

## Ultimate parameters of the photon collider at the international linear collider

V I TELNOV

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

E-mail: telnov@inp.nsk.su

**Abstract.** At linear colliders, the  $e^+e^-$  luminosity is limited by beam-collision effects, which determine the required emittances of beams in damping rings (DRs). In  $\gamma\gamma$  collisions at the photon collider, these effects are absent, and so smaller emittances are desirable. In the present damping ring designs, nominal DR parameters correspond to those required for  $e^+e^-$  collisions. In this note, I would like to stress once again that as soon as we plan the photon collider mode of ILC operation, the damping ring emittances are dictated by the photon collider requirements – namely, they should be as small as possible. This can be achieved by adding more wigglers to the DRs; the incremental cost is easily justified by a considerable potential improvement of the  $\gamma\gamma$  luminosity. No expert analysis exists as of now, but it seems realistic to obtain a factor five increase of the  $\gamma\gamma$  luminosity compared to the ‘nominal’ DR design.

**Keywords.** Photon collider; linear collider; gamma gamma; photon photon; photon electron; Compton scattering.

**PACS Nos** 29.17.+w; 41.75.Ht; 41.75.Lx; 13.60.Fz

### 1. Introduction

It is well-known and publicized that in addition to  $e^+e^-$  physics, linear colliders provide a unique opportunity to study  $\gamma\gamma$  and  $\gamma e$  interactions at high energy and luminosity [1–5]. The physics in  $\gamma\gamma$ ,  $\gamma e$  collisions is very rich [3,6–8]. The photon collider almost doubles the ILC physics program, while the increase of the total cost is only a few per cent.

The next few years are very important for the photon collider. Everything that is required for the photon collider must be properly included in the basic ILC design. It is important to continue the development of the physics program and start the development of the laser system, which is a key element of the photon collider. However, even more urgent are the accelerator and interaction-region aspects, which influence the ILC design and determine the parameters of the photon collider.

At this workshop (LCWS06), I would like to emphasize two very important problems of the photon collider that require special attention of ILC designers: (1) attaining the ultimate luminosities (this article) and (2) the layout of the photon collider at the ILC [9].

## 2. Towards high $\gamma\gamma, \gamma e$ luminosities

The  $\gamma\gamma$  luminosity at the photon collider at ILC energies is determined by the geometric luminosity of electron beams [3,10,11]. There is an approximate general rule: the luminosity in the high-energy part of spectrum  $L_{\gamma\gamma} \sim 0.1L_{\text{geom}}$ , where  $L_{\text{geom}} = N^2\nu\gamma/4\pi\sqrt{\epsilon_{nx}\epsilon_{ny}}\beta_x\beta_y$ . Compared to the  $e^+e^-$  case, where the minimum transverse beam sizes are determined by beamstrahlung and beam instability, the photon collider needs a smaller product of horizontal and vertical emittances and a smaller horizontal  $\beta$ -function.

The ‘nominal’ (for  $e^+e^-$ ) ILC beam parameters are:  $N = 2 \times 10^{10}$ ,  $\sigma_z = 0.3$  mm,  $\nu = 14100$  Hz,  $\epsilon_{nx} = 10^{-5}$  m,  $\epsilon_{ny} = 4 \times 10^{-8}$  m. Obtaining  $\beta_y \sim \sigma_z = 0.3$  mm is not a problem, while the minimum value of the horizontal  $\beta$ -function is restricted by chromo-geometric aberrations in the final-focus system [3]. For the above emittances, the limit on the effective horizontal  $\beta$ -function is about 5 mm [12,13]. The expected  $\gamma\gamma$  luminosity  $L_{\gamma\gamma}(z > 0.8z_m) \sim 3.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \sim 0.17 L_{e^+e^-}$  (here the nominal  $L_{e^+e^-} = 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ) [12]. Taking into account that cross-sections in  $\gamma\gamma$  are larger than those in  $e^+e^-$  collisions by one order of magnitude, the number of events will be somewhat larger than in  $e^+e^-$  collisions even for the ‘nominal’ case.

The above  $\gamma\gamma$  luminosity corresponds to the beam parameters optimized for the  $e^+e^-$  collisions, where the luminosity is determined by collision effects. The photon collider has no such restriction and can work with much smaller beam sizes. The horizontal beam size at the considered parameters (in the  $\gamma\gamma$  case) is  $\sigma_x \approx 300$  nm, while the simulation shows that the photon collider at such energies can work even with  $\sigma_x \sim 10$  nm without fundamental limitations [3,10,11]. So, the nominal beam parameters are very far from the physics limits and we should do everything possible to minimize transverse beam sizes at the photon collider!

Note, the minimum  $\beta_x$  depends on the horizontal emittance: about 5 mm for the nominal emittance and 3.7(2.2) mm for emittances reduced by a factor of 2(4), respectively [12,13]. In the TESLA, emittances close to the latter case were considered:  $\epsilon_{nx} = 0.25 \times 10^{-5}$ ,  $\epsilon_{ny} = 3 \times 10^{-8}$  m, which give the  $\gamma\gamma$  luminosity a factor of 3.5 higher!

The minimum emittances are determined by various physics effects in damping rings such as quantum fluctuations in synchrotron radiation and intra-beam scattering (IBS). The latter is the most difficult to overcome. Where is the limit? One of the possible ways to reduce emittances is decreasing the damping time by adding wigglers [14]. There are no detailed considerations by experts yet. There are many effects in damping rings, and one should believe only in carefully done studies. Nevertheless, I would like to make some rough estimates.

The equilibrium normalized emittance in the wiggler-dominated regime due to quantum fluctuations is [15]

$$\epsilon_{nx} \sim 3.3 \times 10^{-11} B_0^3(\text{T})\lambda_w^2(\text{cm})\beta_x(\text{m}) \text{ m}, \quad (1)$$

where  $\lambda_w$  is the wiggler period and  $B_0$  is the wiggler field (sine-like field). The damping time is

$$T_s = \frac{3m^2c^3}{r_e^2EB_0^2} = \frac{5.2 \times 10^{-3}}{E(\text{GeV})B_0^2(\text{T})} \text{ s}. \quad (2)$$

If wigglers fill 1/3 of the DR, then for  $B_0 = 2$  T and  $E = 5$  GeV one gets  $T_s = 7.5 \times 10^{-4}$  s, which is more than 20 times smaller than the damping time in the present designs.

For  $\lambda_w = 10$  cm and  $\beta_x = 5$  m, the equilibrium normalized emittance due to synchrotron radiation is  $\epsilon_{nx} = 1.3 \times 10^{-7}$  m, which is 60 times smaller than the present nominal emittance. The vertical emittance will be much smaller as well.

The second effect limiting the emittance is the intra-beam scattering (IBS). The growth time for IBS at  $\epsilon_x/\epsilon_y = \text{const}$  depends on the emittances roughly as  $1/T_{\text{IBS}} \sim b/\epsilon_x^2$  [16,17], where  $b$  is a coefficient that depends on the DR structure and only slightly on  $\epsilon_x$ .

In the presence of both synchrotron radiation and IBS, the emittance is damped as

$$\frac{d\epsilon}{\epsilon} \approx -\frac{dt}{T_s} + \frac{\epsilon_s dt}{\epsilon T_s} + \frac{b dt}{\epsilon^2}, \quad (3)$$

where  $\epsilon \equiv \epsilon_x$ ,  $T_s$  is the radiation damping time, and  $\epsilon_s$  the equilibrium emittance in the absence of IBS. This equation gives the equilibrium emittance in the presence of IBS:

$$\epsilon_0 = \frac{\epsilon_s}{2} + \sqrt{\frac{\epsilon_s^2}{4} + bT_s}. \quad (4)$$

In the present DR design, IBS adds about 20% to  $\epsilon_s$  [17] (i.e.,  $\epsilon_0 = 1.2\epsilon_s$ ), which gives  $bT_s \sim 0.25\epsilon_s^2$ . For the design with  $\epsilon_s \rightarrow 0$  (see above) and a shorter damping time,  $T'_s$ , the new equilibrium emittance in IBS-dominated DR would be

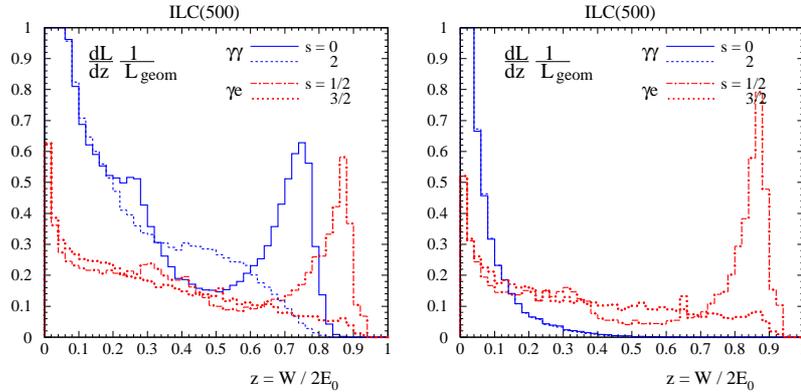
$$\epsilon' = \sqrt{bT'_s} \sim 0.5\epsilon_s \sqrt{\frac{T'_s}{T_s}}, \quad (5)$$

where the latter equality is valid only for the example above. If we decrease the damping time by a factor of 5, the resulting emittance

$$\epsilon'/\epsilon_0 \sim 0.19. \quad (6)$$

So, it would seem that there are a lot of resources for decreasing the damping time and thus decreasing emittances in  $x, y$  directions, as well as  $\beta_x$ . Until  $\beta_{x,y} > \sigma_z$  (the hour-glass effect) and  $\sigma_y > 1$  nm [18] there is a strong dependence of the luminosity on emittances ( $L \propto 1/\sqrt{\epsilon_{nx}\epsilon_{ny}\beta_x\beta_y}$ ). The decrease of the damping time will need more RF peak power, but this problem is solvable. The tune shift due to the beam space charge may not be important due to strong damping.

Let us assume, as an optimistic goal, a reduction (compared to the nominal beam parameters) of  $\epsilon_{nx}$  by a factor of 6,  $\epsilon_{ny}$  by a factor of 4, and  $\beta_x$  down to 1.7 mm (which is possible for such emittances). Then, one can have the following parameters for the photon collider:  $N = 2 \times 10^{10}$ ,  $\nu = 14$  kHz,  $\epsilon_{nx} = 1.5 \times 10^{-6}$  m,  $\epsilon_{ny} = 1 \times 10^{-8}$  m,  $\beta_x = 1.7$  mm,  $\beta_y = 0.3$  mm, the distance between interaction and conversion regions is 1 mm,  $\sigma_x = 72$  nm,  $\sigma_y = 2.5$  nm,  $L_{\text{geom}} = 2.5 \times 10^{35}$ ,  $L_{\gamma\gamma}(z > 0.8z_m) \sim 2.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \sim 1.25L_{e^+e^-, \text{nominal}}$ . The resulting  $\gamma\gamma$  luminosity is larger than at the nominal beam parameters by a factor of 7. This is very attractive and needs serious consideration by DR experts!



**Figure 1.**  $\gamma\gamma$ ,  $\gamma e$  luminosity spectra. Left: both beams are converted to photons. Right: only one beam is converted to photons. See parameters in the text.

The (interesting) event rate in  $\gamma\gamma$  collisions will be higher than in  $e^+e^-$  by one order of magnitude. This opens new possibilities, such as the study of Higgs self-coupling in  $\gamma\gamma$  collisions just above the  $\gamma\gamma \rightarrow hh$  threshold [19].

Figure 1 shows simulated luminosity spectra for these parameters. All important effects are taken into account. In the figure on the right, only one of the electron beams is converted to photons, it is more preferable for  $\gamma e$  studies due to easier luminosity measurement [20] and smaller backgrounds. The corresponding luminosities  $L_{\gamma\gamma}(z > 0.8z_m) \sim 2.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ,  $L_{\gamma e}(z > 0.8z_m) \sim 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ . By increasing the distance between the conversion and interaction regions, one can obtain a much more monochromatic luminosity spectrum with reduced luminosity for the study of QCD processes [21].

I want to stress again that parameters of the ILC damping rings are dictated not by  $e^+e^-$ , but by  $\gamma\gamma$  collisions and a decision on the DR design should be based on the dependence  $L_{\gamma\gamma} = f(\text{DR cost})$ . It could be that the increase of the  $\gamma\gamma$  luminosity by a factor of 7, as suggested above, is too difficult, but even a 3–5 times improvement will be very useful. This is a very important and urgent task!

Another remark is that the photon collider does not need positrons, and so one can consider a scheme without damping rings at all. Unfortunately, the product of emittances in polarized electron guns is larger than in damping rings, though progress is possible. A more radical improvement can be provided by the laser cooling [22,23], where intense laser beams are used instead of wigglers. In this case, the cooling process is very fast, there is no IBS, etc. Preliminary estimates show that the  $\gamma\gamma$  luminosity can be increased by a factor of 30. However, it is too early to consider this method seriously, but it should be kept in mind for the second stage of the photon collider, the ‘ $\gamma\gamma$  factory’.

### 3. Conclusion

In summary, in order to have a high luminosity at the photon collider, damping rings with emittances much smaller than for  $e^+e^-$  are required. No serious study

has been done yet. It is not excluded that optimized wiggler-dominated storage rings would allow  $\gamma\gamma$  luminosity a factor of five higher than that in the present design. The possibility of handling smaller horizontal emittance should be foreseen in designs of all ILC system (bunch compression, big bend, etc.).

## References

- [1] I F Ginzburg, G L Kotkin, V G Serbo and V I Telnov, *Pizma ZhETF* **34**, 514 (1981); *JETP Lett.* **34**, 491 (1982)
- [2] I F Ginzburg, G L Kotkin, V G Serbo and V I Telnov, *Nucl. Instrum. Methods* **205**, 47 (1983)
- [3] B Badelek *et al*, *Int. J. Mod. Phys.* **A30**, 5097 (2004), hep-ex/0108012
- [4] V I Telnov, *Acta Physica Polonica* **B37**, 633 (2006), physics/0602172
- [5] V I Telnov, *Acta Physica Polonica* **B37**, 1049 (2006), physics/0604108
- [6] E E Boos, *Nucl. Instrum. Methods* **A472**, 22 (2001), hep-ph/0009100
- [7] S Brodsky, *Acta Physica Polonica* **B37**, 619 (2006)
- [8] M M Muhlleitner and P M Zerwas, *Acta Physica Polonica* **B37**, 1021 (2006), hep-ph/0511339
- [9] V I Telnov, Layout of the photon collider at the ILC, *These proceedings*
- [10] V Telnov, *Nucl. Phys. Proc. Suppl.* **82**, 359 (2000), hep-ex/9908005
- [11] V I Telnov, *Nucl. Instrum. Methods* **A472**, 43 (2001), hep-ex/0010033
- [12] V I Telnov, *Proc. of 2005 Int. Linear Collider Physics and Detector Workshop and 2nd ILC Accelerator Workshop*, Snowmass, Colorado, 14–27 August 2005, ECONF C0508141:PLEN0020, 2005, physics/0512048
- [13] A Seryi, talk at the *Second ILC Accelerator Workshop*, Snowmass, Colorado, August 14–27, 2005, <http://www.slac.stanford.edu/econf/C0508141/proc/pres/ILCAW1203.TALK.PDF>
- [14] A Wolski, talk at the *Second ILC Accelerator Workshop*, Snowmass, Colorado, August 14–27, 2005, <http://www.slac.stanford.edu/econf/C0508141/proc/pres/ILCAW1202.TALK.PDF>
- [15] H Wiedemann, *Particle accelerator physics: Basic principles and linear beam dynamics* (Springer, Berlin, Germany, 2003)
- [16] J Bisognano *et al*, *Part. Accel.* **18**, 233 (1986)
- [17] K Kubo, S K Mtingwa and A Wolski, *Phys. Rev. ST Accel. Beams* **8**, 081001 (2005)
- [18] V I Telnov, *Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics*, Snowmass, 2001, edited by N Graf, eConf **C010630** (2001) T104
- [19] G V Jikia, *Nucl. Phys.* **B412**, 57 (1994)  
R Belusevic and G Jikia, *Phys. Rev.* **D70**, 073017 (2004)
- [20] A V Pak, D V Pavluchenko, S S Petrosyan, V G Serbo and V I Telnov, *Nucl. Phys. Proc. Suppl.* **126**, 379 (2004), hep-ex/0301037
- [21] V I Telnov, talk at the *ECFA Workshop on Linear Colliders*, Montpellier, France, 12–16 November 2003; [http://www-h1.desy.de/~maxfield/ggcol/montpellier\\_talks/Valery\\_Lumispec.MONT1.PDF](http://www-h1.desy.de/~maxfield/ggcol/montpellier_talks/Valery_Lumispec.MONT1.PDF)
- [22] V I Telnov, *Phys. Rev. Lett.* **78**, 4757 (1997), Erratum: *Phys. Rev. Lett.* **80**, 2747 (1998), hep-ex/9610008
- [23] V I Telnov, *Nucl. Instrum. Methods* **A455**, 63 (2000), hep-ex/0001029