High energy photon colliders.*

Valery Telnov,

_Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia_†

_and DESY, Germany_

Abstract

Using the laser backscattering method at future linear colliders one can obtain $\gamma \gamma$ and $\gamma e$ colliding beams (photon colliders) with energy and luminosity comparable to that in $e^+e^-$ collisions. This option has been included in the pre-conceptual designs of linear colliders and in work on a Technical Design Report which is in progress. The physics motivation for photon colliders is quite clear. The proof of its technical feasibility and the search for the best solutions is of first priority now. A key element of a photon collider is a laser with high peak power and repetition rate. One very promising way to overcome this problem is the optical cavity approach which is discussed in this paper. A very high $\gamma \gamma$ luminosity could be achieved by further decreasing the beam emittances. This will be very challenging. One possible way is laser cooling of electron beams. This method is discussed in my second talk at this symposium. The solution to the first problem is vital for photon colliders and provides an interesting physics program. Solution of the second problem makes photon colliders a very powerful instrument for study of matter, the best for study of many phenomena. How to achieve these goals is the subject of this talk.

1 Introduction.

Fantastic progress in laser technique makes it possible now to consider seriously many different applications of lasers in particle beam physics. I hope that our Symposium (perhaps the first of a series) on New Visions in Laser-Beam Interactions will be very useful for progress in this new branch of science.

In this talk I will report on developments in $\gamma \gamma, \gamma e$ colliders (shortly Photon Colliders) with energies of about $10^{12}$ eV. The key element of the Photon Collider is a powerful laser

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†email:telnov@inp.nsk.su
which is used for production of high energy photons using backward Compton scattering. Such colliders provide a new unique way for the study of matter, similar to $e^+e^-$ or pp colliders but even better for the study of some phenomena.

The history of the $\gamma\gamma$ physics and photon colliders is closely connected with the history of the $e^+e^-$ colliders. Since 1970 two-photon physics has been actively studied at $e^+e^-$ storage rings in collisions of virtual photons. The spectrum of these photons is $dn \sim 0.035d\omega/\omega$, so that $\gamma\gamma$ luminosity was much lower than that in $e^+e^-$ collisions. Nevertheless, these experiments have provided a lot of new information on the nature of elementary particles.

The maximum energy of $e^+e^-$ storage rings is limited by severe synchrotron radiation. To explore the energy region beyond LEP-II, linear $e^+e^-$ colliders (LC) in the range from a few hundred GeV to about 1.5 TeV are under intense study around the world. Three specific projects NLC (North American) [1], TESLA (European) [2] and JLC (Asian) [3] have published their pre-conceptual design reports and intend to submit full conceptual design reports in 2001-2002. One team at CERN is working on the concept of a multi-TeV linear collider (CLIC) [4] which will be able extend the energy range of LC in future.

Unlike the situation in storage rings, in linear colliders each beam is used only once. This make it possible to ”convert” electrons to high energy photons to obtain colliding $\gamma\gamma$, $\gamma e$ beams. Among various methods of $e \rightarrow \gamma$ conversion the best one is Compton scattering of the laser light on the high energy electrons. The basic scheme of a photon collider is shown in Fig. 1. Two electron beams after the final focus system are traveling toward the interaction point (IP) and at a distance of about 0.1-1 cm from the IP collide with the focused laser beams. After scattering, the photons have an energy close to that of the initial electrons and follow their direction to the interaction point (IP) (with some small additional angular spread of the order of $1/\gamma$), where they collide with a similar counter moving high energy beam or with an electron beam. With reasonable

![Figure 1: Scheme of $\gamma\gamma$, $\gamma e$ collider.](image)
laser parameters (several Joules flash energy) one can “convert” most of the electrons into high energy photons. The luminosity of $\gamma\gamma$, $\gamma e$ collisions will be of the same order of magnitude as the “geometric” luminosity of the basic $ee$ beams. Luminosity distributions in $\gamma\gamma$ collisions have the characteristic peaks near the maximum invariant masses with a typical width about 10% (and a few times smaller in $\gamma e$ collisions). High energy photons can have various polarizations, which is very advantageous for experiments. This idea was proposed by the author and colleagues many years ago and has been further developed and discussed in Refs. and many others papers.

The physics at high energy $\gamma\gamma$, $\gamma e$ colliders is very rich and no less interesting than with pp or $e^+e^-$ collisions (some examples will be given below). This option has been included in the pre-conceptual design reports of all LC projects, and work on the full conceptual design is under way.

In the present climate of tight HEP budgets we should give very clear answers to the following questions:

a) can $\gamma\gamma$, $\gamma e$ collisions give new physics information in addition to $e^+e^-$ collisions that could justify an additional collider cost (∼15%, second interaction region, including detector)?

b) is it technically feasible?

c) are there enough people for the design and construction of a photon collider and then exploiting its unique science?

Items a) and b) are discussed in the main part of this paper. As for the last question, the situation is the following. In the last two decades, the conception of photon colliders has been developed and discussed at many workshops. The bibliography on $\gamma\gamma$, $\gamma e$ physics now numbers over 1000 papers, mostly theoretical. The next phase will require much wider participation of the experimental community. Now the work on photon colliders is being continued within the framework of the Worldwide Study on Physics and Detectors at LC, also the International Collaboration on Photon Colliders has recently been initiated.

2 Physics

In general, the physics at $e^+e^-$ and $\gamma\gamma$, $\gamma e$ colliders is quite similar because the same new particles can be produced. However, the events are complimentary, because the cross sections depend differently on the parameters of the theories.

If something new is discovered (Higgs, supersymmetry or ... quantum gravity with extra dimensions), the nature of these new phenomena will be better understood if they are be studied in different reactions. Some phenomena can best be studied at photon colliders. Below I will give several examples.

The second aspect, important for physics study, is the luminosity attained by the collider. In the next section it will be shown that in the current LC designs the $\gamma\gamma$ luminosity in the high energy peak of the luminosity spectrum is about 20% of the $e^+e^-$
luminosity. However, if beams with smaller emittances are used, the $\gamma\gamma$ luminosity can be higher than that of $e^+e^-$ collisions. That is because in $e^+e^-$ collisions the luminosity is restricted by the collision effects (beamstrahlung, instabilities) which are absent in $\gamma\gamma$ collisions.

**Higgs boson**

The present "Standard" model, which describes precisely almost everything at present energies, assumes existence of a very unique particle, the Higgs boson, which is thought to be responsible for the origin of particle masses. It is not found yet, but from existing experimental information it follows that, if it exists, its mass is about 100–200 GeV, i.e. lays in the region of the next linear colliders.

In $\gamma\gamma$ collisions the Higgs boson will be produced as a single resonance. This process goes via the loop and its cross section is very sensitive to all heavy (even super-heavy) charged particles. The effective cross section is presented in Fig. 2 [18]. Note that here

![Cross sections for the Standard model Higgs in $\gamma\gamma$ and $e^+e^-$ collisions.](image)

Figure 2: Cross sections for the Standard model Higgs in $\gamma\gamma$ and $e^+e^-$ collisions.

$L_{\gamma\gamma}$ is defined as the $\gamma\gamma$ luminosity at the high energy luminosity peak ($z = W_{\gamma\gamma}/2E_e > 0.65$ for $x = 4.8$) with FWHM about 15%. For comparison, the cross sections of the Higgs production in $e^+e^-$ collisions are shown. We see that for $M_H = 120–250$ GeV the effective cross section in $\gamma\gamma$ collisions is larger than that in $e^+e^-$ collisions by a factor of about 6–30. If the Higgs is light enough, its width is much less than the energy spread in $\gamma\gamma$ collisions. It can be detected as a peak in the invariant mass distribution or can be searched for by energy scanning using the very sharp ($\sim 1\%$) high energy edge of luminosity distribution [18]. The total number of events in the main decay channels $H \rightarrow b\bar{b}, WW(W^*)$, $ZZ(Z^*)$ will be several thousands for a typical integrated luminosity of 10 fb$^{-1}$. The scanning method also enables the measurement of the Higgs mass with a high precision.
What is most remarkable in this process? The cross section of the process $\gamma\gamma \rightarrow H \rightarrow b\bar{b}$ is proportional to $\Gamma_{\gamma\gamma}(H) \times Br(H \rightarrow b\bar{b})$. The branching ratio $Br(H \rightarrow b\bar{b})$ can be measured with high precision in $e^+e^-$ collisions in the process with the "tagged" Higgs production: $e^+e^- \rightarrow ZH$ \cite{23}. As a result, one can measure the $\Gamma_{\gamma\gamma}(H)$ width at photon colliders with an accuracy better than 2-3\% \cite{24},\cite{25}. On the other hand, the value of this two-photon decay width is determined by the sum of contributions to the loop of all heavy charge particles with masses up to infinity. So, it is a unique way to "see" particles which cannot be produced at the accelerators directly (maybe never).

The measurement of the Higgs two-photon width reminds me of the experiment on the measurement of the number of neutrino generations at LEP. This experiment showned that there are only three light neutrinos, all of them were known already. But there could be more. That would be a great discovery! Measurement of the Higgs two-photon width is also some kind of counting of unknown particles. The Higgs two-gluon decay width is also sensitive to heavy particles in the loop, but only to those which have strong interactions (like quarks). These two measurements together with the $\Gamma_{Z\gamma}(H)$ width, which could be measured in $\gamma e$ collisions, will allow us to "observe" and perhaps understand the nature of invisible heavy charged particles. This would be a great step forward.

Charge pair production

The second example is the charged pair production. It could be $W^+W^-$ or $t\bar{t}$ pairs or some new, for instance, supersymmetric particles. Cross sections for the production of charged scalar, lepton, and top pairs in $\gamma\gamma$ collisions are larger than those in $e^+e^-$ collisions by a factor of approximately 5–10; for WW production this factor is even larger, about 10–20. The corresponding graphs can be found elsewhere \cite{14},\cite{2}.

The cross section of the scalar pair production, predicted in some theories, in collision of polarized photons near the threshold, is higher than that in $e^+e^-$ collisions by a factor of approximately 10–20(see figs in Refs \cite{20},\cite{21}). The cross section in the $\gamma\gamma$ collisions near the threshold is very sharp (while in $e^+e^-$ it contains a factor $\beta^3$) and can be used for measurement of particle masses.

Note, that in $e^+e^-$ collision two charged pairs are produced both via annihilation diagram with virtual $\gamma$ and $Z$ and also via exchange diagrams where new particles can contribute, while in $\gamma\gamma$ collisions it is pure QED process which allows the charge of produced particles to be measured unambiguously. This is a good example of complementarity in the study of the same particles in different types of collisions.

Accessible masses

In $\gamma e$ collisions, charged particle with a mass higher than that in $e^+e^-$ collisions can be produced (a heavy charged particle plus a light neutral), for example, supersymmetric charged particle plus neutralino or new $W$ boson and neutrino. $\gamma\gamma$ collisions also provide higher accessible masses for particles which are produced as a single resonance in $\gamma\gamma$ collisions (such as the Higgs boson).
Quantum gravity effects in Extra Dimensions

This new theory \cite{26} suggests a possible explanation of why gravitation forces are so weak in comparison with electroweak forces. According to this theory the gravitational forces are as strong as electroweak forces at small distances in space with extra dimensions and became weak at large distances due to “compactification” of these extra dimensions. It turns out that this extravagant theory can be tested at linear colliders and according to T.Rizzo \cite{27} (\(\gamma\gamma \rightarrow WW\)) and K.Cheung \cite{28} (\(\gamma\gamma \rightarrow \gamma\gamma\)) photon colliders are sensitive up to a factor of 2 higher quantum gravity mass scale than e\(^+\)e\(^-\) collisions.

Concluding remark. We have seen that the Higgs and charged pair cross sections in \(\gamma\gamma\) collisions are higher that those in e\(^+\)e\(^-\)collisions at least by a factor of 5, so, even with 5 times lower \(\gamma\gamma\) luminosity (as it is approximately in current designs) the number of events in e\(^+\)e\(^-\) and \(\gamma\gamma\) collisions will be comparable (but physics complementary). However, the possibility of much larger \(\gamma\gamma\) luminosity is not excluded, see below.

3 Lasers, optics

The new key element at photon colliders is a powerful laser system which is used for e\(\rightarrow\)\(\gamma\) conversion. Lasers with the required flash energies (several Joules) and pulse duration \(\sim 1\) ps already exist and are used at several laboratories, the main problem here is the high repetition rate, about 10–15 kHz. One very promising way to overcome this problem is discussed in this paper. It is an optical cavity approach, which allows a considerable reduction of the required peak and average laser power.

3.1 Requirements for the laser, wave length, flash energy

The processes in the conversions region: Compton scattering and several other important phenomena have been considered in detail in papers \cite{6},\cite{9},\cite{11},\cite{14},\cite{19} and references therein. There you can find formulae, figures and explanation of various phenomena in the conversion region as well as requirements for lasers for photon colliders.

Laser parameters important for this task are: laser flash energy, duration of laser pulse, wave length and repetition rate. The required wave length follows from the kinematics of Compton scattering \cite{4}. In the conversion region a laser photon with the energy \(\omega_0\) scatters at a small collision angle \(\alpha_0\) on a high energy electron with the energy \(E_0\). The maximum energy of scattered photons (in direction of electrons)

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

For example: \(E_0 = 250\) GeV, \(\omega_0 = 1.17\) eV \((\lambda = 1.06\ \mu\text{m})\) (Nd:Glass laser) \(\Rightarrow x = 4.5\) and \(\omega/E_0 = 0.82\). The energy of the backscattered photons grows with increasing \(x\). However, at \(x > 4.8\) the high energy photons are lost due to e\(^+\)e\(^-\) creation in the collisions with laser photons \cite{11},\cite{4}. The maximum conversion coefficient (effective)
at $x \sim 10$ is about 0.33 while at $x < 4.8$ it is about 0.65 (one conversion length). The luminosity in the first case will be smaller by a factor of 4. Detailed study of dependence of the maximum $\gamma\gamma$ luminosity and monochromaticity on $x$ can be found elsewhere \[1\].

In the laser focus at photon colliders the field is so strong that multi-photon processes can take place, for example, the electron can scatter simultaneously on several laser photons. It is preferable to work in a regime where these effects are small enough, because the shape of the photon spectrum in this case is sharper. Sometimes strong fields can be useful. Due to transverse motion of electrons in the laser wave the effective electron mass is increased and the threshold of $e^+e^-$ production is shifted to the higher beam energies, a factor of 1.5–2 is possible without special problems “simply” by adding a laser power. For some tasks, such as the energy scanning of the low mass Higgs, the luminosity spectrum should be very sharp, that is only possible when multi-photon effects are small.

From all this it follows that an existing powerful Terawatt solid state laser with the wavelength about 1 $\mu$m can be used for photon colliders up to c.m.s. energies about 1 TeV. For low energy colliders (for study of the low mass Higgs, for instance), the doubling of the laser frequency may be useful, this can be done with high efficiency.

In the calculation of the required flash energy one has to take into account the natural “diffraction” emittance of the laser beam \[6\], the maximum allowed value of the field strength (characterized by the parameter $\xi^2 = e^2 B^2 \lambda^2 / m^2 c^4$) \[1\], \[14\] and the laser spot size at the conversion point which should be larger than that of the electron beam. In the collision scheme with the “crab-crossing” \[30\] the electron beam is tilted in respect to the direction of motion that creates an additional effective transverse beam size $\sigma_x = \sigma_z \alpha_c / 2$.

The result of MC simulation of $k^2$ ($k$ is the conversion coefficient, $k^2$ is proportional to the $\gamma\gamma$ luminosity) for the electron bunch length $\sigma_z = 0.3$ mm (TESLA project) as a function of the flash energy and parameter $\xi^2$ (in the center of the laser bunch) are shown in figs. 3 and 4.

In summary: the required laser flash energy is about 3–5 Joules, which is quite reasonable. However, the LC have a repetition rate of about 10–15 kHz, so the average power of the laser system should be about 50 kW. One possible solution is the multi-laser system which combines pulses into one train using Pockels cells \[1\]. However, such a system will be very expensive \[29\].

### 3.2 Multi-pass laser systems

To overcome the “repetition rate” problem it is quite natural to consider a laser system where one laser bunch is used for $e^+e^-$ conversion many times. Indeed, one Joule laser flash contains about $10^{19}$ laser photons and only $10^{10} - 10^{11}$ photons are knocked out in

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1The crab crossing scheme for beam collisions \[30\] is obligatory in photon colliders for the removal of disrupted beams \[11\]. In this scheme the electron bunches are collided with crossing angle $\alpha_c$. To preserve the luminosity the electron bunches are tilted (using an RF cavity) with respect to the direction of the beam motion on the angle $\alpha_c / 2$. The required $\alpha_c$ for the projects considered is about 30 mrad \[2\].
the collision with one electron bunch.

The simplest solution is to trap the laser pulse to some optical loop and use it many times. In such a system the laser pulse enters via the film polarizer and then is trapped using Pockels cells and polarization rotating plates. Unfortunately, such a system will not work with Terawatt laser pulses due to a self-focusing effect.

Fortunately, there is one way to “create” a powerful laser pulse in the optical “trap” without any material inside. This very promising technique is discussed below.

3.3 Laser pulse stacking in an “external” optical cavity.

Shortly, the method is the following. Using the train of low energy laser pulses one can create in the external passive cavity (with one mirror having some small transparency) an optical pulse of the same duration but with much higher energy (pulse stacking). This pulse circulates many times in the cavity each time colliding with electron bunches passing the center of the cavity.

The idea of pulse stacking is simple but not trivial and not well known in the HEP community (and even to laser experts, though it is as old as the Fabry-Perot interferometer). This method is used now in several experiments on detection of gravitation waves. It was mentioned also in NLC ZDR though without analysis and further development. In my opinion, pulse stacking is very natural for photon colliders and allows not only to build a relatively cheap laser system for $e \to \gamma$ conversion but gives us the practical way for realization of the laser cooling, i.e. opens up the way to ultimate luminosities of photon colliders.
As this is very important for photon colliders, let me consider this method in more detail \cite{21}. The principle of pulse stacking is shown in Fig.5. The secret consists in

\begin{figure}
\centering
\includegraphics[width=0.6\textwidth]{fig5.png}
\caption{Principle of pulse stacking in an external optical cavity.}
\end{figure}

the following. There is a well known optical theorem: at any surface, the reflection coefficients for light coming from one and the other sides have opposite signs. In our case, this means that light from the laser entering through semi-transparent mirror into the cavity interferes with reflected light inside the cavity \textbf{constructively}, while the light leaking from the cavity interferes with the reflected laser light \textbf{destructively}. Namely, this fact produces asymmetry between cavity and space outside the cavity!

Let $R$ be the reflection coefficient, $T$ the transparency coefficient and $\delta$ the passive losses in the right mirror. From the energy conservation $R + T + \delta = 1$. Let $E_1$ and $E_0$ be the amplitudes of the laser field and the field inside the cavity. In equilibrium, $E_0 = E_{0,R} + E_{1,T}$. Taking into account that $E_{0,R} = E_0\sqrt{R}$, $E_{1,T} = E_1\sqrt{T}$ and $\sqrt{R} \sim 1 - T/2 - \delta/2$ for $R \approx 1$ we obtain $E_0^2/E_1^2 = 4T/(T + \delta)^2$. The maximum ratio of intensities is obtained at $T = \delta$, then $I_0/I_1 = 1/\delta \approx Q$, where $Q$ is the quality factor of the optical cavity. Even with two metal mirrors inside the cavity, one can hope to get a gain factor of about 50–100; with multi-layer mirrors it can reach $10^5$. ILC(TESLA) colliders have 120(2800) electron bunches in the train, so the factor 100(1000) would be perfect for our goal, but even the factor of ten means a drastic reduction of the cost.

Obtaining of high gains requires a very good stabilization of cavity size: $\delta L \sim \lambda/4\pi Q$, laser wave length: $\delta\lambda/\lambda \sim \lambda/4\pi QL$ and distance between the laser and the cavity: $\delta s \sim \lambda/4\pi$. Otherwise, the condition of constructive interference will not be fulfilled. Besides, the frequency spectrum of the laser should coincide with the cavity modes, that is automatically fulfilled when the ratio of the cavity length and that of the laser oscillator is equal to an integer number 1, 2, 3...

For $\lambda = 1\ \mu m$ and $Q = 100$, the stability of the cavity length should be about $10^{-7}$ cm. In the LIGO experiment on detection of gravitational waves which uses similar techniques with $L \sim 4$ km and $Q \sim 10^5$ the expected sensitivity is about $10^{-16}$ cm. In comparison with this project our goal seems to be very realistic.
In HEP literature I have found only one reference on pulse stacking of short pulses ($\sim 1$ ps) generated by FEL \cite{31} with the wave length of 5 $\mu$m. They observed pulses in the cavity with 70 times the energy of the incident FEL pulses, though no long term stabilization was done.

Possible layout of the optics at the interaction region scheme is shown in Fig.6. In this variant, there are two optical cavities (one for each colliding electron beam) placed outside the electron beams. Another possible variant has only one cavity common for both electron beams. In this case, it is also possible to arrange two conversion points separated by the distance of several millimeters (as it is required for photon colliders), though the distribution of the field in the cavity is not completely stable in this case (though it may be sufficient for not too large a $Q$ and, it can be made stable in more complicated optical system). Also, mirrors should have holes for electron beams (which does not change the $Q$ factor of the cavity too much). The variant presented in fig.6 is simpler though it requires a factor of 2 higher flash energy.

![Figure 6: Possible scheme of optics at the IR.](image)

4 Luminosity of photon colliders in current designs.

Some results of simulation of $\gamma\gamma$ collisions at TESLA, ILC (converged NLC and JLC) and CLIC are presented below in Table 1. Beam parameters were taken the same as those in $e^+e^-$ collisions with the exception of the horizontal beta function at the IP which is taken (quite conservatively) equal to 2 mm for all cases, that is several times smaller than that in $e^+e^-$ collisions due to the absence of beamstrahlung. The conversion point (CP) is situated at distance $b = \gamma \sigma_y$. It is assumed that electron beams have 85% longitudinal polarization and laser photons have 100% circular polarization.

We see that the $\gamma\gamma$ luminosity in the hard part of the spectrum $L_{\gamma\gamma}(z > 0.65) \sim$
Table 1: Parameters of $\gamma\gamma$ colliders based on TESLA, ILC (NLC/JLC)

|                        | T(500) | I(500) | T(800) | I(1000) |
|------------------------|--------|--------|--------|---------|
| no deflection, $b = \gamma \sigma_y$, $x = 4.6$ |
| $N/10^{10}$           | 2.00   | 0.95   | 1.40   | 0.95    |
| $\sigma_z, \text{mm}$ | 0.40   | 0.12   | 0.30   | 0.12    |
| $f_{rep}, \text{Hz}$  | 5.00   | 120    | 3.00   | 120     |
| $n_b$/train           | 2820   | 95.00  | 4500   | 95.00   |
| $f_{rep} \times n_b, \text{kHz}$ | 14.11 | 11.40  | 13.50  | 11.40   |
| $\Delta t_b, \text{ns}$ | 337.00| 2.80   | 189.00 | 2.80    |
| $\gamma \epsilon_{x,y}/10^{-6}, \text{m-rad}$ | 10.00/0.03 | 5.00/0.1 | 8.00/0.01 | 5.00/0.1 |
| $\beta_{x,y}, \text{mm at IP}$ | 2.00/0.40 | 2.00/0.12 | 2.00/0.30 | 2.00/0.16 |
| $\sigma_{x,y}, \text{mm}$ | 200.00/5.00 | 140.00/5.00 | 140.00/2.00 | 100.00/4.00 |
| $b, \text{mm}$        | 2.40   | 2.40   | 1.50   | 4.00    |
| $L(\text{geom}), 10^{33}$ | 48.00 | 12.00  | 75.00  | 20.00   |
| $L_{\gamma\gamma}(z > 0.65), 10^{33}$ | 4.50 | 1.10 | 7.20 | 1.75 |
| $L_{\gamma\epsilon}(z > 0.65), 10^{33}$ | 6.60 | 2.60 | 8.00 | 4.20 |
| $L_{ee}, 10^{33}$     | 1.20   | 1.20   | 1.10   | 1.80    |
| $\theta_x/\theta_{y,\text{max}}, \text{mrad}$ | 5.80/6.50 | 6.50/6.90 | 4.60/5.00 | 4.60/5.30 |

0.1$L(\text{geom})$, numerically it is about $(1/6)L_{e^+e^-}$. Note, that the coefficient 1/6 is not a fundamental constant. The $\gamma\gamma$ luminosity in these projects is determined only by “geometric” ee-luminosity. With some new low emittance electron sources or with laser cooling of electron beams after the damping ring (or photo-guns) one can get, in principle, $L_{\gamma\gamma}(z > 0.65) > L_{e^+e^-}$. The limitations and technical feasibility are discussed in the next section. In addition to the $\gamma\gamma$ collisions, there is considerable $\gamma e$ luminosity (see table) and it is possible to study $\gamma e$ interactions simultaneously with $\gamma\gamma$ collisions.

The normalized $\gamma\gamma$ luminosity spectra for a 0.5 TeV TESLA are shown in Fig.[left]. The luminosity spectrum is decomposed into two parts, with the total helicity of two photons 0 and 2. We see that in the high energy part of the luminosity spectra photons have a high degree of polarization, which is very important for many experiments. In addition to the high energy peak, there is a factor 5–8 larger low energy luminosity. It is produced by photons after multiple Compton scattering and beamstrahlung photons. Fortunately, these events have a large boost and can be easily distinguished from the central high energy events. In the same Fig.[left] you can see the same spectrum with an additional “soft” cut on the longitudinal momentum of the produced system which

\[2^{\text{this is because a) }} L_{e^+e^-} \sim 1.5 L(\text{geom}), \text{ factor 1.5 (roughly) is due to the pinch effect: b) }} L(\text{geom}) \text{ in the case of photon colliders is larger than that in e}^+\text{e}^- \text{ collisions by a factor about 2.5 (in the current projects) due to the smaller } \beta-\text{function} \]
Figure 7: $\gamma\gamma$ luminosity spectra at TESLA(500) for parameters presented in Table 1. Solid line for total helicity of two photons 0 and dotted line for total helicity 2. Upper curves without cuts, two lower pairs of curves have cut on the relative difference of the photon energy. See comments in the text.

suppresses low energy luminosity to a negligible level.

Fig. 7 (right) shows the same spectrum with a stronger cut on the longitudinal momentum. In this case, the spectrum has a nice peak with FWHM about 7.5%. On first sight such cut is somewhat artificial because one can directly select events with high invariant masses and the minimum width of the invariant mass distribution depends only on the detector resolution. However, there is a very important example when one can obtain a “collider resolution” somewhat better than the “detector resolution”; this is the case of only two jets in the event when one can restrict the longitudinal momentum of the produced system using the acollinearity angle between jets ($H \rightarrow b\bar{b}, \tau\tau$, for example).

A similar table and distributions for the photon collider on the c.m.s. energy 130 GeV (Higgs collider) can be found in ref. [20].

5 Ultimate $\gamma\gamma$, $\gamma e$ luminosities

There is only one collision effect restricting the $\gamma\gamma$ luminosity, that is a process of coherent pair creation when the high energy photon is converted into an $e^+e^-$ pair in the strong field of the opposing electron beam [10], [11], [14]. It becomes more important at larger collider energies or(and) very short bunches. Detailed analysis of ultimate luminosities at photon colliders was done in the ref. [17].

In the current projects the $\gamma\gamma$ luminosities are determined by the “geometric” luminosity of the electron beams. Having electron beams with smaller emittances one
can obtain a much higher $\gamma\gamma$ luminosity\textsuperscript{[17]}. Below are results of the simulation with the code which takes into account all main processes in beam-beam interactions\textsuperscript{[14]}. Fig. 8 shows dependence of the $\gamma\gamma$ (solid curves) and $\gamma e$ (dashed curves) luminosities on the horizontal beam size. The vertical emittance is taken as in TESLA(500), ILC(500) projects (see Table 1). The horizontal beam size was varied by change of horizontal beam emittance keeping the horizontal beta function at the IP constant and equal to 2 mm.

One can see that all curves for $\gamma\gamma$ luminosity follow their natural behavior: $L \propto 1/\sigma_x$; with the exception of ILC at $2E_0 = 1$ GeV where at small $\sigma_x$ the effect of coherent pair creation is seen\textsuperscript{[10]}. This means that at the same collider the $\gamma\gamma$ luminosity can be increased by decreasing the horizontal beam size (see table 1) at least by one order ($\sigma_x < 10$ nm is difficult due to some effects connected with the crab crossing).

Additional increase of $\gamma\gamma$ luminosity by a factor about 3 (TESLA), 7 (ILC) can be obtained by a further decrease of the vertical emittance\textsuperscript{[20]}. So, using beams with smaller emittances, the $\gamma\gamma$ luminosity at TESLA, ILC can be increase by almost 2 orders of magnitude. However, even with one order improvement, the number of “interesting” events (the Higgs, charged pairs) at photon colliders will be larger than that in e$^+$e$^-$ collisions by about one order. This is a nice goal and motivation for photon colliders.

In $\gamma e$ collision (Fig. 8, dashed curves), the behavior of the luminosity on $\sigma_x$ is different due to additional collision effects: beams repulsion and beamstrahlung. As a result, the luminosity in the high energy peak is not proportional to the “geometric” luminosity.\textsuperscript{3}

\textsuperscript{3}This curve has also some "bend" at large $\sigma_x$ that is connected with synchrotron radiation in quads (Oide effect) due to a large horizontal emittance. One can avoid this effect by taking larger $\beta_x$ and smaller $\epsilon_{nx}$.  

Figure 8: Dependence of $\gamma\gamma$ and $\gamma e$ luminosities in the high energy peak on the horizontal beam size for TESLA and ILC at various energies. See also comments in the text.
There are several ways of decreasing the transverse beam emittances (their product): optimization of storage rings with long wigglers, development of low-emittance RF (or pulsed photo-guns) with merging many beams with low charge and emittance. Here some progress is certainly possible. Moreover, there is one method which allows further decrease of beam cross sections by two orders of magnitude in comparison with current designs, it is a laser cooling [16],[19]. This method is discussed in my second talk at this Symposium.

Other important aspects for photon colliders are removal of disrupted beams and backgrounds. Discussion of these problems can be found elsewhere [11], [2], [22].

6 Conclusion

The physics program for photon $\gamma\gamma,\gamma e$ colliders is very interesting and the additional cost of the second interaction region is certainly justified.

There are no show-stoppers. All processes in the conversion and interaction regions and the limitations of attainable luminosity are well understood. There are ideas on laser and optical scheme designs. However, much remains to be done in terms of detailed studies and experimental tests.

Special effort is required for the development of the laser and optics which are the key elements of photon colliders. The present laser technology has, in principle, all elements needed for photon colliders, the development of a practical scheme is the most pressing task now. One of the most promising methods is the optical cavity approach which allows a considerable reduction of the required peak and average laser power. A reduction of one order of magnitude is already sufficient, but for the TESLA collider with a large number of bunches in a train and large spacing between the bunches one can think about 2–3 orders, though this may be difficult due to other reasons.

The $\gamma\gamma$ luminosity at photon colliders with energy below one TeV can be higher than that in $e^+e^-$ collisions, typical cross sections are also several times higher, so one could consider an X-factory ($X = \text{Higgs}, W, \text{etc.}$). The main problem here is the generation of polarized electron beams with very small emittances (products of transverse emittances). Optimization of damping rings and development of low emittance multi-gun RF sources is the first step in this direction. The second step requires new technologies. The laser cooling of electron beams is one possible way of achieving ultimate $\gamma\gamma$ luminosity. Realization of this method depends on the progress of Laser Technology, especially promising is the method of the storage (stacking) of laser pulses in an optical cavity.

Dear participants of the Symposium on New Vision in Laser Beam Interactions, and all laser experts, there is a possibility to build a unique instruments for study of the matter in the next decade: The High Energy Photon Collider. The development of the required laser systems is a very challenging task, we need your knowledge, experience and talent, join us in this exciting undertaking!
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