GAMMA-GAMMA, GAMMA-ELECTRON COLLIDERS: ACCELERATOR, LASER AND INTERACTION REGION ISSUES.

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In this report on Photon Colliders the following technical aspects are considered: special requirements to an accelerator, new ideas on laser optics, laser cooling, and interaction region layout issues. In fact it is continuation of my first talk at this workshop where physics motivation, possible luminosities and backgrounds were discussed.

1 Introduction

As a general introduction see my first report from this workshop and references therein.[1] Photon Colliders are based on e^+e^- colliders and the main problem is the same: production of electron beams with low emittances and acceleration to high energies. However, photon colliders have several new features and differences which require special study, especially if we are going to reach ultimate luminosities.[1]

The new key element at photon colliders is a powerful laser system which is used for $e \to \gamma$ conversion. Lasers with required flash energies and pulse duration already exist and are used in several laboratories, the main problem here is the repetition rate. Present technology would already allow the required laser systems to be built now, but it would be very expensive.[2] 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.

As you know, in e^+e^- collisions at linear colliders (LC), the beams should be flat in order to restrict the beamstrahlung energy losses. The typical beam sizes at the interaction point (IP) in the current designs are about $\sigma_x/\sigma_y = (300-500)/(3-5)$ nm. Photon colliders with the energies of several hundred GeV can work with practically round beams with a radius of about 1–3 nm. Due to some technical problems connected with the "crab crossing" and the "big bend" and some increase of backgrounds due to a coherent pair creation obtaining and operation with such small horizontal beam sizes at the IP is problematic, but $\sigma_x \sim 10 - 15$ nm and $\sigma_y \sim 2$ nm is quite a realistic goal.

The main problem in achieving ultimate $\gamma\gamma$ luminosities is the generation of electron beams with very small emittances both in the vertical and horizontal planes. Damping rings can produce, in principle, the required vertical emittance, but the horizontal emittance is larger than desired by two orders of magnitude. Production of such low emittances in both transverse directions is a very challenging task. Now I see only one method to reach this goal, it is laser cooling.[6,7] The required laser system should be much more powerful than that needed for $e \to \gamma$ conversion, but it is not impossible that using the optical cavity scheme such a system can already be built now. The problems in the laser cooling and possible solutions are discussed in sect. 3.

The third group of problems is connected with transportation of low emittance beams to the interaction point, collision and removal of the disrupted beams without generation of additional backgrounds.

2 Lasers, optics

2.1 Requirements for the laser, wave length, flash energy

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.[3] In the conversion region a laser photon with the energy ω_0 scatters at a small collision angle α_0 on a high energy electron with the energy E_0. The maximum energy of scattered photons (in direction of electrons)

$$\omega_m = \frac{x}{x+1} E_0; \quad x = \frac{4E_0\omega_0}{m^2c^4} \simeq 15.3 \left[\frac{E_0}{\text{TeV}}\right]\left[\frac{\omega_0}{eV}\right] = 19 \left[\frac{E_0}{\text{TeV}}\right]\left[\frac{\mu m}{\lambda}\right].$$

For example: E_0 =250 GeV, ω_0 = 1.17 eV (λ = 1.06 μm) (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.[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.[4]

In the laser focus at photon colliders the field is so strong that multiphoton 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 is better. 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 multiphoton effects are small.

From all this it follows that an existing powerful Terawatt solid state laser with the wave length about 1 μm 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, about 45 %.

In the calculation of the required flash energy one has to take into account the natural "diffraction" emittance of the laser beam, the maximum allowed value of the field strength (characterized by the parameter $\xi^2 = (eB\hbar/m\omega_0c)^2$) and the laser spot size at the conversion point which should be larger than that of the electron beam. In the scheme with crab crossing 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 (proportional to the $\gamma\gamma$ luminosity)

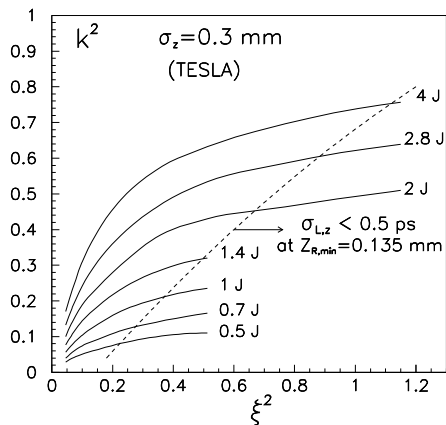as a function of the flash energy and parameter ξ^2 (in the center of the laser bunch) are shown in fig. 1 and 2.

Figure 1: The conversion probability for the various laser flash energies and the values of the parameter ξ^2. Electron beams pass through the holes in the mirrors. See comments in the text.
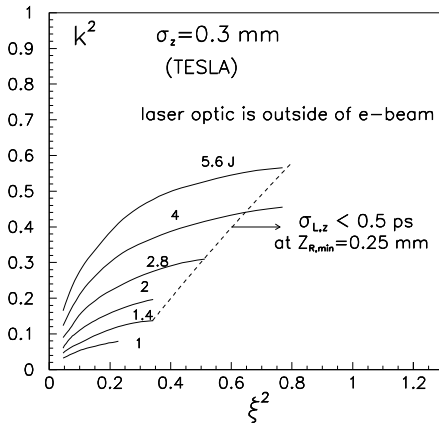
Figure 2: Same as on fig.1, but the mirror system is situated outside the electron beam trajectories.

In summary: the required flash energy is about 3–5 Joules, that 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 up to about 50 kW. [a] One possible scheme is a multi-laser system which combines pulses into one train using Pockels cells. [5] However, such a system will be huge and very expensive. [2]

2.2 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$\rightarrow \gamma$ conversion many times. Indeed, one Joule laser flash contains about 10^{19} laser photons and only 10^{10} 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. [5] 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.

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[a]Though the average power in the one bunch train is higher, the cooling time (namely overheating of the crystals is the main problem) is longer than the time between trains, therefore we can speak about average power.

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 [5] 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 $e \rightarrow \gamma$ conversion but gives us the practical way for realization of 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. The principle of pulse stacking is shown in Fig.3. The secret
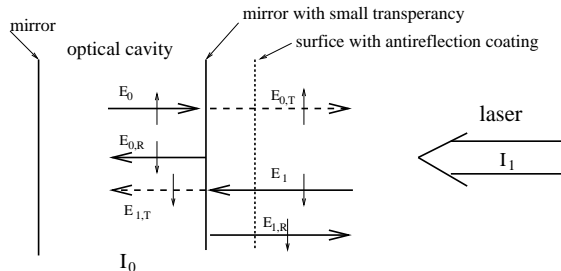

Figure 3: Principle of pulse stacking in an external optical cavity.

consists in 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 **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 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. 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

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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 (~ 1 ps) generated by FEL [8] 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 the optics at the interaction region scheme is shown in Fig.4. 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 previous variant is simpler though it requires a factor of 2 higher flash energy.
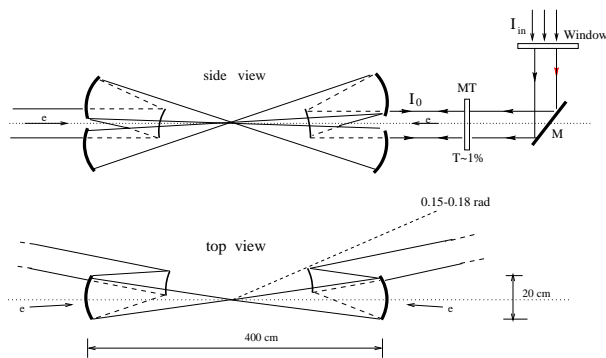

Figure 4: Possible scheme of optics at the IR.

3 Laser cooling of electron beams

The use of pulse stacking in the optical cavity makes the idea of laser cooling [6,7] very realistic, though the required flash energy is one order higher than that required for $e \to \gamma$ conversion. In the method of laser cooling the electron beam at an energy of

about 5 GeV (just after the damping ring and longitudinal compression) is collided 1–2 times with a powerful laser flash losing in each collision a large fraction (~ 90 %) of its energy to the radiation (Compton scattering), with re-acceleration between cooling sections. The physics of the cooling process is almost the same as radiative cooling of electrons in damping rings. However, here the process takes only 1 ps and the ultimate emittance is much lower than that in the damping rings. This is because in the "linear" laser cooling there are no bends which cause a growth of the horizontal emittance. Also the intra-beam scattering is not important due to a short "damping" time and following fast acceleration. Considering a practical scheme for laser cooling we should take into account many important practical aspects:

• Radiation damage of the mirrors. X-ray radiation due to the Compton scattering here is many orders larger than the radiation level at the same angles in the $\gamma \to e$ conversion point. It is so because a) the electron energies are lower and b) each electron undergoes about one hundred Compton scattering. At $\vartheta \gg 1/\gamma$ and $x \ll 1$ (x is defined in sect.2) the energy of the Compton scattered photons $\omega = 4\omega_0/\vartheta^2$ and does not depend on the electron energy.[3] However, at the lower beam energies the spectrum is softer ($\omega_{max} = 4\omega_0\gamma^2$) and more photons (per one Compton scattering) have large angles. Simple calculations show that the number of photons/per electron emitted on the angle ϑ during the cooling of electrons from some large energy to the energy E_{min} is

$$dn/d\Omega = mc^2/4\pi\omega_0\gamma_{min}^3\vartheta^4.$$

The total energy hitting the mirrors/cm^2/sec is

$$dP/dS = mc^2N\nu/\pi\gamma_{min}^3\vartheta^6L^2,$$

where L is the distance between the collision (cooling) point (CP) and the focusing mirrors, N and ν are the number of electrons in the bunch and the collision rate. One can see a strong dependence of X-ray background on γ_{min} and ϑ. During the cooling the electron beam loses almost all its energy to photons. For $E_0 = 5$ GeV, $N = 2 \times 10^{10}$, $\nu = 15$ kHz the total energy losses are about 200 kW, fortunately the flux decreases rapidly with increasing the angle. At $\vartheta = 30$ mrad and $L = 5$ m the power density $dP/dS \sim 10^{-5}$ W/cm^2 and X-ray photons have an energies of about 4 keV (for 1 μm laser wave length). My estimations shows that rescattering of photons on the quads can give a comparable background.

I have describing this item in detail because for laser cooling the required flash energy is very high and to reach the goal we need very high reflectivity of the mirrors in the optical cavity. For TESLA with 3000 bunches in a train it would be nice to have mirrors with $R > 0.999$. Such values of R are not a problem for dielectric mirrors, however the radiation damage may cause problems, better to avoid this problem.

• Laser spot size should be several times larger than that of the focused electron beam to avoid an additional energy spread of the cooled electrons.

• The cooled electron beam at the energy E=500-1000 GeV has an energy spread of $\sigma_E/E \sim 15$ % at the point where the β- function is small ($\sim 1 - 5$ mm). Matching this beam with the accelerator is not a simple problem and requires special

insertions for chromaticity correction. A similar problem exists for the final focus at linear colliders, it has been solved and tested at the FFTB at SLAC. Here the factor $(F/\beta)\sigma_E/E$ characterizing the chromaticity problem is smaller and the beam energy is 500 times smaller, so one can hope that it will be no problem.

• The parameter ξ^2 (defined above) should be small enough (≤ 1) to keep the minimum attainable emittance, depolarization and the energy spread small enough.[6,7] This is impossible with one laser (with required flash energy) without additional "stretching" of the cooling region along the beam line. The simplest way to do this is to focus several lasers at different points along the beam axis.

The possible optical scheme for the TESLA project is shown in fig.5 (only the final focusing mirrors are shown). The system consist of 8 independent identical
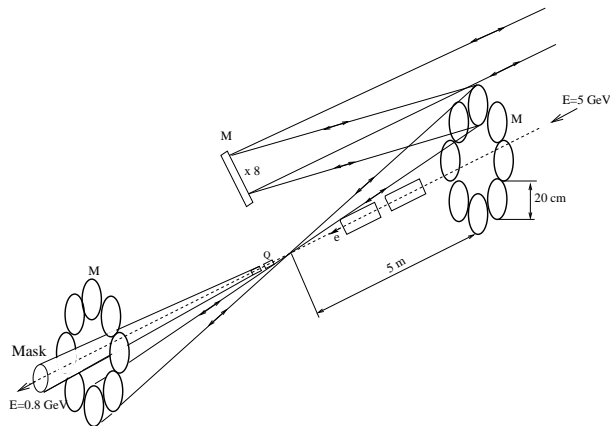

Figure 5: Possible scheme of laser cooling.

optical cavities focusing the laser beams to the points distibuted along the beam direction on the length $\Delta z \sim 2$ mm. The length of the cavity (the distance between the "left" mirror and an entrance semi-transparent mirror (not shown)) is equal to half the distance between the electron bunches in the train, 50 m for TESLA). The large enough angle between the edges of the mirrors and the beam axis (30 mrad) makes X-ray flux rather small (see the estimation above). Also this clear angle allows the final quads to be placed at a distance about 50 cm (from the side of the cooled beam), much closer than the focusing mirrors. Smaller focal distance makes the problem of chromaticity correction easier.

The maximum distance from the CP to the mirrors is determined only by the mirror size, the diameter of 20 cm seems reasonable, which gives $L = 5$ m. The laser spot size at the CP is 7.5 μm, at least 3 times larger than the horizontal electron beam size with $\beta_x < 5$ mm. The circulating flash energy in each cavity is 25 J and 200 J in the whole system, not small. The average power circulating inside the system is 200×15 kHz = 3 MW! However, if the Q factor of the cavities is about 1000–3000 (3000 bunches in the electron train at TESLA), the required laser power is only 1–3 kW, or 0.15–0.4 kW/per each laser, that is already reasonable.

What about damage to the mirrors by such powerful laser light? The maximum

laser flash energy/cm^2 on the mirrors is 0.13 J/cm^2 (0.7-2 has been achieved for 1 ps pulses [5]), the average power/cm^2 is 2 kW/cm^2 (there are systems with > 5 kW/cm^2 working long time [5]). The average power inside one train ($\Delta t = 1$ msec) is 200 times higher (400 J/1 msec), but from the same ref.[5] is known that 100 J for a time of 100 ns is OK, and extrapolating as $\sqrt{t}$ (thermoconductivity) one can expect the limit of about 10 kJ for 1 msec, much larger that expected in our case. Note, here we are speaking about circulating, not absorbed energy. So, all power densities are below the known limits, this all depends, of course, on specific choice of mirrors.

At last, the main numbers. After one stage of such a cooling system the normalized emittance is decreased by a factor of 6. The ultimate normalized emittance (after several cooling sections) is proportional to the β-function at the CP, at $\beta_{x,y} = 1$ mm it is about 2×10^{-9} m rad, smaller than can be produced by the TESLA damping ring by a factor of 5000(15) in x(y) directions. From this point of view such a small β_x is not necessary, but it should be small enough (< 5 mm to have a small electron spot size in the cooling region. The first stage of cooling will be the most efficient because the beam is cooled in both horizontal and vertical directions (far from the limits). Besides after decreasing the horizontal emittance the β- function at the LC final focus can be made as small as possible, $\sim \sigma_z$. All together this can give a factor of ten in the luminosity.

Having no space for discussion of accelerator aspects in this paper I would like to note only that all systems of the LC should allow beam emittances to be reached which are lower than are necessary for e^+e^- collisions (see the intoduction). Many technical decisions should be done before the beginning of construction works.

4   Conclusion

Photon colliders is a very inspiring new field of high energy physics and I invite you to take part in this venture.

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