Problems of multi-TeV photon colliders

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Abstract

A high energy photon collider (γγ, γe) based on backward Compton scattering of laser light is a very natural supplement to e+e− a linear collider and can significantly enrich the physics program. 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 γγ luminosity. In the multi-TeV energy region the situation is more complicated: the optimum laser wave length increases in proportionally with the energy, the required flash energy also increases due to nonlinear effects in the Compton scattering; bunch trains are shorter (for warm high gradient linacs), this leads to higher backgrounds; the collision effects (coherent pair e+e− pair creation) restrict the luminosity. These problems and possible solutions are discussed in this paper. A method of laser focusing is considered which allows the decrease of the required laser flash energy and the practical elimination of the problem of nonlinear effects in Compton scattering; a way to reduce collision effects and obtain ultimate γγ luminosities at multi-TeV photon colliders is suggested.

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1 Introduction

The next generation of linear colliders JLC [2], NLC [1], TESLA [3] are being developed at the energies from 100 GeV to about 1 TeV. In this energy region, $e^+e^-$ linear colliders are the best machines for study of elementary particles; they can have a sufficient luminosity, good monochromaticity, and rather low backgrounds. Though already at these energies attainable $e^+e^-$ luminosity is determined by collision effects. In order to reduce beamstrahlung during the beam collisions very flat beams should be used with a vertical size of several nm. To obtain a sufficient luminosity one has to increase average beam current, as a result of which the total power consumption approaches 100 MW.

At multi-TeV linear colliders, such as CLIC [4,5], all problems are much more severe. The required luminosity should vary proportionally to $E_0^2$ (as soon as cross sections $\propto 1/E_0^2$). To get a sufficient luminosity at a reasonable beam power one has to further decrease beam sizes and admit larger energy spread due to beamstrahlung, and increase total power consumption. So, the problem of multi-TeV $e^+e^-$ colliders is not just the acceleration of beams up to a high energy, besides there are many other problems caused by collisions effects. As a result, the maximum energy of linear colliders (with a reasonable luminosity) is about $2E_0 \sim 5$ TeV, namely such as is considered in the CLIC project.

Photon colliders [6–8] are based on the Compton scattering of laser light on high energy electrons. This is only possible at linear colliders where the beams are used only once. Photons are neutral particles therefore there is no beamstrahlung nor beam instabilities. So, at first sight, it seems that in $\gamma\gamma$ colliders can be optimized completely differently and perhaps, in $\gamma\gamma$ mode of operation, linear colliders can reach higher energies.

In this paper I will try to give answers these questions and also consider the problem of lasers for multi-TeV photon colliders. Consideration of the general principles of photon colliders and the present status can be found elsewhere [7–12]. Though the present paper focuses on problems of multi-TeV colliders the results are valid and useful for all energies.

2 Conversion of electrons to high energy photons

At multi-TeV energies there are several complications connected with the conversion of electrons to high energy photons:

(1) the optimum laser wave length increases proportionally to the electron energy;
(2) nonlinear effects in the Compton scattering become more important;
(3) due to nonlinear effects the required flash energy is higher;
(4) it is not so clear as to what kind of laser can be used.
2.1 Laser wave length

The maximum energy of the scattered photons is [7]

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

where \( E_0 \) is the electron energy, \( \omega_0 \) the energy of the laser photon, see Fig.1a.

![Diagram of laser and electron interaction](image)

Fig. 1. Scheme of \( \gamma\gamma, \gamma e \) collider.

The Compton cross section depends on the longitudinal electron polarization \( \lambda_e \) (\( |\lambda_e| \leq 1/2 \)) and the circular polarization of laser photons \( P_c \)

\[ \sigma_c = \sigma_{c,np} + 2\lambda_e P_c \sigma_{c,1}. \tag{2} \]

Expressions for these cross sections can be found elsewhere [8,10,13]. The energy spectrum of the scattered photons also depends on the product \( 2\lambda_e P_c \). A typical spectrum of scattered photons for \( x = 4.8 \) is shown in Fig.2. One can see that in the case \( 2\lambda_e P_c = -1 \) (curve a) the energy spectrum has a high energy peak at the maximum energy, while in the case \( 2\lambda_e P_c = 1 \) (curve b) the distribution is flat and even approaches to zero at the maximum energies.

With increasing \( x \) the spectrum corresponding to \( 2\lambda_e P_c = -1 \) becomes narrower, while the spectrum for \( 2\lambda_e P_c = 1 \) remains quite wide, though the fraction of photons in the high energy part increases: at \( x = 4.8 \) about half of the photons have energy above \( 0.5\omega_m \).
while at $x = 50$ half of the photons have energy above $0.8\omega_m$. Corresponding graphs for large $x$ can be found in Ref. [14] in these proceedings.

Typical curves for polarization of the scattered photons for $x = 4.8$ are shown in Fig.3. For further discussion the following features are important: in both cases a) and c) (same as in the previous figure) the polarization of the highest energy photons ($\omega = \omega_m$) is 100% and opposite to the polarization of the laser photons. However, for the case a) ($2\lambda e P_c = -1$)

most of high energy photons (see Fig. 2) have the polarization $\lambda_\gamma \approx -P_c$, while for the
case c) \((2\lambda_c P_c = 1)\) only very small number of photons with \(\omega \approx \omega_m\) have \(\lambda_\gamma \approx -P_c\), while most of photons have the opposite polarization \(\lambda_\gamma \approx P_c\).

Dependence of the Compton cross section on \(x\) for two cases of polarization is shown in Fig. 4 in units of \(\sigma_0 = \pi r_e^2\), where \(r_e = e^2/mc^2 = 2.8 \times 10^{-13}\) cm is the classical radius of the electron. Note, in this section we only consider the case of the linear Compton effect, when only one laser photon is scattered from an electron. In the next section, we note that for multi-TeV photon colliders nonlinear effects (simultaneous interaction of the electron with several laser photons) are very important.

![Fig. 4. Compton cross section vs \(x\) for two combinations of laser and electron polarizations.](image)

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 [7,9,10].

The cross section for \(e^+e^-\) production in a two-photon collision is given by [16,17]

\[
\sigma_{\gamma\gamma \rightarrow e^+e^-} = \sigma_{np} + \lambda_1 \lambda_2 \sigma_1, \tag{3}
\]

\[
\sigma_{np} = \frac{4\sigma_0}{x_\gamma} \left[ 2 \left( 1 + \frac{4}{x_\gamma} - \frac{8}{x_\gamma^2} \right) \ln \frac{\sqrt{x_\gamma + \sqrt{x_\gamma}} - 4}{2} - \left( 1 + \frac{4}{x_\gamma} \right) \sqrt{1 - \frac{4}{x_\gamma}} \right],
\]

\[
\sigma_1 = \frac{4\sigma_0}{x_\gamma} \left[ 2 \ln \frac{\sqrt{x_\gamma + \sqrt{x_\gamma}} - 4}{2} - 3 \sqrt{1 - \frac{4}{x_\gamma}} \right], \tag{4}
\]

where \(x_\gamma = 4\omega_m\omega_o/m^2c^4\) or \(x_\gamma = x^2/(x+1)\), and \(\lambda_1, \lambda_2\) are photon helicities.
The ratio $\sigma_{\gamma\gamma\to e^+e^-}/\sigma_c$ is shown in Fig.5. Calculating this ratio we took $\lambda_1\lambda_2 = -1$ for $2\lambda_e P_c = -1$ and $\lambda_1\lambda_2 = 1$ for $2\lambda_e P_c = 1$ (this was explained earlier).

![Fig. 5. Ratio of cross sections for $e^+e^-$ pair creation in the collision of laser and high energy photon and for the Compton scattering.](image)

Creation of high energy photons in the conversion region and its conversion to $e^+e^-$ pairs is described by the corresponding kinetic equation [9]. The maximum yield of the high energy photons from the conversion region (under the assumption that all photons have energy close to $\omega_m$) is equal to

$$k_{\text{max}} = \frac{N_{\gamma\gamma}^{\text{max}}}{N_0} = \frac{1}{p-1}(p^{1/(1-p)} - p^{p/(1-p)}),$$

(5)

where $p = \sigma_{\gamma\gamma\to e^+e^-}/\sigma_c$. Dependence of the maximum conversion coefficient on $x$ is shown in Fig.6. For $x < 4.8$, $k_{\text{max}} = 1$ (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 $k_{\text{max}} = 1 - \exp(-1) = 0.632$. For $x = 50$ ($E_0 = 2.5$ TeV, $\lambda = 1$ $\mu$m) $k_{\text{max}}$ is equal to 0.425 (0.187) 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. We see that the reduction of the luminosity for the case $2\lambda_e P_c = 1$ is not dramatic and for multi-TeV photon colliders one can use lasers with $\lambda \sim 1$ $\mu$m, which are optimal for $2E = 500$ GeV ($x \sim 4.8$).

So, there are two possibilities for multi-TeV photon colliders:

1) $x \sim 4.8$ ($\lambda \sim 4E_0[\text{TeV}]$ $\mu$m), $2\lambda_e P_c = -1$. 

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2) $\lambda \sim 1 \, \mu m$, $2\lambda_e P_c = 1$, $L_{\gamma\gamma} \sim 0.4L_{\gamma\gamma}(x = 4.8)$

Note, that all this is valid only in the case of linear Compton scattering. Below we will see that, in the second case, the picture is more complicated due to nonlinear effects in a strong field of the laser wave.

### 2.2 Nonlinear effects in Compton scattering

The field in the laser wave at the conversion region is very strong, so that the electron (or high energy photon) can interact simultaneously with several laser photons. These nonlinear effects are characterized by the parameter $[15]$:

$$
\xi^2 = \frac{e^2 B^2 \hbar^2}{m^2 c^2 \omega_0^2} = \frac{2n_\gamma r_e^2 \lambda}{\alpha},
$$

where $n_\gamma$ is the density of laser photons. At $\xi^2 \ll 1$ the electron is scattered on one laser photon, while at $\xi^2 \gg 1$ – on several. Nonlinear effects in Compton scattering at photon colliders are considered in detail in Ref. [14] in these proceedings. Shortly, with grows of $\xi^2$ the Compton spectrum becomes wider and is shifted to lower energies. Evolution of $\gamma\gamma$ luminosity distributions with the increase of $\xi^2$ at $x = 4.8$ and $2\lambda_e P_c = -1$ is shown in Fig. 7 from Ref. [14]. One can see the shape of the luminosity spectra are still acceptable.
up to $\xi^2 \sim 0.5 - 1$. For $x = 50$ and $2\lambda_e P_c = 1$ (see Figs in Ref.[14] the spectrum does not change too much up to $\xi^2 < 3$. Sensitivity of the Compton spectrum to the nonlinear effects can be estimated as following. Due to transverse motion in the electromagnetic wave the electron has the effective mass $m^2 = m_e^2(1 + \xi^2)$ [15]. As a result the maximum energy of the scattered photons is decreased

$$\omega_m = x E_0 / (x + 1 + \xi^2). \quad (7)$$

The relative shift of $\omega_m$

$$\Delta \omega_m / \omega_m \sim \xi^2 / (x + 1) \quad (8)$$

is smaller for larger $x$.

Beside worsening of the luminosity spectrum, large $\xi^2$ also leads to decrease of the polarization in the maximum of the luminosity spectrum. Partially, this is connected with the fact that photons of the same energy can be produced in the region with high or low $\xi^2$. In the later case, the polarization will be lower, because the ratio $\omega / \omega_m$ is lower while the polarization is high only for $\omega$ close to $\omega_m$.

One of the main practical consequences of the nonlinear effects is the increase of the required laser flash energy. This problem is considered in the next section.
2.3 Laser flash energy

The collision probability of an electron with laser photons in the scheme shown in Fig.1 can be estimated as follows

\[ p \approx \frac{2\sigma_x n_0}{\theta} \int_{-\infty}^{\infty} e^{-\frac{x^2}{\sigma_x^2}} dx = \frac{2\sqrt{2\pi\sigma_x n_0} \sigma_x}{\theta}, \quad (9) \]

where \( n_0 \) is the density of laser photons at the focal point, \( \sigma_x \) is the r.m.s. transverse size of the laser beam in the conversion region (it is assumed to be constant), \( \theta \) is the collisions angle. The r.m.s. beam size can be expressed via the beam divergence

\[ \sigma_x = \frac{\lambda}{4\pi \sigma_x'}, \quad (10) \]

(this follows from the Heisenberg uncertainty principle: \( \sigma_p \sigma_x = \hbar/2 \)). To confine a Gaussian laser beam, \(^3\) the collision angle \( \theta \) should be several times larger than the beam divergence

\[ \theta = s\sigma_x' = \frac{s\lambda}{4\pi \sigma_x}, \quad (11) \]

where \( s \sim 2 \) (mirrors cover \( 1 - e^{-2} = 0.865 \) of the Gaussian beam) \(^4\) Substituting \( \sigma_x \) from (11) and \( n_0 \) from (6) into (9) we get the collision probability

\[ p \approx \frac{\sqrt{2\pi \alpha \sigma} \xi^2 s}{4\pi \theta^2 r_e^2}. \quad (12) \]

This is a useful relation between the conversion probability, angular size of the focusing system (\( \pm \theta \)) and parameter \( \xi^2 \). Substituting (11) to (12) we get the radius of the laser beam

\[ \sigma_x^2 \approx \frac{r_e^2 \lambda^2 s p}{4\pi \sqrt{2\pi \alpha \sigma} \xi^2}. \quad (13) \]

\(^3\) From the practical point of view the flat shape may be better, but here we consider Gaussian beams, for simplicity
\(^4\) this is not the loss of the 13% of energy, the laser beam can have any profile (superposition of many transverse modes), this number just means that formulas for a Gaussian beam describe the density distribution near the laser focus with a sufficient accuracy.
The distribution of photons in a Gaussian beam with uniform longitudinal density is given by
\[ dN = \frac{N}{2\pi l_\gamma \sigma_x \sigma_y} e^{-x^2/2\sigma_x^2 - y^2/2\sigma_y^2} dx dy dz, \tag{14} \]
where \( l_\gamma \) is the bunch length. Hence, for a round beam \( N = 2n_0\pi \sigma_x^2 l_\gamma \), where \( n_0 \) is the photon density at the focal point, which can be expressed via the parameter \( \xi^2 \) using Eq.(6). The laser flash energy
\[ A = N\omega_0 = 2\pi \sigma_x^2 n_0\omega_0 l_\gamma, \tag{15} \]
where the length of the laser bunch follows from the requirements that laser photons should be present in the conversion region all the time until an electron bunch crosses the region \( \pm \sigma_x/\theta \), this gives
\[ l_\gamma = 4\sigma_x/\theta + l_e = 16\pi \sigma_x^2 /\lambda s + l_e. \tag{16} \]
Substituting (6,13,16) to (15) we get the required laser energy
\[ A = \frac{mc^2l_ep s}{ar_e\sqrt{8\pi}} \left( \frac{\sigma_0}{\sigma_c} \right) \left[ 1 + \frac{4\lambda p}{\sqrt{2\pi\alpha l_e} \xi^2} \left( \frac{\sigma_0}{\sigma_c} \right) \right]. \tag{17} \]
For \( s = 2 \) the flash energy is equal to
\[ A_0[J] = 16p \left( \frac{\sigma_0}{\sigma_c} \right) l_e \left[ 1 + p \frac{70\lambda \sigma_0}{\xi^2 l_e \sigma_c} \right], \tag{18} \]
where all lengths are expressed in cm. Comparison with the simulation shows that this formula works better with somewhat larger coefficients: \( 16 \to 20 \) and \( 70 \to 150 \). We will use these numbers for further estimations. The first term in Eqs.17,18 is some minimum flash energy determined by the diffraction of laser beams, the second term is due to the nonlinear effects (when the maximum value of the parameter \( \xi^2 \) is fixed). With the increase of the electron beam energy the second term becomes more important for three reasons: 1) if \( x = \text{const} \), then \( \lambda \propto E_0 \), 2) if \( \lambda = \text{const} \), then \( x \propto E_0 \) and the ratio \( \sigma_c/\sigma_c \) decreases (this increases the first term as well), 3) the electron bunch length is smaller for accelerators with higher acceleration gradient. So, to have a reasonable laser flash energy at multi-TeV photon colliders one has to increase the value of the parameter \( \xi^2 \), this leads to a worsening of the luminosity spectrum.\[5\]
\[5\] Section 3 shows how this problem can be overcome.
The required flash energy and contribution of each term for three cases are given in Table 1. Here, in the line $\sigma_c/\sigma_0$ the second number after “·” is due to nonlinear effects. Let me remind also that in the case c) the luminosity is lower by a factor of 2.3 than in the case b) (for small $\xi^2$) due to $e^+e^-$ production.

So, in both cases of multi-TeV colliders b) and c), the flash energy seems acceptable. Of course, in the case b) it is better to have $\xi^2 < 0.3$ but in this case the flash energy would be too large, about 25 J.

One more remark concerning the case c). Here we have assumed $\xi^2 = 3$, but, in the case of large $x$ and large $\xi^2$, the linear theory of $e^+e^-$ production in collisions between laser and high energy photons may be not be valid due to the coherent $e^+e^-$ production [20,9]. This problem needs accurate study, here I would just like to give some comment. The coherent pair creation in the uniform field starts at $\Upsilon = \gamma B/B_0 > 1$ (here $B_0 = \alpha e/r_e^2$ is the critical field). In the case of the electromagnetic wave $\Upsilon \sim 0.5\xi x$. For $x = 50$ and $\xi^2 = 3$, we have $\Upsilon \sim 75 > 1$. Besides that, in order to consider the coherent $e^+e^-$ creation in the wave using the same formulas as for the constant field, the formation length for this process should be shorter than the wave length. This is also fulfilled for $\xi > 1$. If that is so, then one can forget about using large $x$ and $\xi^2 > 1$ at photon colliders. But now I am not sure about the accuracy of the numbers in the transition regime considered, it would be worth making an accurate study on this subject.

For convenience, a set of useful approximate formulas for the conversion region expressed via the f-number ($f_\\# = $ focal length/diameter $= 1/2\theta$) is presented below, the right part of equations is given for $s = 2$:

$$l_\gamma \sim 4f_\\#^2 s\lambda/\pi + l_e \approx 2.5f_\\#^2 \lambda + l_e$$

$$\sigma_x \approx s\lambda f_\\#/2\pi \sim \lambda f_\\#/\pi$$

### Table 1

| Laser flash energies for three sets of parameters. |
|-----------------------------------------------|
| $2E_0$, GeV | a | b | c |
| 2$P_c\lambda_e$ | -1 | -1 | 1 |
| $\lambda_e$, $\mu$m | 1 | 10 | 1 |
| $\xi^2$ | 0.3 | 1 | 3 |
| $\sigma_c/\sigma_0$ | 0.7-0.95 | 0.7-0.89 | 0.235-0.68 |
| $l_e$, $\mu$m | 600 | 200 | 200 |
| $p$ | 1 | 1 | 0.75 (close to opt.) |
| $A$, J | $1.8(1+1.25)=4$ | $0.64(1+12)=8.3$ | $1.9(1+1.17)=4.1$ |
The last line is equation (18) with corrected coefficients. The input parameter for these equations is $\xi^2$. The third equation gives $f_\#$ which should be substituted into the other equations.

Obtaining these formulas we assumed that the transverse size of the electron bunch is much smaller than $\sigma_x$ of the laser beam. This is not always correct. In the scheme with crab crossing (see Fig.1), the electron beam is tilted by the angle $\alpha_c/2 \sim 0.015$, that is equivalent to the effective transverse size

$$\sigma_{x,e} = \sigma_z \alpha_c/2.$$  \hfill (20)

This is an additional constraint for choice of $f_\#$. It can be taken into account in the following way.

1) If $\sigma_{x,e} < \sigma_x$ given by Eq.19b, then all remains the same, just Eq.19d for the energy should be multiplied by a factor of $\sqrt{1 + \sigma^2_{x,e}/\sigma^2_x}$.

2) If $\sigma_{x,e} > \sigma_x$, then one should start the calculation from

$$\sigma_{x,e} = \lambda f_\# / \pi,$$

this gives $f_\#$, which should be substituted in eqs.19a,c,d. Besides that, Eq.19d should be multiplied by a factor of $\sqrt{2}$.

### 3 Conversion region with a “traveling laser focus”

In the previous section we have considered the “usual” method of laser beam focusing. In this case the laser energy is not effectively used. In order to get high conversion probability at a fixed value of the parameter $\xi^2$, the length of the laser target and the diameter of the laser beam should be large enough, 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 [19], see Fig.8. In this scheme, the laser beam follows the electron beam. This can be done...
using chirped laser pulses (the wave length changes linearly along the bunch). Chirped pulse technique is used for stretching and compression of laser pulses in practically all powerful short-pulse lasers. In order to make a traveling focus the beam should be pre-focused using elements with some chromaticity, (Fresnel lenses, dispersive lenses, wedges, gratings). The picosecond pulses which are needed for photon colliders have naturally quite broad spectrum and it is not a big problem to vary the focal length on about $\Delta f/f \sim \text{mm/m} \sim 10^{-3}$ and change the direction on $\Delta \theta \sim d\Delta f/f^2 \sim 10^{-5} - 10^{-4}$. The 

![Fig. 8. Traveling laser focus at the conversion region.](image)

optimum diameter of the laser beam should be approximately equal to $2\sigma_x \sim 2\sigma_z \theta$. The length of the laser beam can now be arbitrary, it should only be shorter than the distance between the conversion and interaction points which is about $\gamma \sigma_y$ or 3.7 mm for $2E = 5$ TeV with $\sigma_y = 0.75$ nm (CLIC). In fact, now the effective thickness of the laser target is equal to the laser bunch length. For obtaining a high conversion probability in such a scheme, one can use a laser with much smaller flash energy and have much smaller values of the parameter $\xi^2$.

Let us calculate $A$ and $\xi^2$. The laser bunch radius

$$\sigma_x \sim \sigma_z \theta. \quad (22)$$

The probability of scattering for the electron is

$$p \sim (2/\sqrt{2}) n_0 \sigma_c l_{\gamma}, \quad (23)$$

here factor the 2 is due to the relative motion and $1/\sqrt{2}$ due to the collision of the Gaussian
beams with equal radius. Substituting (11) into (22) we get

$$\sigma_x = \sqrt{\frac{\lambda \sigma_z s}{4\pi}}. \quad (24)$$

Substituting (24),(23) into (15) we obtain the flash energy

$$A = \frac{\pi \hbar \sigma_z sp}{\sqrt{2\sigma_e}}. \quad (25)$$

Assuming $s = 2$, $p = 1$, $l_e \approx 2\sigma_z$ we obtain

$$A \sim 2.2 \frac{hcl_e}{\sigma_e} \sim 28l_e[\text{cm}] \left(\frac{\sigma_0}{\sigma_e}\right) [\text{J}]. \quad (26)$$

The value of $\xi^2$ follows from (6) and (23)

$$\xi^2 = \frac{\sqrt{2}\lambda}{\pi \alpha l_\gamma} \left(\frac{\sigma_0}{\sigma_e}\right) p. \quad (27)$$

One remark. All this is valid for infinitely thin electron beams. In the case of the crab crossing the effective radius of the electron beam is $\sigma_{x,e} = 0.5\alpha_c \sigma_z$. The above formulas in this section are valid when $\sigma_x$, given by Eq.24, is larger than $\sigma_{x,e}$. For $s = 2$ this gives

$$\sigma_z < \lambda/\alpha_c^2. \quad (28)$$

For $\alpha_c = 0.03$ this gives $\sigma_z < 1000\lambda$, that is valid practically always.

Let us consider, for example, the case b) from table 1. Taking $l_\gamma = 0.3 \text{ cm}$ (we discussed this in the second paragraph of this section), $\lambda = 10 \mu\text{m}$, $\sigma_c/\sigma_0 = 0.7$, $l_e = 0.02 \text{ cm}$ we obtain

$$A \sim 0.8 \text{ J}, \quad \xi^2 \sim 0.3. \quad (29)$$

This should be compared with $A = 8.3 \text{ J}$ and $\xi^2 = 1$ for the usual focusing (see table 1). To obtain $\xi^2 = 0.3$, using the usual method of focusing, one would need 25 J flash energy.

So, the traveling focus is a very attractive solution for one of the most serious problems of multi-TeV photon colliders. Certainly, this method of focusing is more complicated, but it can significantly reduce the required flash energy and solve the problem of nonlinear
effects. The chirped pulses needed for this method can be obtained, not only with usual lasers, but also with free electron lasers.

4 Interaction region aspects

4.1 Collision effects

Photons are neutral particles, nevertheless there is one collision effect which restricts the $\gamma\gamma$ luminosity, that is the coherent pair creation — conversion of high energy photons into $e^+e^-$ pairs in the field of the opposing electron beam [20,9,10]. Detailed study of this limitation was given in Ref.[22]. At high energies, one cannot just collide electron beams and convert them to high energy photons, as is possible for low energy photon colliders where $L_{\gamma\gamma}$ is determined only by the geometric electron-electron luminosity.

Let me compare, just for illustration, the probabilities of beamstrahlung and coherent pair creation in a strong electromagnetic field. For $\Upsilon \gtrsim 20$ (in $e^+e^-$ collisions in the CLIC (5 TeV) project $\Upsilon \sim 20$) the probabilities of these processes per unit length are $p_{e\rightarrow e\gamma} = 5\alpha^2 T^{2/3}/(2\sqrt{3}r_e\gamma)$ [21] and $p_{\gamma\rightarrow e^+e^-} = 0.38\alpha^2 T^{2/3}/(r_e\gamma)[20,9]$. The ratio of beamstrahlung/pair creation is about 3.8. At $e^+e^-$ colliders the average number of emitted photons is usually 1–3, so at photon colliders the conversion probability to $e^+e^-$ pairs will be the same at somewhat smaller horizontal beam size.

In Fig. 9 from Ref.[22] the dependence of the $\gamma\gamma$ luminosity in the high energy peak on the horizontal beam size at various energies and numbers of particles in the electron bunches is shown. It was assumed that $N \times f = 10^{14}$, the electron vertical beam size is somewhat smaller than the photon beam size due to Compton scattering (equal to $b/\gamma$) and the distance, $b$, between the conversion and interaction points was taken as small as possible (but sufficient for conversion) $b = 3\sigma_x + 0.04E_0[\text{TeV}]$, cm. In this figures one can see that some curves follow $L_{\gamma\gamma} \propto 1/\sigma_x$ as is expected in the absence of collision effects, while some curves make zigzags due to the coherent pair creation.

For CLIC ($2E_0 = 5$ TeV) with $N \times f = 0.3 \times 10^{14}$ the maximum $\gamma\gamma$ luminosity at a reasonable $\sigma_x$ is about $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$. Note, this result very weakly depends on $\sigma_z$. So, the luminosity is not too large, only about a factor of two larger than that at the TESLA collider at $2E = 500$ GeV [12].

At low energies the coherent pair creation is considerably reduced (even suppressed) due to the beam repulsion [22], see Fig.9a. At high energies this effects works only for long electron bunches and a small number of particles in the bunch. In Fig.9 for $2E = 5$ TeV this regime corresponds to the region of very small $\sigma_x$, where the luminosity is really
large. This regime, with small numbers of particles, high collision rate and very small $\sigma_x$, is practically impossible to reach in reality.

4.2 A way to avoid coherent pair creation

Below I would like to present a new idea on how the problem of the coherent pair creation can be overcome in photon colliders (at least in principle).

The field of the electron beam at the interaction point is

$$B_b = |B| + |E| \sim \frac{eN}{\sigma_x\sigma_z}.$$  \hspace{1cm} (30)

The coherent pair creation occurs when $\Upsilon = \gamma B/B_0 > 1$ ($B_0 = \alpha e/r_e^2$) and the conversion probability grows with the increase of $\Upsilon$ [20,9]. For low energy colliders the field at the interaction point in $ee$ collisions is lower than $B_b$ given by (30) due to the beam repulsion. As result, at the energies below about $2E_0 = 500 - 800$ GeV the coherent pair creation is not essential even for very tight electron beams [22,23,12]. At multi-TeV energies the

Fig. 9. Dependence of the $\gamma\gamma$ luminosity on the horizontal beam size for $\sigma_z = 0.2$ mm, see comments in the text.
deflection is not sufficient for suppression of coherent pair creation. What can be done (besides, the old idea of neutralization of the beam field using four beam \( e^+e^- \) collisions) about this?

One idea is the following. Let us collide electron beams tilted around the collision axis by some relative angle \( \phi \sim \mathcal{O}(0.1)\sigma_y/\sigma_x \). Having initial displacement each of the electron beams will be split during the collision in two parts, see Fig.10. If the transverse deflection during the beam collision, \( \Delta > \sigma_x \), then the maximum field in the region of high energy photons (at \( x \sim \sigma_x \)) is

\[
B_r = B_b(\sigma_x/\Delta)^2 \propto \sigma_x. \tag{31}
\]

So, with the decrease of \( \sigma_x \), the \( \gamma\gamma \) luminosity grows but the field at the interaction region is decreased!

The main problem here is the production of beams with sufficiently small sizes. The required horizontal beam size is larger for longer beams (the dependence is between linear and quadratic). For the bunch lengths, \( \sigma_z \sim 25 \, \mu m \), now considered for CLIC, this idea, certainly, does not work. But why should \( \sigma_z \) be so short for photon colliders? Short bunches are needed during the acceleration to reduce wake fields, but after acceleration one can stretch the beam (using energy spread).

So, the idea is interesting and worth more detailed consideration. Further study and optimization should be based on full simulation.

\(^6\) and to reduce instabilities in collisions of \( e^+e^- \) beams which is not necessary in the case of photon colliders
5 Conclusion, acknowledgments

Multi-TeV photon colliders have many specific problems, several of them were considered
in this paper, but the main study and R&D are still ahead.

I appreciate efforts of the CLIC team towards the multi-TeV linear collider and their
desire to have a second interaction region for $\gamma\gamma$ and $\gamma e$ collisions.

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