$\gamma\gamma,\gamma e$ at linear colliders

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Abstract

Review of problems in obtaining $\gamma e,\gamma\gamma$-beams at linear colliders is given.

1. *Introduction*

In linear colliders (see Table 1) each bunch is used only once. This makes it possible to use electrons for production of high energy photons to obtain colliding $\gamma\gamma$-and γe-beams. This idea was proposed in Ref.[1] and was further discussed in Ref[2-12]. The best method of $\gamma \to e$ conversion is Compton scattering of laser light on high energy electrons. The scattered photons have energy close to that of the initial electrons and follow their directions. This method is well known[13]. Small bunch size in linear colliders makes it possible to get a conversion coefficient (N_γ/N_e) $k \sim 1$ at a moderate laser flash energy of a few Joules. In $\gamma\gamma$-collisions a luminosity higher than in e^+e^--collisions is possible due to the absence of some collision effects. Monochromaticity of collisions $\Delta W_{\gamma\gamma}/W_{\gamma\gamma} \sim 10\%$ can be obtained. Photons may have various polarizations, that is very advantageous for experiments.

Table1

Some parameters of linear colliders now under development

	VLEPP	TLC	JLC	CLIC	DESY/THD	TESLA
$2E_0$, TeV	1	0.5	1	1	0.5	0.5
G(MeV/m)	100	50	80	80	17	25
N/bunch(10^{10})	20	1.5	2	0.5	2	5
rep.rate, Hz	100	120	150	1700	50	10
# bunches	1	10	20	1	170	800
Δt bunch(ns)	-	1	1.4	-	10	1000
σ_z (mm)	0.75	0.1	0.1	0.2	0.5	2
σ_x (nm)	1300	170	370	70	300	640
σ_y (nm)	3	4	3	15	40	100

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The detailed consideration of the conversion, photon spectra and monochromatization of collisions can be found in Ref.[3]. The polarization effects have been considered in Ref.[7]. Collision effects restricting the luminosities, the scheme of interaction region, requirements to accelerators, attainable luminosities and other aspects of obtaining $\gamma\gamma,\gamma e$-collisions have been considered in Ref.[10,11]. Physical problems, which can be studied in $\gamma\gamma,\gamma e$-collision were discussed in Ref.[12,14-19] and other papers. Undoubtedly $\gamma\gamma,\gamma e$- collisions will increase the potential of linear colliders.

1. Backward Compton scattering.

If laser light is scattered on an electron beam, the photons after scattering have a high energy ($\omega \sim E_0$) and follow the initial electron direction with additional angular spread $\sim 1/\gamma$. This method of conversion has obvious advantages in comparison with other methods(bremsstrahlung on amorphous or crystal target, beamstrahlung) because of much better background conditions, the possibility of monochromatization (~10% in $\gamma\gamma$- collisions) and a high degree circular polarization.

1.1 Kinematics.

In the conversion region a photon with the energy ω_0 is scattered on an electron with the energy E_0 at a collision angle α_0. The energy of the scattered photon ω depends on its angle ϑ with respect to the direction of motion of the incident electron as follows:

$$\omega = \frac{\omega_m}{1+(\vartheta/\vartheta_0)^2}$$

where $\omega_m = \frac{x}{x+1} E_0$; $\vartheta_0 = \frac{mc^2}{E}\sqrt{x+1}$; ; $x = \frac{4E_0\omega_0\cos^2\alpha_0/2}{m^2c^4}$;

ω_m - is the maximum photon energy.

The energy spectrum of the scattered photons is defined by the Compton cross section, which can be found in convenient form elsewhere[3,7,10,11].

For the polarized beams the spectrum only varies, if both electron mean helicity λ ($|\lambda| \le 1/2$), and that of the laser photons (P_c) are nonzero. At $2\lambda P_c = -1$ and $x > 2$ the relative number of hard photons nearly doubles (fig.1), improving significantly the monochromaticity of the photon beam.

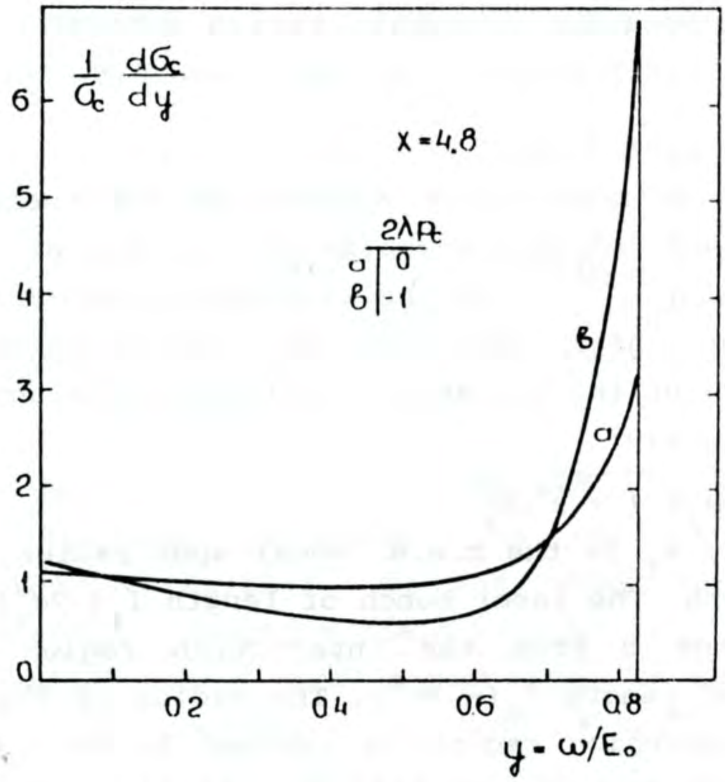

Fig.1 Energy spectrum of scattered photons

1.2. Choice of a laser wave length.

With increasing the energy of laser photons the maximum energy of scattered photons also increases and monochromaticity improves. However, besides the Compton scattering, in the conversion region other processes become possible[3,10,11]. The most important one is $\gamma_0 + \gamma \longrightarrow e^+ + e^-$. In this process an e^+e^- pair is created in a collision of a laser photon with a high energy (scattered) photon. The threshold of this reaction is $x \approx 4.8$. The wave length of laser light at x = 4.8 is

$$\lambda = 4.2\ E_0(\mathrm{TeV}),\ \mu\mathrm{m}$$

Above the threshold region the two photon cross section exceeds the Compton one by a factor of 1.5-2 [10,11]. Due to this fact the maximum conversion coefficient at large x is limited by 25-30%. Besides, produced e^+ make the problem of removing particles from conversion region more difficult. For these reasons it is preferable to work at x <4.8.

1.3. Conversion coefficient.

The conversion coefficient depends on the energy of the laser flash A as $k = N_\gamma/N_e \approx 1-\exp(A/A_0)$ $(\sim A/A_0$ at $A < A_0)$ Let us estimate A_0 [3,10,11]: At the conversion region the r.m.s radius of the laser beam in the dif f raction limit o focusing depends on the distance z to the focus(along the beam) in the following way:

$$r_\gamma = a_\gamma\sqrt{1 + z^2/\beta_\gamma^2}$$

where $\beta_\gamma=2\pi a_\gamma^2/\lambda$, a_γ is the r.m.s. focal spot radius, λ is the laser wave length. The laser bunch of length $l_\gamma(\sim 2\sigma_z^\gamma)$ collides at some distance b from the interaction region with the electron beam of length $l_e(\sim 2\sigma_z^e)$. The radius of the electron beam at the conversion region is assumed to be $r_e \ll a_\gamma$. The probability of an electron collidings with laser photons is p $\sim n_\gamma\sigma_C l$, where the density of laser photons at the focus is $n_\gamma \sim A/(\pi\omega_0 a_\gamma^2 l_\gamma)$ and the length of the conversion region with high density of photons is $l\approx 2\beta_\gamma=4\pi a_\gamma^2/\lambda$ (we assume $l\le l_\gamma$). Taking $l= l$ we obtain p ~ 1 at

$$A_0\sim \pi\hbar c l_e/2\sigma_C$$

It is remarkable, that A_0 doesn't depend on the size of the focal spot when $2\beta_\gamma<l_e$, i.e. $a_\gamma<\sqrt{\lambda l_e/4\pi}$. When the focal radius a_γ is decreased, then the length of the region with high photon density becomes shorter and the probability of conversion almost does not change. Many people make mistakes in this respect. For x=4.8 $\sigma_C=1.9\cdot 10^{-25}\mathrm{cm}^2$ and we get

$$A_0\sim 25\ l_e[\mathrm{cm}],\ \mathrm{J}$$

which corresponds to the power ~ 1 TW. With such a focusing the angular divergence of the laser light is

$$\alpha_\gamma = a_\gamma/\beta_\gamma = \lambda/2\pi a_\gamma = \sqrt{\lambda/\pi l_e}$$

The value of A only slightly varies until the collision angle $\alpha_0 < \alpha_\gamma$. In principle, at $\alpha_0=\pi/2$ one can get almost the same conversion coefficient as at $\alpha_0=0$ (at fixed flash energy) and $x(\pi/2)=0.5\cdot x(0)$. In this case the focal spot size is ~ $\lambda\times l_e$ and the depth of focus ~ λ.

1.4. Influence of a strong field on processes in the conversion region.

In the conversion region the density of laser photons can be so high that multiphoton processes may occur [20-21]. Nonlinear effects are described by the parameter

$$\xi = \frac{eF\hbar}{m\omega_0 c}$$

where F is the field strength (E,B) and ω_0-photon energy. At $\xi \ll 1$ an electron interacts with one photon from the field(Compton scattering). On the other hand at $\xi \gg 1$ an electron feels a collective field (synchrotron radiation).

What values of ξ are acceptable? In a strong field electrons have transverse motion, which increase their effective mass [22]: $m^2 \longrightarrow m^2(1+\xi^2)$. The max.energy of photons in Compton scattering is decreased by 5% at $\xi^2 = 0.3$. Considerations of this effects in the conversion region show[10,11] that to keep k~1 at x=4.8 and $\xi^2=0.3$ the following parameters of laser photon bunch are required:

$$l_\gamma \sim 0.17\ E_0[\text{TeV}],\text{cm} \qquad *$$

$$A_0 \sim 4E_0[\text{TeV}]\ ,\text{J}$$

These Eqs work when $l_\gamma(*) > l_e$, otherwise $l_\gamma \approx l_e$ and A_0 is found by formula of sect.1.3. For large E_0 and short electron bunches this requirement on the energy of laser flash is stronger than what follows from the simple consideration of the conversion probability.

1.5. Polarization

If electrons or laser photons are longitudinally polarized, the scattered high energy photons have circular polarization too.[7] The degree of polarization is shown in fig.2 for various helicities of electron and laser beams.

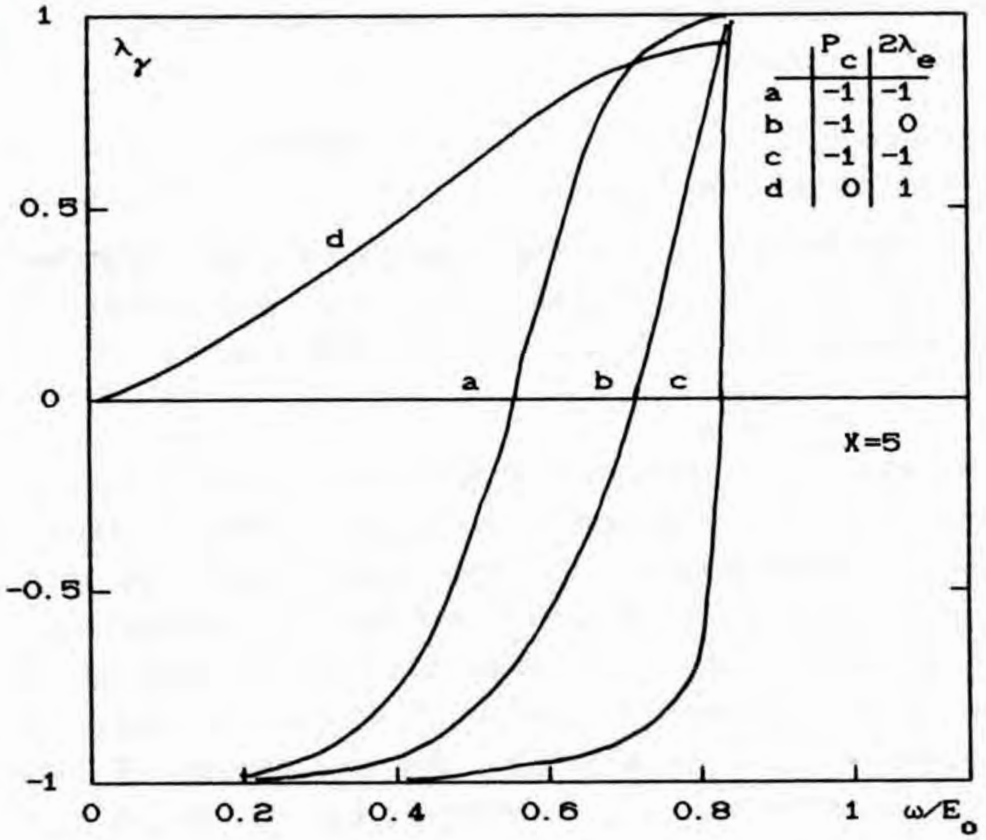

Fig.2 The circular polarization degree of photons vs ω/E for various polarization of laser photons and electrons.

Note that if polarization of laser photons $P_c=\pm1$, then $\lambda_\gamma=-P_c$ at $y=y_m$. In the case of $2P_c\lambda_e=-1$ all the photons in the high energy peak have a high degree like-sign polarization. Photon polarization is crucial for some experiments.

1.6 Monochromaticity and luminosity

The spectrum of scattered photons is very broad, but because of energy-angle correlation in the Compton scattering it is possible to have much better monochromaticity of γe-and $\gamma\gamma$-collisions[3,7,10]. If the spot size of the photon beam due to Compton scattering (b/γ) is larger than the r.m.s. radius of electron beam at i.p.(a), then in the γe-collisions electrons collide only with the photons of highest energy. Similarly, in $\gamma\gamma$-collisions photons with higher energy collide at smaller spot size and, therefore, contribute more to the luminosity.

In fig.3 the plots of spectral luminosities are shown for round, unpolarized and polarized beams($2P_c\lambda_e$=-1 for both beams)[3,7,10].

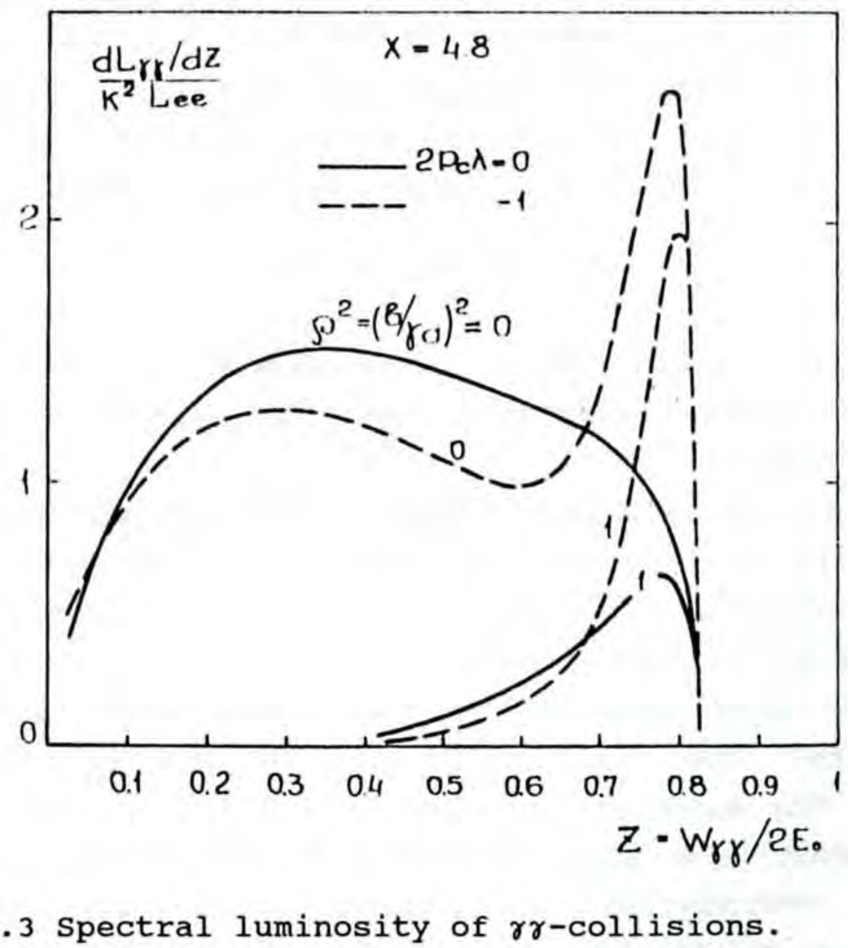

Fig.3 Spectral luminosity of $\gamma\gamma$-collisions.

One can see that at ρ=1 the luminosity in the low mass region is suppressed and the full width at half of maximum is about 10% for polarized and 20% for unpolarized beams. With further growth of ρ the monochromaticity of collisions improves slowly up to certain limit(but total luminosities go down).

2. Lasers

2.1 Summary of requirements for lasers.

To get the conversion probability k=65% ($A=A_0$) at x=4.8 a laser with the following parameters is required:

Flash energy	A_0= max(25 l_e[cm], 4E_0[TeV]),J
Duration	$c\tau$=max(l_e,0.17 E_0[TeV],cm)
Repetition rate	n bunches x rep.rate of a collider
Wave length	λ~4.2 E_0[TeV], μm or ω_0=0.3/E_0[TeV],eV
Angular divergence	- near to diffraction limit

For example, at E_0=0.25 TeV and l_e=200 μm (NLC,JLC) a laser with flash energy A_0~ 1J, l_γ~ 400 μm and λ~1 μm is required. The first two numbers are determined by nonlinear effects. For VLEPP with l_e~1.5 mm a laser with A_0~2.5 J and l_γ~ 0.15 mm is required. Here nonlinear effects are not essential.

2.2 Lasers, state of art.

Obtaining Joule pulses of picosecond duration is not a problem for modern laser technique. The main problem is high repetition rate.

Some data on existing eximer and solid state lasers,taken from K.Geissler report in Saariselka(see ref.[11]), are presented in Table 2. The first laser is of room size and two others are of table-top size. For both types of lasers the energy and time duration of the flash are close to our requirements. The repetition rate of the KrF laser is promising. For Nd:glass the situation with rep.rate is worse - only about one shot per minute. It is restricted by amplifier overheating. A promising way for increasing rep.rate up to ten Hz is to use moving slab-geometry amplifiers instead of rods. Hopes are connected also with new materials:Ti-sapphire and Alexandrite. They are very good storage media and have high heat conductivity.

Table 2. Parameters of some laser systems in ps region.

medium	λ, μm	E,GeV at X=4.8	W, TW	A, J	τ, ps	ν, Hz	ø, cm	Authors
KrF	0.25	60	4	1.6	0.4	20	20	S.Watanabe et al (Japan)
Nd:ph. glass	1.06	250	3.2	3.2	1	?	3	F.Paterson et al (Livermore)
Nd:ph. glass	1.06	250	2.5	1.5	0.6	1/60	?	M.Ferray et al (Sacley)

The success of obtaining of picosecond pulses is connected with a chirped pulse technique ("chirped" means time-frequency correlation in the pulse). This correlation can be obtained by using nonlinear effects in fibers or by grating pairs. After amplification a long chirped pulse is compressed by a grating pair to picosecond duration. Stretching and compression by a factor 1000 has been demonstrated. In a little more detail chirped pulse schemes are described in ref [11].

This nice technique can be used for a free-electron lasers(FEL). Indeed, FEL is a very attractive type of laser for a Photon Linear Collider. They have tunable wave length and a high repetition rate. However, it will be difficult to generate Joules in 1 ps. The task is much simpler, if FEL generate long chirped pulse, which is compressed after that by a grating pair. At present, the peak power obtained with FEL is about few tenth of GW (without chirping technique).[22]

In principle, one photon bunch can be used many times for collision with a chain of electrons bunches in the collider. Losses due to reflections can be compensated by one amplifier stage. However, this scheme does not work for small distances between electron bunches(Δl~30 cm for SLAC project).

3. Scheme of $\gamma e, \gamma\gamma$-collision..

Two schemes are discussed:

Scheme A. The conversion region is situated close to the interaction point(i.p) at the distance $b \geq 2\sigma_z$. After conversion all particles travel directly to the i.p..

Scheme B. After conversion at some distance b from the interaction region, particles pass through the region with a transverse magnetic field, where "used" electrons are swept aside. Thereby one can get more or less clean γe- or $\gamma\gamma$-collisions.

The first scheme is simpler, but background conditions are much worse (mixture of $\gamma\gamma, \gamma e$, ee collisions, larger disruption angles). Below, estimates of attainable luminosities for both schemes will be given..

4. Beam collision effects[10,11]

During beam collisions electrons and photons are influenced by the field of opposing electron beam. In the case of $\gamma\gamma$-collisions the field is created by "used" electrons deflected after conversion by the external field (not deflected in the scheme A). In γe-collisions the field is created also by the main electron bunch used for γe-collisions. A strong field leads to:

a) energy spread of the electrons in γe-collisions;

b) conversion of photons into e^+e^--pairs in γe - and $\gamma\gamma$-collisions(coherent pair creation[23]).

c),d) beam displacement and spin rotation in γe-collisions.

Restrictions on the $\gamma e, \gamma\gamma$-luminosities due to these effects were considered in ref.[10,11] The results are summarized below.

5. Ultimate luminosity in γe-collisions.

5.1 *Scheme A(without deflection)*.[11]

There are three main collision effects here:

a)beamstrahlung; b) pair creation;c) beam-beam instabilities.

The effects a) and c) are the same as in e^-e^- collisions. It can also be shown that, if beamstrahlung losses are small, pair creation probability is also small. Therefore

$$L_{\gamma e\ max} \sim k\ L_{ee}$$

5.2 Scheme B (with deflection).[10,11]

In this scheme of γe-collisions there are the following effects

a) photons are affected by the field of the opposing electron beam. To avoid coherent pair creation electron, the beams must be flat at the i.p.. This requirement determines the minimum horizontal beam size.

b) the electrons of the main beam have beamstrahlung energy losses in the field of the deflected beam used for $e \to \gamma$ conversion. To reduce these losses one has to increase the deflection, i.e. the distance between the conversion region and the i.p., which leads to a growth of the vertical photon spot size ($\sigma \sim b/\gamma$) (the other size is determined by the previous effect).

c) The displacement of the electron bunch during collisions due to repulsion from deflected,"used" beam must be less than σ_x. This also implies some restrictions on the deflection, i.e. on the distance b.

It can also be shown , that in all practical cases (when previous requirements are satisfied) the longitudinal polarization of electrons in γe-collisions changes by less than a few percent.

Estimates of ultimate γe-luminosities due to effects a)-c) for the three projects at E_0=0.25 and 1 TeV are presented in Table 3. For beam energies above 0.5 TeV the effect of beam displacement is not essential and $L_{\gamma e}$ is determined by beamstrahlung and pair creation. The estimate were done for k=0.65 and an external deflecting field B_e=30 kG.

Note that these ultimate $L_{\gamma e}$ were obtained under the assumption that the contribution of beam emittance is negligible.

Table 3. Ultimate $L_{\gamma e}$ (scheme B) due to
a) beamstrahlung and pair creation
b) beam displacenent
c) optimum

				E_0=0.25 TeV			E_0=1 TeV
	$N(10^{10})$	σ_z(mm)	f(kHz)	$L_{\gamma e}(10^{33})$, $cm^{-2}s^{-1}$			$L_{\gamma e}(10^{33})$
NLC	1.5	0.1	1.2	a) 0.7	b) 2.7	c) 0.7	0.35
DESY/THD	2	0.5	8.5	20	4.2	9.	10*
VLEPP	20	0.75	0.1	1.1	0.95	1.	0.67

We see that the ultimate $L_{\gamma e}$ is good enough at E_0=0.25 TeV, but not sufficient (for VLEPP and NLC) at E_0=1 TeV($\sigma \propto 1/E^2$).

6. Ultimate luminosity in $\gamma\gamma$-collisions.

In $\gamma\gamma$-collisions there is only one effect restricting the luminosity-coherent pairs creation by photons in the field of the opposing electron beam(deflected in the scheme B).

6.1 Scheme A(without deflection).[11]

In this scheme electron beams must be flat. The horizontal size σ_x at the i.p. is determined by coherent pair creation. The minimum vertical size at the i.p. is $\sigma_y \sim b/\gamma$, where distance between the i.p. and the conversion region $b \ge 2 l_\gamma$, where l_γ is given in sect.2.1. Estimates of attainable luminosities in this scheme are presented in Table 4.

Table 4. Ultimate $L_{\gamma\gamma}[cm^{-2}c^{-1}]$ (scheme A-without deflection)

				E_0=0.25 TeV	E_0=1 TeV
	$N(10^{10})$	σ_z(mm)	f(kHz)	$L_{\gamma\gamma}(10^{34})$	$L_{\gamma\gamma}(10^{34})$
SLAC	1.5	0.1	1.2	0.9	0.3
DESY/THD	2	0.5	8.5	10	9.5*
VLEPP	20	0.75	0.1	1	1.4

* in DESY/THD-project E_0=1 TeV is not considered

6.2 Scheme B (with deflection).[10,11]

In this scheme the beams are round. The spot size at the i.p. is $\sigma \sim b/\gamma$. The distance b must be large enough to provide such deflection of "used" beams that probability of e^+e^--pair creation by photon at i.p. is small.

The attainable $\gamma\gamma$-luminosities in this scheme for E=0.25 TeV are presented in Table 5. Here a_γ-photon spot size, x - deflection of "used" beams are taken at the i.p..

Table 5. $L_{\gamma\gamma}$ at E=0.25 TeV in the scheme B(with deflection)

	$N(10^{10})$	σ_z(mm)	f(kHz)	$L_{\gamma\gamma}(10^{34})$	a_γ(nm)	b(cm)	x_0,nm
NLC	1.5	0.1	1.2	0.45	14	0.7	80
DESY/THD	2	0.5	8.5	12	9	0.5	40
VLEPP	20	0.75	0.1	2.0	25	1.3	300

The luminosity in this scheme only slightly depends on the beam energy. We see that restriction on the $L_{\gamma\gamma}$ occurs at a much higher level than in γe-collisions.

6.3 Screening effect in $\gamma\gamma$-collisions in presence of pair creation [11]

Above we considered $\gamma\gamma$-collisions in the case when probability of the coherent pair creation(p) is small. If some(~5%) pair creation at the i.p. takes place, new interesting phenomena take place. Pairs produced at the i.p. in the field of opposing deflected beam travel in this field and get some separation on the collision length σ_z. These separated pairs produce their own field in the region of the photon beam. In the cases when e^-e^- beams are deflected after conversion in the same direction or e^+e^-parent beams are deflected in opposite direction, these pairs decrease the field produced by deflected beams. Although by assumption, the number of pairs is smaller than that of deflected particles, they can produce a comparable field, because they are situated closer to the axis. It can happen that after production of some small amount of pairs, the process of pair creation is stoped.

This effect was considered roughly in ref.[11] The result is the following. The effect should take place (under certain conditions) at all considered colliders. At VLEPP the effect can help at beam energies $E_0 > 0.2$ TeV, and the maximum luminosity in this case become $L_{\gamma\gamma} \sim 3\cdot10^{35}\cdot E^2[\mathrm{TeV}], \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (in estimation $k=0.65$, $p=0.05$, $B_e=30$ kG were assumed). At NLC the effect may take place at $E>0.5$ TeV and the attainable luminosity is $L_{\gamma\gamma} \sim 2\cdot10^{34}\cdot E^2[\mathrm{TeV}], \mathrm{cm}^{-2}\mathrm{s}^{-1}$. It is remarkable that $L \propto E^2$! To obtain these luminosities electrons must be focused to a spot size less than $\sim 5/E_0$(TeV), nm in both directions.

6.4 *Resume on* $L_{\gamma\gamma}$ *(scheme B).*

There is only one collision effect in $\gamma\gamma$-collisions restricting the luminosity- coherent pair creation in the field of deflected electron beams used for conversion. If pair creation is kept on a negligible level, the attainable luminosity is restricted at a level of about $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (Table 5). Using screening effect in the case of "restricted"($p\sim0.05$) pair creation probability, it is possible, in principle, to get $L \propto E^2$ behavior of the luminosity at high energies. Then there are no real problems with collision effects in $\gamma\gamma$-collisions at all. The luminosity will be determined by the attainable emittances of electron beams or by other reasons(background, for example).

7. Backgrounds in $\gamma\gamma$-collisions.

One problem for $\gamma\gamma$, γe-colliders is the removal of used beams from the interaction region. How to do this was discussed in ref.[10] Besides this "machine" backgrounds, there is physical background- the reaction $\gamma\gamma \to$ hadrons itself. The cross section of this process is approximately 300 nb at $E \leq 15$ GeV and must grow slowly with the energy(like in $p\bar{p}$ collisions). Reaction products travel predominantly in the forward direction, as in hadron-hadron collisions. Due to high cross section many event of this reaction will take place in each beam collision. This problem has been known for a long time ago.

Recently M.Drees and R. Godbole[24] have predicted very large growth of the $\gamma\gamma$- cross section with energy due to minijets production via the subprocess gluon + gluon $\longrightarrow$ 2 jets (predominantly). According to their prediction at $\sqrt{s}$ =500 GeV $\sigma_{jets} \sim$ 2000 nb ! If it is so, then at $L_{\gamma\gamma}=10^{32}cm^{-2}s^{-1}$ per collision there will be ~ 200 events in each beam collision! Later, it was noticed that in this process the number of minijets per $\gamma\gamma$-collision may be greater than one, which should be taken into account properly. As a result, the increments in the cross section is likely not so large(see reports of P.Chen, M.Drees, J.Storrow and A.Levi on this conference). This correction does not make life simpler, because the "eikonalization" procedure doesn't change the total number of minijets per beam collision. It is important only when the number of reactions per beam collision is less than one. In our example ($L=10^{32}$), even at $\sigma \sim 500$ nb we have 50 events/collision. It is not clear how to work at such background. This question requires further study and MC-simulation.

For this reason, colliders with a higher rate of beam collisions(and with large enough distance between bunches) have obvious advantages.

8. Physics in γe,$\gamma\gamma$-collisions.

Below some examples of reactions in γe-and $\gamma\gamma$-collisions at high energy are given.

8.1 γe-collisions

8.1.1 $\gamma e \longrightarrow W\nu$. The cross section of this reaction[14-19] is

$$\sigma_{\gamma e \longrightarrow W\nu} = (1-2\lambda)\sigma^{np}$$

where λ-is the average helicity of electrons. By varying λ, one can switch this process on and off. At $s_{\gamma e} = 4\omega E_0 \gg M_W^2$ the cross section for unpolarized beams is σ^{np}=47 pb. This reaction is sensitive to the anomalous dipole magnetic moment and electric quadrupole moment of the W-boson.

8.1.2 $\gamma e \rightarrow Z^0 e$ -"single" Z^0 boson production[14-16]. Just above the threshold, the cross section has a maximum of 90 pb, then falls down by the law $\sigma \propto \ln(s)/s$. At $s \gg M_Z^2$

$$\sigma \sim 1.2/s_{\gamma e}[\mathrm{TeV}^2],\mathrm{pb}$$

The process is sensitive to anomalous Z^0-boson interactions. Both reactions (8.1.1),(8.1.2) can be used for the search for nonstandard W and Z bosons.

8.1.3 $\gamma e \rightarrow e^* \rightarrow e\gamma$-resonance production of excited electron[12,16]

8.1.4 $\gamma e \rightarrow \tilde{\gamma}\tilde{e} \rightarrow e\tilde{\gamma}\tilde{\gamma}$ - production of selectron and photino superpartners of electron and photon in supersymmetrical model[12].

8.2 $\gamma\gamma$ -collisions

8 2.1 $\gamma\gamma \longrightarrow$*hadrons*. See section 7.

8.2.2 $\gamma\gamma \rightarrow W^+W^-$[14-19]. At $s \gg M_W^2$ the cross section tends to σ=const=86 pb. The reaction enables one to investigate vertices γWW, $\gamma\gamma WW$ without the complicating effect of ZWW(in $e^+e^- \rightarrow W^+W^-$). The cross section is sensitive to the anomalous magnetic dipole moment and electric quadrupole moment of the W-boson.

8.2.3 $\gamma\gamma \rightarrow S^+S^-$-pair of charged scalars. At $s \gg M_S^2$

$$\sigma_{\gamma\gamma \rightarrow S^+S^-} \approx \frac{2\pi\alpha^2}{s} = 1.5\ \sigma_{e^+e^- \rightarrow \mu^+\mu^-} = \frac{0.12}{s[\mathrm{TeV}^2]}, \mathrm{pb}.$$

Note that $\sigma_{\gamma\gamma \rightarrow S^+S^-} = 6\ \sigma_{e^+e^- \rightarrow S^+S^-}$(only QED production).

8.2.4 $\gamma\gamma \longrightarrow L^+L^-$ (pair of leptons). At $s \gg M_L^2$

$$\sigma_{\gamma\gamma \rightarrow L^+L^-} = \frac{4\pi\alpha^2}{s}\ln\left(\frac{s}{4M_L^2}\right) \approx 3\ln\left(\frac{s}{4M_L^2}\right)\sigma_{e^+e^- \rightarrow L^+L^-}.$$

We see, that for standard electrodynamic processes $\gamma\gamma \rightarrow S^+S^-, L^+L^-$

$$\sigma_{\gamma\gamma}/\sigma_{e^+e^-} \sim 3-6$$

8.2.5 $\gamma\gamma \rightarrow H^0$ *(neutral Higgs boson)*[11,12,14-19]

The SM Higgs with $M_H < 80$ GeV will be found at LEP II. If $M_H > 2M_Z$, it will be discovered at LHC,SSC in the decay mode $H \rightarrow Z^0 Z^0 \rightarrow l^+ l^- l^+ l^-$. The region $80 < M_H < 2M_Z$ is of primary importance for linear colliders. Besides, Minimal SUSY predicts neutral Higgs in this region. But, even if Higgs is found, it is nevertheless of great interest to detect it in $\gamma\gamma$-interaction, because the cross section is determined by the virtual heavy particles. Considerations show that Higgs can be found in the range $M_H \sim 100$-150 GeV in the decay into a $b\bar{b}$-pair* and at $M_H \sim 180$-350 GeV in the decay to $Z^0 Z^0 (1Z^0 \rightarrow ee, \mu\mu)$ (J.Gunion, see for example ref.[12]). If the next heavy W' exists, then the cross section is much larger. For $M_{W'} = 600$ GeV and standard coupling, the number of Higgs events at $M_H = 500$ GeV increases[11] by a factor of 30 !

We see that $\gamma\gamma, \gamma e$ linear colliders of high energy provide unique opportunities for particle physics.

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* I.F.Ginzburg has noticed at the Workshop that beside $\gamma\gamma \rightarrow b\bar{b}$ QED background[12] there is another background reaction- $\gamma\gamma \rightarrow e^+ e^- Z$, which is important at $M_H \sim M_Z$.

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