}(geom) [10^{34}]	4.5
$L_{\gamma\gamma}(z > 0.8z_{m,\gamma\gamma})[10^{34}]$	0.45
$L_{\gamma e}(z > 0.8z_{m,\gamma e})[10^{34}]$	0.9
$L_{ee}(z > 0.65)[10^{34}]$	0.6

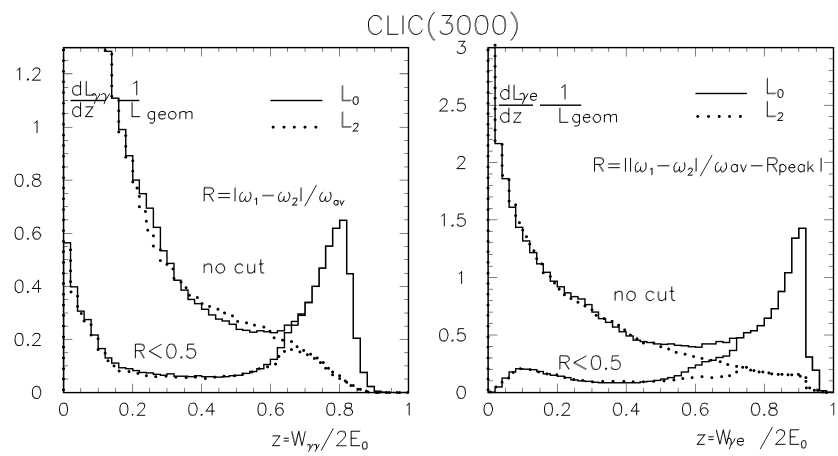

Figure 2: Left: possible parameters of the photon collider at CLIC(3000), right: $\gamma\gamma$ and γe luminosity spectra.

opposing electron beam [5, 9]. Detailed study of luminosity limitation at high energy photon colliders was given in [10]. Note that at $\Upsilon \gg 1$ (case of multi-TeV colliders) the ratio of beamstrahlung/pair creation is about 3.8 [7]. At e^+e^- colliders the average number of emitted photons is usually 1–3, so at multi-TeV photon colliders the horizontal beams size may be only somewhat (2–3 times) smaller than in e^+e^- collisions.

In Figure 3 parameters of the photon collider at CLIC with $2E_0 = 3000$ GeV are given together with corresponding luminosity spectra obtained by full simulation. Parameters of electron beams are taken the same as for e^+e^- collisions. It was checked by simulation that using electron beams with two times smaller transverse sizes the $\gamma\gamma$ luminosity can be increased by a factor of 3.3. However, it is not easy to achieve, because decreasing of beta-functions is problematic due to the Oide limit (radiation in quads), decreasing of emittances in damping rings is also big problem. More than two times decrease of the horizontal beam sizes leads only to small increase of the $\gamma\gamma$ luminosity due to coherent pair creation. Further decrease of the vertical beam size (below 0.5

nm) is also problematic due to minimum size caused by crab crossing and Compton scattering. For Compton scattering minimum vertical beam size is b/γ, the IP-CP distance b should be larger than the conversion length. From condition $n_\gamma \sigma_c b = 1$ and Eqs.1,2 we get the minimum vertical size of the photon beam

$$\sigma_{\gamma,\min} \sim \frac{b}{\gamma} \sim \frac{16 r_e}{\alpha^2 x \xi^2} \left(\frac{\sigma_0}{\sigma_c}\right). \tag{4}$$

For $x = 4.8$, $\sigma_c/\sigma_0 = 0.7$, $\xi^2 = 0.3$, $\alpha = 1/137$, we get $\sigma_{\gamma,\min} \sim 0.8\,\text{nm}$.

At last, there is one idea how one can suppress coherent pair creation in multi-TeV photon colliders (at least in principle) [7]. If electron beams are tilted around the collision axis by some relative angle $\phi \sim \mathcal{O}(0.1)\sigma_y/\sigma_x$, each of the electron beams will be split during the collision in two parts (may be impossible due to beam asymmetries). If the transverse deflection during the beam collision, $\Delta > \sigma_x$, then due to cancellation the maximum field in the region of high energy photons (at $x \sim \sigma_x$) is $B_r = B_b(\sigma_x/\Delta)^2 \propto \sigma_x$. So, with the decrease of σ_x, the $\gamma\gamma$ luminosity grows but the field at the interaction region decreases! To make this possible the horizontal beam size should be sufficiently small and the bunch length sufficiently long (detail study was not done yet). It may be very difficult technically, but "on paper" such possibility for photon colliders exists.

Acknowledgments

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