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PHOTON COLLIDERS: KEY PROBLEMS, NEW IDEAS

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Photon colliders: key problems, new ideas [1]

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Abstract

High energy photon colliders based on laser backscattering are a very natural extension of a e^+e^- linear colliders and open new possibilities to study of the matter. This option has been included in the pre-conceptual designs of linear colliders and work on Technical Design Reports is in progress. The physics motivation for photon colliders is quite clear though more studies are needed. The proof of its technical feasibility and the search for the best solutions is of first priority now. In this talk we discuss: physics motivation, laser problems and new possible solutions, and generation of low emittance beams needed for obtaining very high luminosities.

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1 Introduction

Linear colliders (LC) in the range of a few hundred GeV to several TeV are under intense study in the world [1]-[3]. In addition to e^+e^- collisions, linear colliders provide a unique possibility to study $\gamma\gamma$ and γe interactions at energies and luminosities comparable to those in e^+e^- collisions [4]-[6]. High energy photons can be produced using laser backscattering. This option has been included in the conceptual designs of the linear collider projects and the next goals are the Technical Design Reports which should be prepared within the next 1–2 years.

In this short time period we should clearly show that $\gamma\gamma$,γe collisions can give new physics information in addition to e^+e^- collisions and that all technical problems of photon colliders have solutions. A key element in the project is a powerful laser system. Solution of this problem is vital for photon colliders. From the accelerator side polarized electron beams with very low emittances are required, smaller than those necessary for e^+e^- collisions (especially in the horizontal direction). At the beginning one can use the same electron beams as for e^+e^-, which is already acceptable for study of a good physics, but the luminosity in this case will be much lower than its real limit determined by collisions effects. In addition, there are many other technical aspects which should be developed and taken into account in the basic LC designs (before beginning of the construction).

In this paper we will briefly consider physics motivation, new ideas on laser schemes, ways to high luminosities and associated problems.

2 Physics

Physic motivation of photon colliders is quite clear. In general, the physics in $\gamma\gamma$,γe collisions is complimentary to that in e^{+}e^{-} interactions. Some phenomena can best be studied at photon colliders. Several examples are given below.

The present "Standard" model predicts a very unique particle, the *Higgs boson.* It is very likely that 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 graphs for effective cross section of the Higgs production in $\gamma\gamma$ collisions and in e^{+}e^{-} collisions can be found elsewhere [7]. For $M_H = 120$–250 GeV the effective cross section $\gamma\gamma$ in collisions is larger than that in e^{+}e^{-} collisions by a factor of about 6–30. The Higgs can be detected as a peak in the invariant mass distribution or can be searched for by energy scanning using the very sharp high energy edge of luminosity distribution [7].

The cross section of the process $\gamma\gamma \to H \to b\bar{b}$ is proportional to $\Gamma_{\gamma\gamma}(H) \times Br(H \to b\bar{b})$. The branching ratio $Br(H \to b\bar{b})$ can be measured with high precision in e^{+}e^{-} collisions [8]. As a result, one can measure the $\Gamma_{\gamma\gamma}(H)$ width at photon colliders with an accuracy better than 2-3% [9],[10]. The value of the 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 Higgs two-gluon decay width (which can be extracted from joint LHC, LC data) is also sensitive to heavy particles in the loop, but only to those which have strong interactions. These two measurements together with the $\Gamma_{Z\gamma}(H)$ width, which could be measured in γe collisions, will allow us to "observe" and perhaps understand the nature of invisible heavy charged particles. This would be a great step forward in our understanding of the matter.

The second example is the *charged pair production.* Cross sections for the production of charged pairs in $\gamma\gamma$ collisions are larger than those in e^{+}e^{-} collisions by a factor of approximately 5–10 [11],[2]. The cross section of the scalar pair production in collisions of polarized photons near the threshold, is higher than that in e^{+}e^{-} collisions by a factor of 10–20 (see figures in Refs. [12],[13]). Near the threshold the cross section in the $\gamma\gamma$ collisions is very sharp (while in e^{+}e^{-} it contains a factor β^3) and can be used for measurement of particle masses. Note, that in e^{+}e^{-} collisions two charged pairs are produced both via annihilation diagrams with virtual γ 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 spin and charge of produced particles to be measured unambiguously.

In γe collisions, charged particles 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).

A new theory "Quantum gravity effects in Extra Dimensions" proposed recently [14] suggests a possible explanation of the fact why gravitation forces are so weak in comparison with electroweak forces. It turns out that this extravagant theory can be tested at linear colliders, moreover, photon colliders are sensitive up to a factor of 2 higher quantum gravity mass scale than e^+e^- collisions [15].

3 Lasers, Optics

The new key element at photon colliders is a powerful laser system which is used for $e \to \gamma$ conversion. The laser system should have the following parameters: flash energy of 2-5 J with "diffraction" quality, wave length about 1 μm (for 2E = 500 GeV), pulse duration about 1 ps, repetition rate 10–15 kHz with the same pulse structure as for electron beams. Detailed consideration of requirements to lasers can be found elsewhere [16],[11],[17], [2],[13],[18],[22].

Picosecond Terawatt laser pulses can be produced using the chirped pulse technique which allowed a peak laser power to be increased by three order of magnitude during the last decade. The main problem at photon colliders is the high repetition rate and correspondingly very high average power, about 50 kW. An additional complication is due to the train structure of pulses at LC which means even larger average power inside the train. 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 One-pass Laser Systems

Let me start with a discussion of a one pass laser system. One possible solution is the multi-laser system where pulses are combined into one train using Pockels cells [1]. Several (about 20 in the NLC Zero Design Project) lasers allow spliting the average power between lasers and thus solving the problem with cooling of the amplifying medium. It is clear that these lasers should use crystals with high thermal conductivity, diode (semiconductor lasers) pumping with very high efficiency, adaptive optics. These topics were discussed at this workshop in a nice talk given by M. Perry. He pointed out two main problems for NLC laser system (these problems are not essential for TESLA):

1. Due to the short distance between electron bunches (2.8 ns between bunches, with 95 bunches in the train), the power of the diode pumping system should be very high, about 2 J/2.8 ns/efficiency, that is huge. The estimated cost of the diode system is about 100 M$.

2. Combining Pockels cells should be very fast (switching time is less than 3 ns) which is very difficult (or even impossible) for the considered powers.

In my opinion, the situation here is not so bad and there are ways to overcome these problems. First, the storage time of most promissing crystals such as Yb:S-FAP is about 1 msec, so I do not understand why diodes should work only during 270 ns (length of the pulse train). The ratio of these times is 3700! These crystals can be pumped before the pulse train during more than 2 orders longer time! What is wrong? Discharge by spontaneous radiation can be suppresed by proper choice of geometry or (and) use of optical locks. Pulse energies in several sequential pulses passing one amplifier can be equalized by adjusting the pulse energies of incoming pulses. If all these is correct, one can decrease the pumping power at least by 2 orders of magnitude and there will be no problem.

The second problem also has a solution, see Fig. 1. Using Pockels cells we can prepare two trains of laser pulses with somewhat different average frequences ($\Delta\nu \sim$ bandwidth) and then join them using a chromatic combiner. Each of the trains is prepared in the following way.[3] At the beginning (before the final amplifiers) we manipulate with low energy pulses and prepare 10 short subtrains consisting of 5 pulses spaced by 2.8 ns. At this stage, power is low and there is no problem with Pockels cells. Then these subtrains are amplifiered and combined using Pockels cells into one train with the distance between subtrains equal to the length of one subtrain which is equal 6×2.8

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[3] The technique of combining pulses in the train using Pockels cells and thin-film-polarizers is explained elsewhere [1].

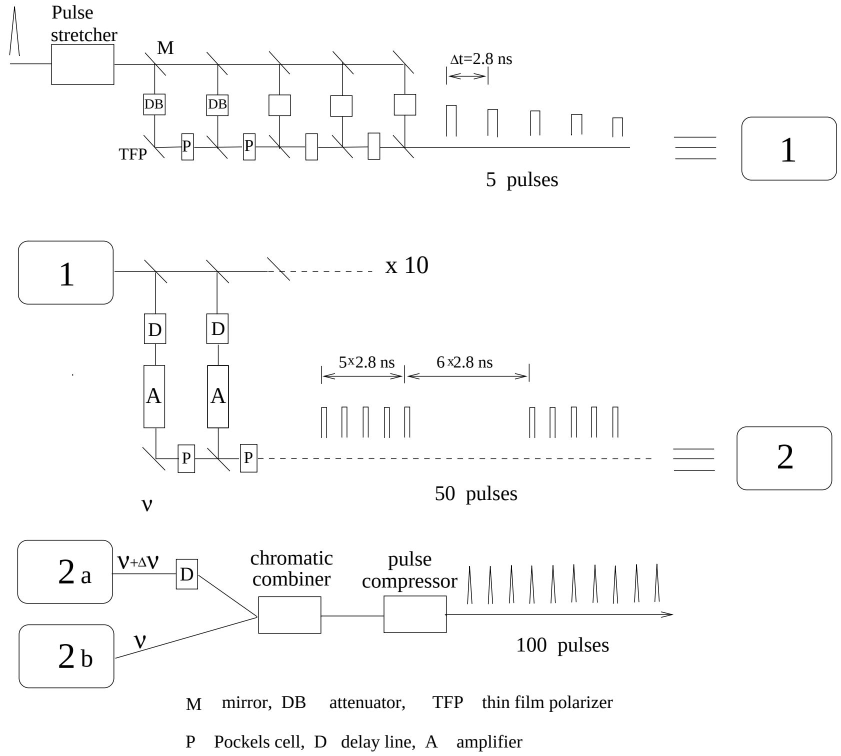

Figure 1: Possible laser scheme for one-pass mode of operation at NLC/JLC

ns. Here we can use already rather slow Pockels cells with larger diameter, so that the power/cm^2 can be much lower than that for 2.8 ns Pockels cells.

So, it seems, both problems have solutions. Of course, a final answer should be given by laser experts.

3.2 Multi-pass Laser Systems

To overcome the “repetition rate” problem in a radical way it is quite natural to consider a laser system where one laser bunch is used for e$\to\gamma$ 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 the collision with one electron bunch.

The simplest solution is to trap the laser pulse to some optical loop and use it many times [1]. 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.

However, 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. 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. This method is used now in several experiments on detection of gravitation waves. It was mentioned also in NLC ZDR [1], though without analysis and further development. In my opinion, pulse stacking is very natural for photon colliders and allows not only building 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.

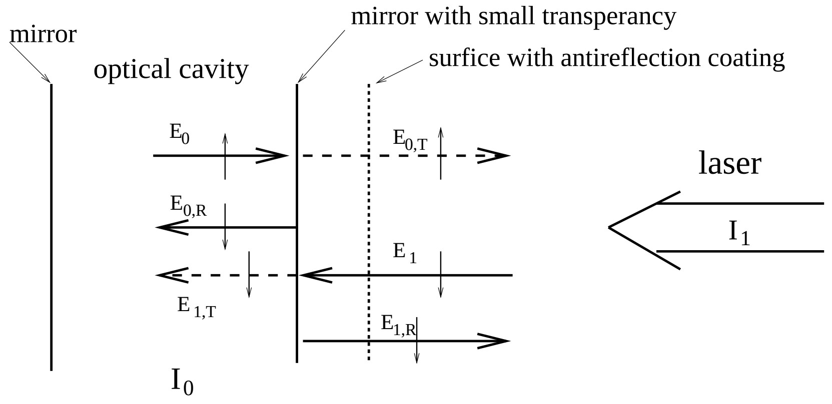

Figure 2: Principle of pulse stacking in an external optical cavity.

As this is very important for photon colliders, let me consider this method in more detail [13]. The principle of pulse stacking is shown in Fig. 2. The secret consists of 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 a semi-transparent mirror into the cavity interferes with reflected light inside the cavity *constructively*, while the light leaking from the cavity interferes with the laser light reflected from the cavity *destructively*. Namely, this fact produces asymmetry between cavity and space outside the cavity!

Let R be the reflection coefficient, T the transparency coefficient and δ 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. The TESLA collider has 2800 electron bunches in the train, so a factor of 1000 would be perfect for our goal, but even a factor of ten means a drastic reduction of the cost.

Obtaining 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... .

In HEP literature I have found only one reference on pulse stacking of short pulses ($\sim$ 1 ps) generated by the free electron laser with the wave length of 5 μm [19]. 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. 3. There are two optical cavities (one for each colliding electron beam) placed outside the electron beams. The required flash energy in this case is larger by a factor of 2 than in the case of head-on collisions but all other problems (holes in mirrors etc) are much simpler.

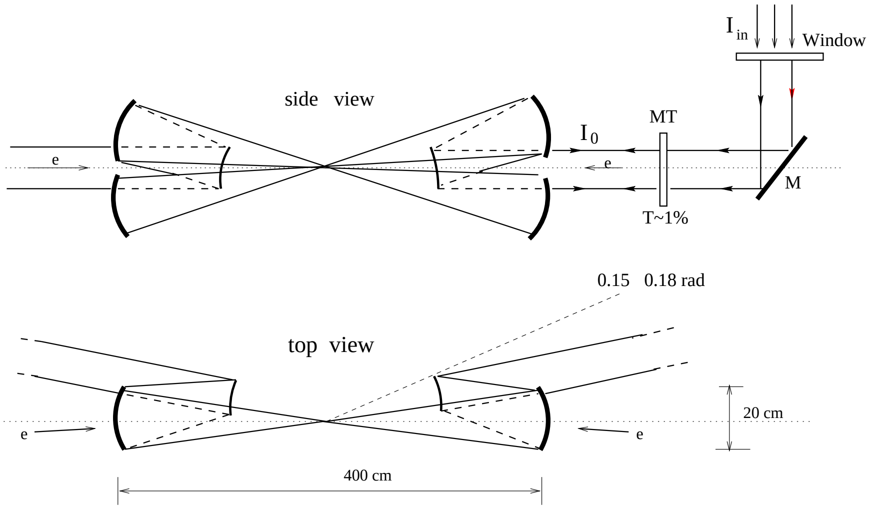

Figure 3: Possible scheme of optics at the IR.

4 Luminosity of Photon Colliders in Current Designs

Some results of simulation of $\gamma\gamma$ collisions at TESLA, ILC (converged NLC and JLC) 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. The conversion point (CP) is situated at distance $b = \gamma\sigma_y$. It is assumed that the "Compton" parameter $x = 4.6$, electron beams have 85% longitudinal polarization and laser photons have 100% circular polarization.

The $\gamma\gamma$ luminosity in these projects is determined only by "geometric" ee-luminosity. With some new low emittance electron sources 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.

The normalized $\gamma\gamma$ luminosity spectra for a 0.5 TeV TESLA are shown in Fig. 4(left). 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

Table 1: Parameters of $\gamma\gamma$ colliders based on TESLA, ILC (NLC/JLC)

	T(500)	I(500)	T(800)	I(1000)
$N/10^{10}$	2.	0.95	1.4	0.95
σ_z, mm	0.4	0.12	0.3	0.12
$f_{rep} \times n_b$,	5×2821	120× 95	3×4500	120×95
Δt_b, ns	337	2.8	189	2.8
$\gamma\epsilon_{x,y}/10^{-6}$,m·rad	10/0.03	5/0.1	8/0.01	5/0.1
$\beta_{x,y}$,mm at IP	2/0.4	2/0.12	2/0.3	2/0.16
$\sigma_{x,y}$,nm	200/5	140/5	140/2	100/4
$L(geom)$, 10^{33} cm^{-2}c^{-1}	48	12	75	20
$L\gamma\gamma(z > 0.65), 10^{33}$	4.5	1.1	7.2	1.75
$L\gamma\mathrm{e}(z > 0.65), 10^{33}$	6.6	2.6	8	4.2
$L\mathrm{ee}, 10^{33}$	1.2	1.2	1.1	1.8

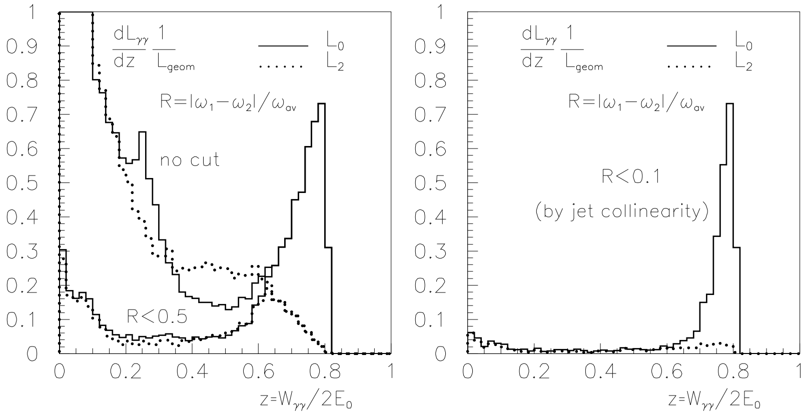

Figure 4: $\gamma\gamma$ luminosity spectra at TESLA(500) for parameters presented in Table 1. See comments in the text.

low energy luminosity. The events in this region have a large boost and can be easily distinguished from the central high energy events. In the same Fig. 4 (left) you can see the same spectrum with an additional "soft" cut on the longitudinal momentum of the produced system which suppresses low energy luminosity to a negligible level.

Fig. 4 (right) shows the same spectrum with a stronger cut on the longitudinal momentum. In this case, the spectrum has a nice peak with the width at half of maximum about 7.5%. For two jet events one can obtain this nice "collider resolution" without accurate energy measurement in the detector applying only a cut on the acollinearity angle between jets ($H \to b\bar{b}, \tau\tau$, for example).

A similar table and distributions for the photon collider on the c.m.s. energy 130 GeV (Higgs collider) can be found elsewhere [12].

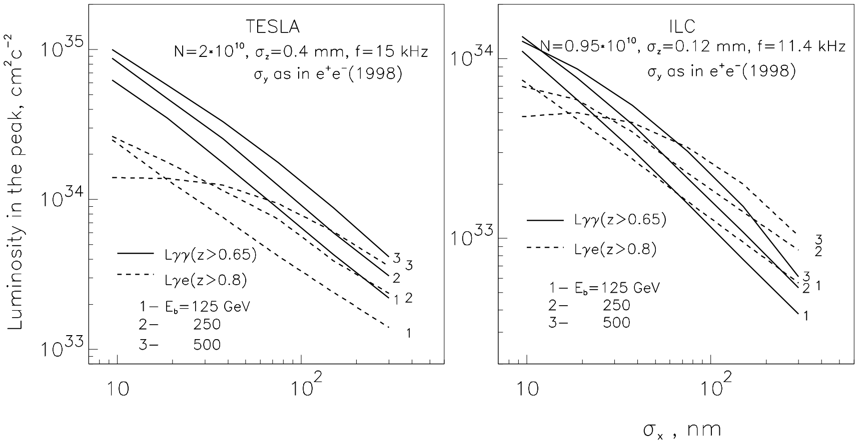

Figure 5: Dependence of $\gamma\gamma$ and γe luminosities in the high energy peak on the horizontal beam size for TESLA and ILC at various energies. See also comments in the text.

5 Ultimate $\gamma\gamma$, γe Luminosities

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 [20]. Below are results of the simulation with the code which takes into account all main processes in beam-beam interactions [11]. Fig. 5 shows dependence of the $\gamma\gamma$ (solid curves) and γe (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 changing horizontal beam emittance keeping the horizontal beta function at the IP 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 $2E_0 = 1$ TeV where at small σ_x the effect of coherent pair creation [16] is seen. 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 [12]. So, using beams with smaller emittances, the $\gamma\gamma$ luminosity at TESLA, ILC can be increased 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 γe collision (Fig. 5, dashed curves), the behavior of the luminosity on σ_x is different due to additional collision effects: beam repulsion and beamstrahlung. As a result, the luminosity in the high energy peak is not proportional to the "geometric" luminosity.

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 [7]. 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 [21],[17],[22].

6 Conclusion

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

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. Two laser schemes has been discussed in this paper. The optical cavity approach allows a considerable reduction of the required peak and average laser power.

The $\gamma\gamma$ luminosity at photon colliders 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 = Higgs, W, etc.). The main problem here is the generation of polarized electron beams with very small 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 laser pulse stacking pulses in an optical cavity.

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References

[1] *Zeroth-Order Design Report for the Next Linear Collider* LBNL-PUB-5424, SLAC Report 474, May 1996.

[2] *Conceptual Design of a 500 GeV Electron Positron Linear Collider with Integrated X-Ray Laser Facility* DESY 97-048, ECFA-97-182; R. Brinkmann et al., *Nucl. Instr. Meth. A* **406** (1998) 13, e-print: hep-ex/9707017,

[3] *JLC Design Study*, KEK-REP-97-1, April 1997; I.Watanabe et. al., KEK Report 97-17.

[4] I. Ginzburg, G. Kotkin, V. Serbo, V. Telnov, *Pizma ZhETF*, **34** (1981)514; *JETP Lett.* **34** (1982) 491.

[5] I. Ginzburg, G. Kotkin, V. Serbo, V. Telnov,*Nucl.Instr. Meth.* **205** (1983) 47.

[6] I. Ginzburg, G. Kotkin, S. Panfil, V. Serbo, V. Telnov, *Nucl. Instr. Meth.* **219**(1984)5.

[7] V.Telnov, *Int. J. Mod. Phys.* **A 13** (1998) 2399, e-print:hep-ex/9802003.

[8] M. Battaglia, HU-P-264, Apr 1999, To be published in the Proceedings of 4th International Workshop on Linear Colliders (LCWS 99), Sitges, Barcelona, Spain, 28 Apr - 5 May 1999, e-print: hep-ph/9910271.

[9] G. Jikia, S. Soldner-Rembold, To be published in the Proceedings of 4th International Workshop on Linear Colliders (LCWS 99), Sitges, Barcelona, Spain, 28 Apr - 5 May 1999. e-print: hep-ph/9910366.

[10] M. Melles, W.J. Stirling, V.A. Khoze, DTP-99-70, July 1999, e-print: hep-ph/9907238.

[11] V. Telnov, *Nucl.Instr.Meth.A* **355**(1995)3.

[12] V. Telnov, *Proc. of 17th Intern. Conference on High Energy Accelerators (HEACC98)*, Dubna, Russia, 7-12 Sept. 1998, KEK preprint 98-163, e-print: hep-ex/9810019.

[13] V. Telnov, Proc. of the International Conference on the Structure and Interactions of the Photon (Photon 99), Freiburg, Germany, 23-27 May 1999, Nucl. Phys. Proc. Suppl. **B, v.82**, e-print: hep-ex/9908005.

[14] N. Arkani-Hamed, S. Dimopoulos, G. Dvali. SLAC-PUB-7769, March 1998, Phys. Lett. **B 429** (1998) 263, hep-ph/9803315.

[15] Thomas Rizzo, SLAC-PUB-8114, April 1999, hep-ex/9904011.

[16] V.Telnov, *Nucl. Instr. Meth.A* **294** (1990)72.

[17] V.Telnov, *Proc. Advanced ICFA Workshop on Quantum aspects of beam physics,* Monterey, USA, 4-9 Jan. 1998, World Scientific, p.173, e-print: hep-ex/9805002.

[18] V.Telnov, *Proc. of World-Wide Study of Physics and Detectors for Future Linear Colliders (LCWS 99)*, Sitges, Barcelona, Spain, 28 Apr - 5 May 1999, e-print: hep-ex/9910010, hep-ex/9910011.

[19] T. Smith, P. Haar, H. Schwettman, *Nucl. Instr. Meth. A* **393** (1997) 245

[20] V. Telnov, *Proc. of ITP Workshop "Future High energy colliders"* Santa Barbara, USA, October 21-25, 1996, AIP Conf. Proc. No 397, p. 259–273; e-print: physics/9706003.

[21] V.Telnov, SLAC-PUB-7337, *Phys. Rev. Lett.*, **78** (1997) 4757, erratum: ibid **80** (1998) 2747, e-print: hep-ex/9610008.

[22] V.Telnov, *Proc. of Intern. Symp. on New Visions in Laser-Beam Interactions*, October 11-15, 1999, Metr. Univ. Tokyo, Japan. To be published in Nucl. Instr. Meth. B, hep-ex/0001029.