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Status of gamma-gamma, gamma-electron colliders *

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Abstract

This report on Photon Colliders briefly reviews three main issues: physics motivation, possible parameters and technical feasibility, plans of works and international cooperation. New scheme of laser optics at the interaction region is described which can drastically (at least by one order) reduce the cost of the laser system.

1 Introduction

As you certainly know, Linear colliders in the range of a few hundred GeV to 1.5 TeV range are under intense study around the world. Three specific project studies in Europe, Asia, and North America are going forward, with the intent to submit full conceptual design reports in the 2001-2002 time frame. In parallel, several hundred high energy physicists are contributing to advancing the physics case for linear colliders, and optimizing detector design and technologies.

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 [1]-[6]. High energy photons for $\gamma\gamma$, γe collisions can be obtained using laser backscattering. Modern laser technology presents the real possibility for construction of the laser system for $\gamma\gamma$, γe collider ('photon collider'). This option is included now in the pre-conceptual design of the NLC (North American) [7], TESLA (European) [8] and JLC (Asian) [9] projects, and is attracting an increasing interest among both theorists and experimentalists.

However, in our time of tight HEP budgets the physics community needs a very clear answer to the following question: a) can $\gamma\gamma$,γe collisions give new physics information in addition to e^+e^- collisions that could justify an additional collider cost (~15%, including detector); b) is it technically feasible; c) is there enough people who are ready to spend a significant part of their career for the design and construction of a photon collider, and exploiting its unique science?

Shortly, my answers are the following:

a) Certainly yes. There are many predictions of extremely interesting physics in the region of the next linear colliders. If something new will be discovered (Higgs, supersymmetry or ... quantum gravity with extra dimensions), to understand better a nature of these new phenomena they should be studied in different reactions which give complementary information.

b) There are no show-stoppers. There are good ideas on obtaining very high luminosities, on laser and optical schemes. It is clear how to remove disrupted beams and there is an understanding of backgrounds. However, much remains to be done in terms of detailed studies and experimental tests. Special efforts are required for the development of the laser and optics which are the key elements of photon colliders.

c) This is a new direction, not well known to physics community, and, as usually, it has to pass several natural phases of development. In the last decade, there has been growing interest to $\gamma\gamma$, γe collisions and the bibliography of recent reports on $\gamma\gamma$, γe physics now numbers over 1000 papers, mostly theoretical. The next phase will require much wider participation of the experimental community.

To this end, recently, it was decided to initiate International collaboration on Photon Colliders. This Collaboration does not replace the regional working groups, but rather supports and strengthens it. The Invitation letter, signed by Worldwide Study contact persons on photon colliders: V.Telnov (Europe), K. Van Bibber (North America), T.Takahashi (Asia) will be send to you shortly.

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2 Physics

The most interesting physics ("expected" discoveries) at next linear colliders is the search for and study of the Higgs boson(s), supersymmetric particles, and many other new phenomena such as quantum gravity (very popular topic in the last year). Photon colliders can make a considerable contribution.

2.1 Higgs

The Higgs boson (which is thought to be responsible for the origin of particle masses) will be produced at photon colliders as a single resonance. The cross section is proportional to the two-photon decay width of the Higgs boson which is very sensitive to all heavy charged particles (even super-heavy) which get their mass via the Higgs mechanism. The mass of the Higgs most probably lies in the region of 100< M_H <250 GeV. The effective cross section is presented in Fig. 1 [10]. Note that here $L_{\gamma\gamma}$ is

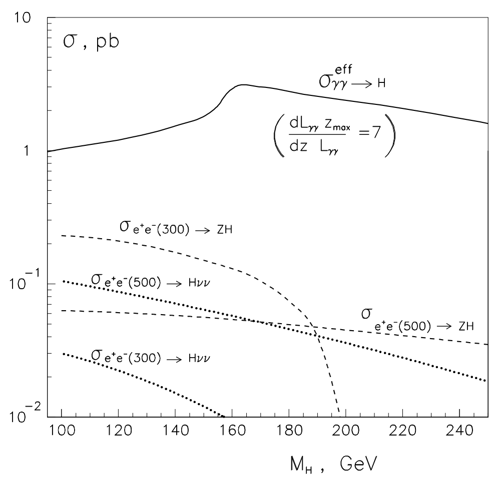

Figure 1: Cross sections for the Standard model Higgs in $\gamma\gamma$ and e^+e^- collisions.

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 in the same figure.

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 by energy scanning using the very sharp ($\sim$ 1%) high energy edge of luminosity distribution [10].

Observation of a sharp step in the visible cross section will imply narrow resonance production with subsequent decay in the considered channel. This method is very attractive for the study of the Higgs in the $\tau\tau$ decay mode where the direct reconstruction is impossible due to undetected neutrinos while it can be seen as a step in visible cross section for events consisting of two low multiplicity collinear jets. The total number of events in the main decay channels $H \to b\bar{b}, WW(W^*), ZZ(Z^*)$ 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.

2.2 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 [4],[8],[10].

The cross section of the scalar pair production (sleptons, for example) in collision of polarized photons is shown in Fig.2. One can see that for heavy

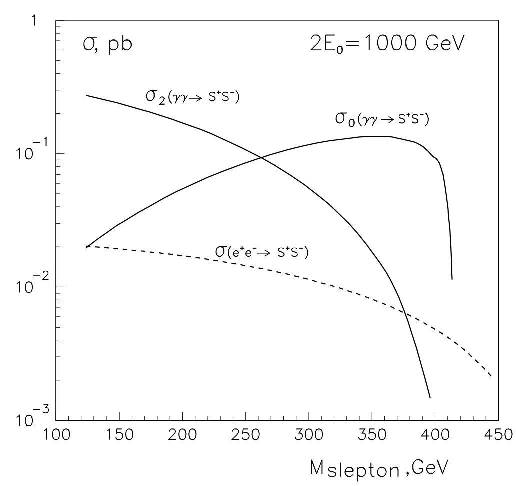

Figure 2: Cross sections for charged scalars production in e^+e^- and $\gamma\gamma$ collisions at $2E_0 = 1$ TeV collider (in $\gamma\gamma$ collision $W_{max} \approx 0.82$ GeV, $x = 4.6$); σ_0 and σ_2 correspond to the total $\gamma\gamma$ helicity 0 and 2.

scalars the cross section in collisions of polarized photons is higher than that in e^+e^- collisions by a factor of 10–20. The cross section near the threshold is very sharp (in e^+e^- it contains a factor β^3) that can be used for measurement of particle masses.

Note that for scalar selectrons the cross section in e^+e^- collisions is not described by the curve in Fig.2 due to existence of additional exchange diagram (exchange by neutralino), correspondingly the cross section is not described by pure QED (as it takes place in $\gamma\gamma$). Measurement of cross sections in both channels give, certainly, complimentary information.

2.3 Accessible masses

In γe collisions, charged supersymmetric particles with masses higher than those in e^+e^- collisions can be produced (a heavy charged particle plus a light neutral); $\gamma\gamma$ collisions also provide higher accessible masses for particles which are produced as a single resonance in $\gamma\gamma$ collisions (such as the Higgs boson). This is very important argument.

One very close example. It is very likely that LEP-II does not see the Higgs because its energy is only somewhat lower than $e^+e^- \to ZH$ threshold. Having $\gamma\gamma$ mode at LEP-II (this is impossible for storage rings, of course) one could produce Higgs with the mass higher on 60 GeV. The same story is with the search for the supersymmetry where γe mode could help very much.

2.4 Quantum gravity effects in Extra Dimensions.

This new theory [11] is very interesting though beyond my imagination. It suggests one of possible explanation 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 [12] ($\gamma\gamma \to WW$) and K.Cheung [13] ($\gamma\gamma \to \gamma\gamma$) photon colliders are sensitive to a factor of 2 higher quantum gravity mass scale than e^+e^- collisions.

3 Luminosity of photon colliders in current designs.

3.1 0.5–1 TeV colliders

Some results of simulation of $\gamma\gamma$ collisions at TESLA, ILC (converged NLC and JLC) and CLIC are presented below. Beam parameters were taken the same as those in e^+e^- collisions with the exception of horizontal beta function at IP, which is taken equal to 2 mm for all cases. In $\gamma\gamma$ collisions, the beamstrahlung is absent and the horizontal size can be made much smaller than that in e^+e^- collisions. Minimum β_x is determined by the Oide effect (radiation in quads) which is included in the simulation code and also by technical problems connected with the chromatic corrections in both transverse directions – the limit here is not clear so far. 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.

Table 1: Parameters of $\gamma\gamma$ colliders based on Tesla(T), ILC(I) and CLIC(C).

	T(500)	I(500)	C(500)	T(800)	I(1000)	C(1000)
no deflection, $b = \gamma\sigma_y$, $x = 4.6$						
$N/10^{10}$	2.	0.95	0.4	1.4	0.95	0.4
σ_z, mm	0.4	0.12	0.05	0.3	0.12	0.05
$f_{rep} \times n_b$, kHz	15	11.4	30.1	13.5	11.4	26.6
$\gamma\epsilon_{x,y}/10^{-6}$,m·rad	10/0.03	5/0.1	1.9/0.1	8/0.01	5/0.1	1.5/0.1
$\beta_{x,y}$,mm at IP	2/0.4	2/0.12	2/0.1	2/0.3	2/0.16	2/0.1
$\sigma_{x,y}$,nm	200/5	140/5	88/4.5	140/2	100/4	55/3.2
b, mm	2.4	2.4	2.2	1.5	4	3.1
$L(geom)$, 10^{33}	48	12	10	75	20	19.5
$L_{\gamma\gamma}(z > 0.65), 10^{33}$	4.5	1.1	1.05	7.2	1.75	1.8
$L_{\gamma e}(z > 0.65), 10^{33}$	6.6	2.6	2.8	8	4.2	4.6
$L_{ee}, 10^{33}$	1.2	1.2	1.6	1.1	1.8	2.3
$\theta_x/\theta_{y,max}$, mrad	5.8/6.5	6.5/6.9	6/7	4.6/5	4.6/5.3	4.6/5.5

We see that $\gamma\gamma$ luminosity in the hard part of the spectrum is $L_{\gamma\gamma}(z > 0.65) \sim 0.1L(geom) \sim (1/6)L_{e^+e^-}$. Beside $\gamma\gamma$ collisions, there is considerable γe luminosity and it is possible to study γe interactions simultaneously with $\gamma\gamma$ collisions.

The normalized $\gamma\gamma$ luminosity spectra for a 0.5 TeV TESLA are shown in Fig.3(upper). 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 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 af-

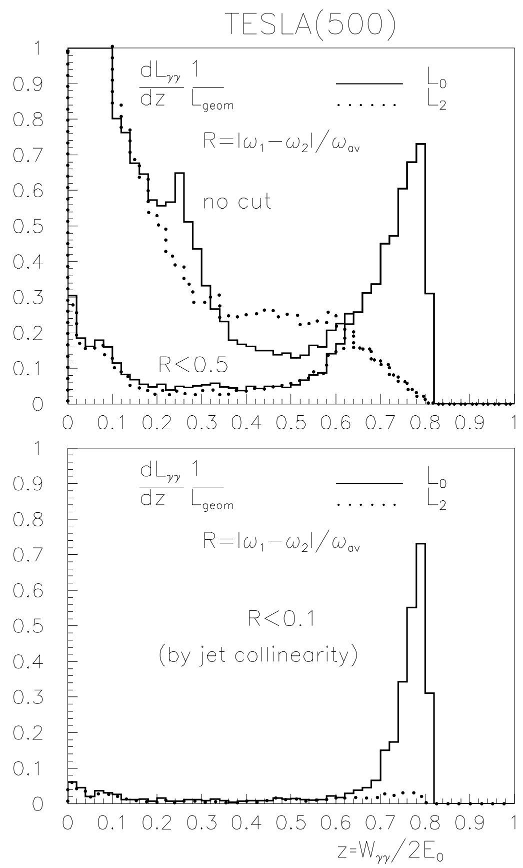

Figure 3: $\gamma\gamma$ luminosity spectra at TESLA(500) for parameters presented in Table 1. Solid line for total helicity of two photons 0 and dotted line for total helicity 2. Upper curves without cuts, two lower pairs of curves have cut on the relative difference of the photon energy. See comments in the text.

ter multiple Compton scattering and beamstrahlung photons. Fortunately, these events have large boost and can be easily distinguished from the central high energy events. In the same Fig.3(upper) 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.3 (lower) 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%. Of course, such procedure is somewhat artificial because instead of such cuts one can directly selects events with high invariant masses, the minimum width of the invariant mass distribution depends only on the detector resolution. However, there are very important examples when one can obtain a "collider resolution" somewhat better than the detector resolution, such as 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 ($H \to b\bar{b}, \tau\tau$, for example).

3.2 $\gamma\gamma$ collider for low mass Higgs

It is very possible that the Higgs boson has a mass in the region 115-150 GeV as predicted in some theories. It is of interest to consider possible parameters of a $\gamma\gamma$ collider based on TESLA and ILC at these energies. Two variants were considered for H(130): 1) the "Compton" parameter x is fixed near the threshold of e^+e^- creation ($x \approx 4.6$), which corresponds to $\lambda \sim 325$ nm and $E_0 = 79$ GeV; 2) the laser is the same as for $2E_0 = 500$ GeV colliders, namely a Nd:glass laser with $\lambda = 1.06\ \mu m$, which corresponds to $x = 1.8$ and $E_0 = 100$ GeV. All other beam parameters are taken the same as for $2E_0 = 500$ GeV (see Table 1). Results of simulation for these two cases are shown in Table 2 (TESLA and ILC) and in Fig.4 (TESLA). Comparing these two variants we can conclude that one can use the same Nd:glass laser at all energies below $2E_0 \sim 500$ GeV.

Table 2: Parameters of the $\gamma\gamma$ colliders for Higgs(130) at TESLA(T)and ILC(I).

	T(2x100)	I(2x100)	T(2x79)	I(2x79)
	$x = 1.8$		$x = 4.6$	
$\sigma_{x,y}$,nm	320/7.8	230/7.8	360/8.8	250/8.8
b, mm	1.5	1.5	1.4	1.4
$L(geom)$, 10^{33}	19	4.6	15	3.7
$L_{\gamma\gamma}(z/z_m > 0.8), 10^{33}$	1.55	0.37	1.45	0.35
$L_{\gamma e}(z/z_m > 0.8), 10^{33}$	3.	1.45	1.7	0.83
$\theta_x/\theta_{y,max}$, mrad	5.2/6.2	5.2/7	$\sim$ 10/12	$\sim$ 10/12

4 Ultimate $\gamma\gamma$, γe luminosities

The $\gamma\gamma$ luminosities in the current projects are determined by the "geometric" luminosity of the electron beams. The only collision effect restricting the maximum value of the $\gamma\gamma$ luminosity is the coherent pair creation when the high energy photon is converted into an e^+e^- pair in the field of the opposing electron beam [14],[4]. Having electron beams with smaller emittances one can obtain much higher $\gamma\gamma$ luminosity [15]. Fig.5 shows dependence of the

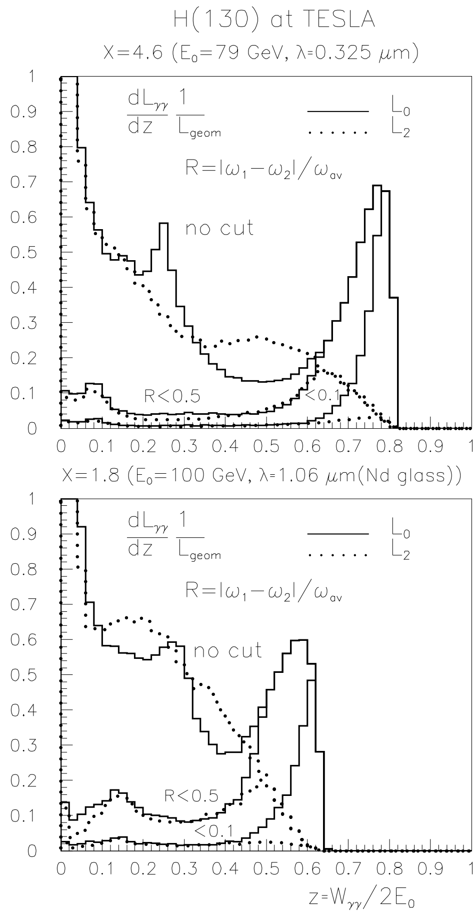

Figure 4: Luminosity spectra of $\gamma\gamma$ collision of "low" energy $\gamma\gamma$ collider (TESLA beam parameters) for study of the Higgs with a mass $M_H = 130$ GeV, upper figure for $x = 4.8$ and lower for $x = 1.8$ (the same laser as for $2E_0 = 500$ GeV).

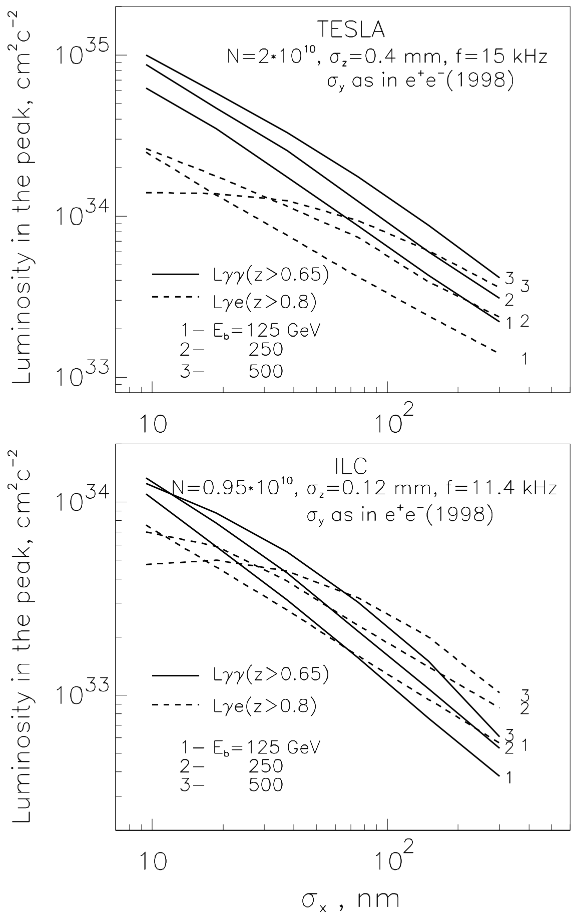

Figure 5: Dependence of $\gamma\gamma$ and γe luminosities in the high energy peak on the horizontal beam size for TESLA and ILC at various energies. See also comments in the text.

$\gamma\gamma$ (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 change of horizontal beam emittance keeping the horizontal beta function at the IP constant and equal 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 σ_x the effect of coherent pair creation is seen.[1] This means that at the same colliders the $\gamma\gamma$ luminosity can be increased by decreasing horizontal beam size at least by one order ($\sigma_x < 10$ nm is difficult due to some effects connected with crab crossing). Additional increase of $\gamma\gamma$ luminosity by a factor about 3 (TESLA), 7(ILC) can be obtained by further decrease of the vertical emittance [16]. So, if to use beams with smaller emittances, the $\gamma\gamma$ luminosity at TELSA, 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 γe collision (Fig.5, dashed curves), the behavior of the luminosity on σ_x is different due to additional collisions effects: beams repulsion and beamstrahlung. As a result, the luminosity in high energy peak is not proportional to the "geometric" luminosity.

[1] This curve has also some bend at largest σ_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 β_x and smaller ϵ_{nx}.

There are several ways of decreasing 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 emittances. Here some progress is certainly possible. Moreover, there is one method which allows further decrease of beam cross sections by two orders in comparison with current designs. It is laser cooling [17],[18].

In the method of laser cooling the electron beam at an energy of several GeV is collided 1–2 times with a powerful laser flash, losing in each collision a large fraction ($\sim 90\%$) of its energy to radiation, with reacceleration between cooling sections. The physics of the cooling process is the same as in a wiggler. One of problems here is the required laser flash energy, it should be about 10-100 J depending on beam energy, laser wave length and optical scheme. One very promising variant of laser optics for laser cooling is discussed in the next section. Other problem here is capture (equal to focusing) of the electron beam with the large energy spread (about 10-15 % at $E \sim 0.5$ GeV) without dilution of the emittance. The similar problem has been solved for final focusing of beams at linear colliders, where it is also necessary to correct effects of chromaticity to high orders. The corresponding parameter of the problem $(F/\beta) \times (\sigma_E/E)$ in the laser cooling is smaller and the energy is smaller, so there are hopes that such magnetic system can be build.

5 New ideas on laser optics.

The laser flash energy required for conversion of 65% (one collision length) of electrons to high energy photons is about 1.5(2.5) J for ILC (TESLA). At collision rate 10-15 kHz, the average laser power will be about 20-30 kW. Such system will be a huge and expensive. Livermore experts give cost estimate to such laser system of the order of 200 M$ [19].

Fortunately, there is a solution which can decrease the cost by one order (at least). One flash contains about 10^{19} laser photons and only 10^{10} photons are knocked out in collision with one electron bunch. It is very natural to use laser pulse many times, and optics presents us such a possibility. Shortly, the method is the following. Using the train of low energy pulses from the laser 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 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 [7] though without analysis and further development.

To my opinion, pulse stacking is very natural for photon colliders and allows not only to build relatively cheap laser system for $e \to \gamma$ conversion but give us the practical way for realization of laser cooling, i.e. opens up the way to ultimate luminosities of photon colliders.

As it is the key problem of photon colliders, let me consider this method in more detail. The principle of pulse stacking is shown in Fig.6. The secret consists

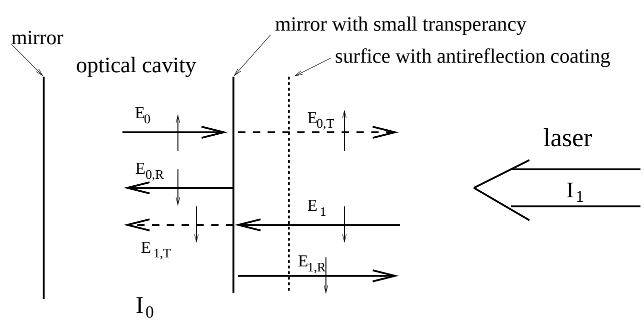

Figure 6: Principle of pulse stacking in an external optical cavity.

in the following. There is well known optical theorem: at any surface, the reflection coefficients for light coming from one and 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 **constructively**, while the light leaking from the cavity interferes with the reflected laser light **destructively**. Namely, this fact produces asymmetry between cavity and space outside the cavity!

Let R be the reflection coefficient, T is transparency coefficient and δ are 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,

$$E_0 = E_{0,R} + E_{1,T}. \qquad (1)$$

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

$$E_0^2 = E_1^2 \frac{4T}{(T+\delta)^2}. \quad (2)$$

The maximum ratio of intensities is obtained at $T = \delta$, then

$$I_0/I_1 = 1/\delta \approx Q, \quad (3)$$

where Q is the quality factor of the optical cavity. Even with two metal mirrors inside cavity, one can hope to get the gain factor about 50-100, with multilayer mirrors it could 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 the 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 construction interference will be not 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 laser oscillator is equal to integer number 1, 2, 3... .

For $\lambda = 1$ μm 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 (~ 1 ps) generated by FEL [20] with the wave length of 5 μm. 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 optics at the interaction region scheme is shown in Fig.7. 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 may be sufficient for not too large Q). Also, mirrors should have holes for electron beams (which does not change Q factor of the cavity too much).

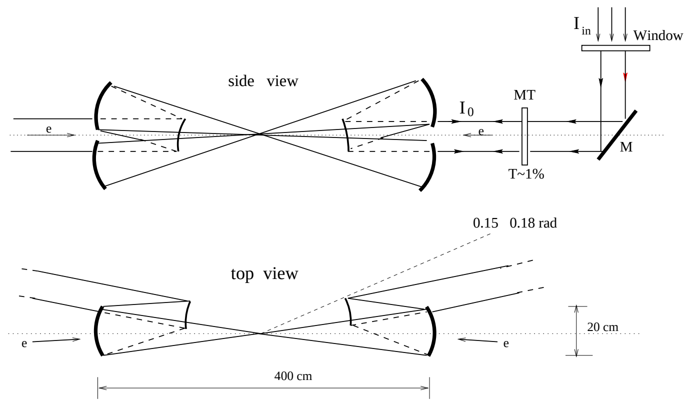

Figure 7: Possible scheme of optics at the IR.

The use of the pulse stacking in the optical cavity make the idea of laser cooling (previous section) very realistic, though the required flash energy should be more than by one order higher than that required for $e \to \gamma$ conversion.

6 Conclusion

Prospects of photon colliders for particle physics are great; the physics community should not miss this unique possibility.

7 Acknowledgement

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