Vol. 37 (2006) *ACTA PHYSICA POLONICA B* No 3

PHOTON COLLIDERS: THE FIRST 25 YEARS*

V.I. Telnov

Budker Institute of Nuclear Physics, Russian Academy of Sciences
Prospekt Lavrent'eva 11, 630090 Novosibirsk, Russia
telnov@inp.nsk.su

(Received February 20, 2006)

In this invited talk at the "historical" session of PHOTON2005, I was asked to recount the history and the development, from its earliest days to the present, of the idea of photon colliders based on conversion of high energy electrons to high-energy photons at a future high-energy linear e^+e^- collider. Described in this talk are the general features and schemes of a photon collider, the evolution in understanding of what the parameters of a realistic photon collider are, possible solutions of various technical problems, the physics motivation, and the present status of photon collider development. For a more detailed description of the photon collider at the ILC and a discussion of the associated technical issues, please refer to my talks at PLC2005, the conference that immediately followed PHOTON2005 (to be published in *Acta Phys. Pol. B* as well).

PACS numbers: 29.17.+w, 41.75.Ht, 41.75.Lx, 13.60.Fz

1. Prehistory and the idea of the photon collider

Photon colliders do not exist yet, but already have a rich 25-year history. The early history of $\gamma\gamma$ physics, studied mainly in collisions of virtual photons at e^+e^- storage rings, has been presented at PHOTON2005 by Brodsky [1] and Ginzburg [2]. Hence, I begin my narration by describing the circumstances that led to the birth of the idea of the high-energy photon collider. This is the first time I share an account of these events with the public; this conference, subtitled "*The Photon: Its First Hundred Years and the Future*", provides an appropriate venue for such historical reviews. I will also mention the story of the observation of $C = +$ resonances in $\gamma\gamma$ collisions at SLAC in 1979, which is also an important event in the $\gamma\gamma$ history.

* Presented at the PHOTON2005 Conference, 31 August–4 September 2005, Warsaw, Poland.

Two-photon physics had been talked about since 1930s, but as an active research field is began in early 1970s, when production of e^+e^- pairs was discovered in collisions of *virtual* photons at the e^+e^- storage ring VEPP-2 in Novosibirsk and theorists realized that this method can be used to study a variety of two-photon processes.

To study two-photon physics at a greater depth, we in Novosibirsk decided to build MD-1, a dedicated detector with a transverse magnetic field and a tagging system for scattered electrons. Before experiments at the VEPP-4 collider started, in 1978–79 I had the privilege of having been able to visit SLAC for four months and work with the Mark II group, where I observed two-photon production of the η' and f_2 mesons. It then became clear that tagging of the scattered electrons is not necessary for study of many two-photon processes; the MARK II paper on two-photon η' production [3] triggered a wave of results from all e^+e^- experiments.

Many interesting two-photon reactions were studied in the years that followed, but the results could not compete with the revolutionary discoveries made in e^+e^- annihilation. The reason for this is that the luminosity and the energy in virtual $\gamma\gamma$ collisions are small. Indeed, the number of equivalent photons surrounding each electron is $dN_\gamma \sim 0.035\, d\omega/\omega$, and the corresponding $\gamma\gamma$ luminosity for $W_{\gamma\gamma}/2E_0 > 0.2$ is only $L_{\gamma\gamma} \approx 4 \times 10^{-3} L_{e^+e^-}$, which is an order of magnitude smaller than for $W_{\gamma\gamma}/2E_0 > 0.5$.

The other important element that led to the conception of the idea of high-energy photon colliders is the activity on e^+e^- linear colliders in Novosibirsk. In December 1980, the first USSR workshop on physics at VLEPP was held in Novosibirsk [4]. Only one talk on $\gamma\gamma$ physics was on the agenda, an overview by Ginzburg and Serbo of the physics of two-photon production of hadrons at VLEPP energies (in collisions of virtual photons). I was not planning to give any talks, but several days before the workshop I began to think about the possibility of converting electrons to *real* photons in order to increase the $\gamma\gamma$ luminosity at VLEPP. At the discussion session, which was part of the workshop's schedule, I gave a short talk on this subject using blackboard.

The idea was rather simple. At linear colliders, electron beams are used only once, which makes it possible to convert electrons to photons, and thus to obtain collisions of real photons. All that is needed is some sort of a target at a small distance from the interaction point (IP), where the conversion would take place. For example, if one were to place a target of $0.3\, X_0$ thickness, the number of bremsstrahlung photons would be greater than the number of virtual photons by one order of magnitude, and the corresponding $\gamma\gamma$ luminosity would increase by two orders of magnitude; however, this approach suffers from photo-nuclear backgrounds. I continued my talk by saying that there are other methods of conversion: for example, crystals are better than amorphous targets because the effective X_0 is much shorter, leading to smaller backgrounds; undulators produce photons whose energies are too low... At this exact moment G. Kotkin interjected from his chair, "Lasers!". In fact, this method was already well-known in our community: at SLAC, Compton backscattering had been used since mid-1960s for production of high-energy photons; in Novosibirsk, such a facility had been constructed for our experiments at VEPP-4 for the measurement of the electron polarization in the method of resonant beam depolarization.

During the following discussion, several people expressed quite a negative reaction to the idea of laser $e \to \gamma$ conversion due to the very low conversion probability. In the 4.5-page summary on two-photon physics written for the workshop proceedings by Ginzburg, Serbo and me, there was only one paragraph about the photon collider idea, with the conclusion that a more detailed study is needed.

Immediately after this workshop, a group of $\gamma\gamma$ enthusiasts, namely: I. Ginzburg (Institute of Mathematics), G. Kotkin (Novosibirsk State University), V. Serbo (also NSU) and V. Telnov (INP) decided to pursue the method of the laser photon conversion further: if feasible, it would be the best among all the alternatives. It was a very exciting study, and contributions from all members of this team were vitally important to make possible the first publication and further advances on the concept of photon colliders.

The method of production of high-energy photons by Compton scattering of laser light off high-energy electrons was proposed in 1963 by Arutyunian, Goldman and Tumanian [5] and independently by Milburn [6], and soon afterwards was utilized [7, 8]. However, the conversion coefficient was very small, about $k = N_\gamma/N_e \sim 10^{-7}$ [8]. For the photon collider, we needed $k \sim 1$, seven orders of magnitude more!

We determined the required laser flash energy, then checked the literature on powerful lasers, consulted with laser experts, and found that lasers with required flash energies, about 10 J, already existed, albeit with much longer pulse durations and lower repetition rates than those required by a photon collider (the repetition rate in the VLEPP project circa 1980 was only 10–100 Hz, compared with 15 kHz in the present ILC design). Discussions with laser experts gave us some hope that these problems will be solved in future. Extrapolating the progress of laser technologies into the next two decades and adding our optimism, we came to the conclusion that a photon collider based on laser photon conversion is not such a crazy idea and deserves being published.

The preprint INP 81-50, dated February 25, 1981 (in English), was sent to all major HEP laboratories and to many individual physicists, but publication of the corresponding paper was a problem. The original submission of our paper to *Pisma Zh. Eksp. Teor. Fiz.* was rejected: *"... the editorial* *board does not consider worthwhile a rapid publication of your article because the realization of such an experiment is not possible in the near future … lasers of the required parameters do not exist … and their creation is not likely in near future.*" We resubmitted the article to the same journal with additional comments, but once again received a confirmation of the previous refusal. We then sent the paper to *Physics Letters*, were was declined as well, *"...the article is very interesting but does not need urgent publication. You can publish it, for example, in Nuclear Instruments & Methods."* What do we do? Fortunately, in August 1981 we had a chance to meet personally with I. Sobelman, the editor of *Pisma Zh. Eksp. Teor. Fiz.*, who was visiting Novosibirsk; following that meeting, the paper was published on November 5, 1981 (received March 10) [9]. Two additional, more detailed papers written in 1981–1982 [10, 11] were published in NIM; their combined citation index now surpasses 1000.

In September 1981, Akerlof of the University of Michigan published a preprint [12] that contained a similar idea. However, he considered only γe collisions and underestimated the required laser flash energy by 1–2 orders of magnitude. That was after two of our preprints [9, 10], and mentioning of the photon collider concept in August 1981 at the Symposium on Lepton and Photon Interactions at High Energies in Bonn in VLEPP status report [13]. In November 1981, Kondratenko, Pakhtusova and Saldin from our institute suggested the use of single-pass free-electron lasers in a future photon collider [14].

In the following sections, we consider the main principles and features of photon colliders, the technical issues, and how the laser and linear collider technologies and our understanding of them evolved with time.

Two remarks are in order. Firstly, we consider only *high-energy* photon colliders of luminosities that are of real interest to particle physics. As for low-energy photon–photon scattering, in 1928–30 Vavilov in attempted detection of scattering of visible photons from two lamps [15]; later, people experimented with laser photons, but these experiments also failed due to the very small cross section for photon–photon scattering at low energies. There existed ideas of using synchrotron radiation, beamstrahlung photons, and even nuclear explosions (Csonka [16]) to study photon–photon interactions. Beamstrahlung photons can indeed have high energies, but the idea is not practicable as collisions of virtual photons at storage rings provide a much higher luminosity.

Secondly, it is well known that during collisions at e^+e^- linear colliders electrons and positrons emit hard photons, about one such photon per electron. So, simultaneously with e^+e^- collisions, for free, one gets a photon–photon collider of a high luminosity and a rather high energy (typically several percents of the beam energy, but can be higher). At very high energies, the average energy of such beamstrahlung photons is about 25% of the electron energy. In 1988, Blankenbecler and Drell even considered the prospects for such a photon–photon collider in the quantum beamstrahlung regime [17]. The disadvantages of this method are the following [18]: one needs a multi-TeV linear collider (or very small beam sizes), the luminosity is limited by beam-collision instabilities, the photon spectrum is wide, and in the strong field ($\Upsilon > 1$) of the opposing beam the high-energy photons will convert to e^+e^- pairs. At the photon colliders based on Compton backscattering, beamstrahlung photons contribute to the low-energy part of the $\gamma\gamma$ luminosity spectrum and are taken into account in all simulations.

2. Nomenclature of linear collider projects

Over the past two decades, several projects of linear colliders were in existence, see Table I. Only one of them, the SLC, was actually built and operated quite successfully at Z-boson energy. The SLC was quite a special linear collider, constructed on the base of the existing SLAC linear accelerator by adding two arcs to achieve e^+e^- collisions. Its luminosity was about 3 orders of magnitude lower than the luminosity that can be obtained at an optimized linear collider. At present, two projects remain: the International Linear Collider (ILC) with the energy of up to 1 TeV and the Compact Linear Collider (CLIC) with the energy of up to 3 (perhaps 5) TeV. Neither of the projects has been approved; however, there is an "intent", and a hope, to have the ILC built by 2015.

TABLE I

Linear collider projects, the past and the present.

Name	Center	Type	Energy [GeV]	Years
VLEPP	BINP	S, X-band	500–1000	~ 1978–1995
SLC	SLAC	S-band	90	~ 1987–2000 (oper.)
NLC	SLAC	X-band	500–1000	~ 1986–2004
JLC	KEK	X-band	500–1000	~ 1986–2004
TESLA	DESY	L-band, s-cond.	500–800	~ 1990–2004
SBLC	DESY	S-band	500–100	~ 1992–1997
CLIC	CERN	X, two-beam	500–3000	~ 1986–...
ILC	????	L-band, s-cond.	500–1000	~ 2004–...

3. Basics of the photon collider

Here, we briefly consider the main characteristics of backward Compton scattering and the requirements on the lasers.

3.1. Kinematics and photon spectra

In the conversion region, a laser photon of energy ω_0 collides with a high-energy electron of energy E_0 at a small collision angle α_0 (almost head-on). The energy of the scattered photon ω depends on the photon scattering angle ϑ in respect to the initial direction of the electron as follows [10]:

$$\omega = \frac{\omega_{\rm m}}{1+(\vartheta/\vartheta_0)^2}, \qquad \omega_{\rm m} = \frac{x}{x+1}E_0, \qquad \vartheta_0 = \frac{mc^2}{E_0}\sqrt{x+1}\,, \tag{1}$$

where

$$x = \frac{4E\omega_0}{m^2c^4}\cos^2\frac{\alpha_0}{2} \simeq 15.3\left[\frac{E_0}{\rm TeV}\right]\left[\frac{\omega_0}{eV}\right] = 19\left[\frac{E_0}{\rm TeV}\right]\left[\frac{\mu{\rm m}}{\lambda}\right], \tag{2}$$

$\omega_{\rm m}$ being the maximum energy of scattered photons. For example: $E_0 = 250\,{\rm GeV}$, $\omega_0 = 1.17\,{\rm eV}$ ($\lambda = 1.06$ μm) (for the most powerful solid-state lasers) $\Rightarrow x = 4.5$ and $\omega_{\rm m}/E_0 = 0.82$. Formulae for the Compton cross section can be found elsewhere [10, 11].

The energy spectrum of the scattered photons depends on the average electron helicity λ_e and that of the laser photons P_c. The "quality" of the photon beam, *i.e.*, the relative number of hard photons, is improved when one uses beams with a negative value of $\lambda_e P_c$. The energy spectrum of the scattered photons for $x = 4.8$ is shown in Fig. 1 for various helicities of the electron and laser beams.

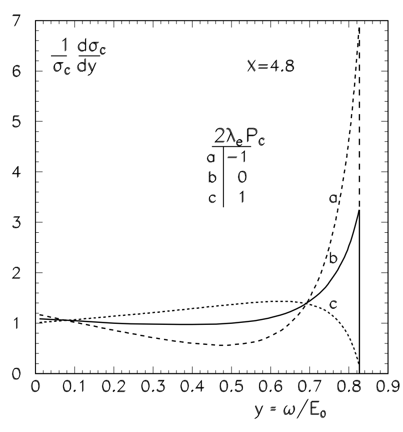

Fig. 1. Spectrum of the Compton-scattered photons.

With increasing x, the energy of the backscattered photons increases, and the energy spectrum becomes narrower. However, at large values of x, photons may be lost due to creation of e^+e^- pairs in the collisions with laser photons [10, 18, 19]. The threshold of this reaction is $\omega_{\rm m}\omega_0 = m^2c^4$, which corresponds to $x = 2(1+\sqrt{2}) \approx 4.83$. One can work above this threshold, but with a reduced luminosity; the luminosity loss factor is about 5–10 for $x = 10$–20. Therefore, $x \approx 4.8$ is the most preferable value. The optimum wavelength of the laser photons corresponding to $x = 4.8$ is

$$\lambda = 4.2E_0\ [\mathrm{TeV}]\ \mu\mathrm{m}\,. \tag{3}$$

The mean helicity of backscattered photons at $x = 4.8$ is shown in Fig. 2 for various helicities of the electron and laser beams. For $2P_c\lambda_e = -1$ (the case of the peaked energy spectrum), all photons in the high-energy peak have a high degree of like-sign polarization. A high degree of circular photon polarization is essential for the study of many physics processes.

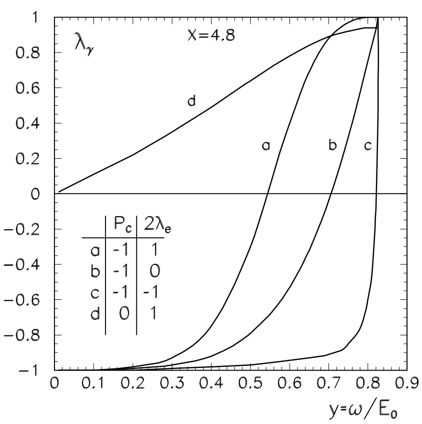

Fig. 2. Average helicity of the Compton-scattered photons.

3.2. Multi-photon (nonlinear) effects at the conversion region

The electromagnetic field in the laser wave at the conversion region is very strong, and so electrons can interact with several laser photons simultaneously. These nonlinear effects are characterized by the parameter [22, 23, 25]

$$\xi^2 = \frac{e^2\overline{F^2}\hbar^2}{m^2c^2\omega_0^2} = \frac{2n_\gamma r_e^2\lambda}{\alpha} = 0.36\left[\frac{P}{10^{18}\ \mathrm{W/cm^2}}\right]\left[\frac{\lambda}{\mu\mathrm{m}}\right]^2, \tag{4}$$

where F is the r.m.s. strength of the electric (magnetic) field in the laser wave and n_γ is the density of laser photons. At $\xi^2 \ll 1$, the electron scatters on one laser photon, while at $\xi^2 \gg 1$ scattering on several photons occurs.

The transverse motion of an electron through the electromagnetic wave leads to an effective increase of the electron's mass: $m^2 \to m^2(1+\xi^2)$, and so the maximum energy of the scattered photons decreases: $\omega_{\rm m}/E_0 = x/(1+x+\xi^2)$. At $x = 4.8$, the value of $\omega_{\rm m}/E_0$ decreases by about 5% for $\xi^2 = 0.3$. For figures demonstrating evolution of the Compton spectra as a function of ξ^2 please refer to Refs. [25, 26]. With increasing ξ^2, the Compton spectrum is shifted towards lower energies, and higher harmonics appear; the part of the $\gamma\gamma$ luminosity spectra that is due to nonlinear effects becomes broader. So, the value of $\xi^2 \sim 0.3$ can be taken as the limit for $x = 4.8$; for smaller values of x it should be even lower. The complete set of formulae for pair production in the laser wave for any combination of polarizations and field strengths can be found in Ref. [27].

Nonlinear effects also exist in e^+e^- creation at the conversion region in collisions of laser and high-energy photons [20, 23, 24, 26]. There exist some other interesting effects in the conversion region, such as the variation of polarization of electrons [28] and high-energy photons [29] in the laser wave.

3.3. Laser flash energy

While calculating the required flash energy, one must take into account the diffractive divergence of the laser beam and to keep small the nonlinear parameter ξ^2. The r.m.s. radius of the laser beam near the conversion region depends on the distance z to the focus (along the beam) as [10]

$$a_\gamma(z) = a_\gamma(0)\sqrt{1+\frac{z^2}{Z_{\rm R}^2}}\,, \qquad a_\gamma(0) \equiv \sqrt{\frac{\lambda Z_{\rm R}}{2\pi}}\,, \tag{5}$$

where $Z_{\rm R}$ is the Rayleigh length characterizing the length of the focal region.

Neglecting multiple scattering, the dependence of the conversion coefficient on the laser flash energy A can be written as

$$k = \frac{N_\gamma}{N_e} \sim 1 - \exp\left(-\frac{A}{A_0}\right)\,, \tag{6}$$

where A_0 is the laser flash energy for which the thickness of the laser target is equal to one Compton collision length. The value of A_0 can be roughly estimated from the collision probability $p \sim 2n_\gamma\sigma_c\ell = 1$, where $n_\gamma \sim A_0/(\pi\omega_0 a_\gamma^2 \ell_\gamma)$, $\sigma_{\rm c}$ is the Compton cross section ($\sigma_{\rm c} = 1.8\times10^{-25}$ cm^2 at $x = 4.8$), ℓ is the length of the region with a high photon density, which is equal to $2Z_{\rm R} = 4\pi a_\gamma^2/\lambda$ at $Z_{\rm R} \ll \sigma_{L,z} \sim \sigma_z$ ($\sigma_z, \sigma_{L,z}$ are the r.m.s. lengths of the electron and laser bunches), and the factor 2 due to the relative velocity of electrons and laser photons. This gives, for $x = 4.8$

$$A_0 \sim \frac{\pi\hbar c\sigma_z}{2\sigma_{\rm c}} \sim 3\sigma_z[\mathrm{mm}]\,\mathrm{J}\,. \tag{7}$$

Note that the required flash energy decreases when the Rayleigh length is reduced to σ_z, but it hardly changes with further decreasing $Z_{\rm R}$. This happens because the density of photons grows but the length decreases, and as a result the Compton scattering probability remains nearly constant. It is not helpful either to make the radius of the laser beam at the focus smaller than $a_\gamma(0) \sim \sqrt{\lambda\sigma_z/2\pi}$, which may be much larger than the transverse electron bunch size in the conversion region. From (7) one can see that the flash energy A_0 is proportional to the electron bunch length, and for $\sigma_z = 0.3$ mm (ILC) it is about 1 J. The required laser power is

$$P \sim \frac{A_0 c}{2\sigma_z} \sim \frac{\pi\hbar c^2}{4\sigma_{\rm c}} \sim 0.4 \times 10^{12}\, W\,. \tag{8}$$

More precise calculations of the conversion probability in head-on collision of an electron with a Gaussian laser beam can be found elsewhere [10,18,19,21]; they are close to the above estimate.

However, this is not a complete picture, since one should also take into account the following effects:

- *Nonlinear effects in Compton scattering.* The photon density is restricted by this effect. For shorter bunches, nonlinear effects will determine the laser flash energy.
- *Collision angle.* If the laser and electron beams do not collide head-on (if the laser optics is outside the electron beam), the required laser flash energy is larger by a factor of 2–2.5.
- *Transverse size of the electron beam.* In the crab-crossing scheme, the electron beam is tilted, which leads to an effective transverse beam size comparable to the optimum laser spot size.

Simulations show [30, 36, 61] that if all the above effects are taken into account, the required flash energy for the photon collider at the ILC with $2E_0 = 500$ GeV and for $\lambda = 1.05\,\mu$m is about $A \approx 9$ J, $\sigma_t \sim 1.5$ ps, $a_\gamma(0) \sim 7\,\mu$m. The corresponding peak power is 2.5 TW. The optimum divergence of the laser beam is about ± 30 mrad. Lasers with $\lambda \approx 1\ \mu$m can be used up to $2E_0 \sim 700$ GeV [36] (due to the e^+e^- pair creation in the conversion region).

4. The most important advances in photon colliders

4.1. Early considerations, collision schemes

In early 1980s, two linear colliders were under consideration: VLEPP [31] and SLC [32]. For the photon collider, we used the parameters presented in Table II.

For e^+e^- collisions at VLEPP flat beams were considered from the beginning. As the flatness was not necessary for $\gamma\gamma$, for simplicity we considered round beams with the same beam cross section. At SLC, round beams were

TABLE II

Parameters of VLEPP and SLC used for $\gamma\gamma$ collider in 1980.

	VLEPP	SLC
CM energy, GeV	200–600	100–140
Luminosity, $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	10^{32}	2×10^{30}
Particles in one bunch	10^{12}	2×10^{10}
Repetition rate	10	180
Trans. sizes* $a_e = \sqrt{2}\sigma_x = \sqrt{2}\sigma_y$, μm	1.25	1.8
Bunch length, σ_z, mm	1.8	1.0
Beta-function at IP, cm	1.0	0.5

planned even for e^+e^-. These parameters differ very much from those in the present projects.

The second fact that influenced the initial consideration of the photon-collider scheme was the minimum focal spot size achieved with powerful lasers: it was about 20 μm, much larger than the optimum one for a diffraction-limited laser beam.

The originally proposed scheme of the photon collider is shown in Fig. 3 [9, 10]. The laser light is focused on the electron beam in the conversion region A, at a distance of $b \sim 10$ cm from the interaction point O; after Compton scattering, the high-energy photons follow along the initial electron trajectories with a small additional angular spread $\sim 1/\gamma$, *i.e.*, they are focused in the interaction point O. Electrons are swept away by a magnetic field $B \sim 1$ T. The obtained γ beam collides downstream with the oppositely directed electron beam or another γ beam. The required laser flash energy (for VLEPP or SLC beam parameters) was about 10–20 J.

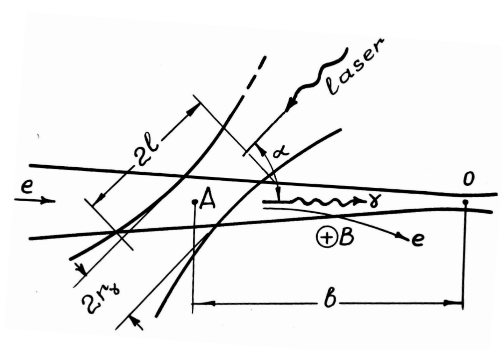

Fig. 3. The scheme of the photon collider with magnetic deflection [9, 10].

The scheme with the magnetic deflection of used beams allowed rather clean $\gamma\gamma$ or γe collisions to be produced. Taking $b \gg \gamma a_e$, one can obtain a $\gamma\gamma$ luminosity spectrum with the width of $\sim$10–15 % (the "monochromatization" effect [10,11]). The optimum distance b corresponds to the case when the size of the photon beams at the IP due to Compton scattering is comparable to the vertical (minimum) size of the electron beam: $b \sim \sigma_y \gamma$, that is, about $b \sim 20\,\mathrm{cm}$ for $E_0 = 100\,\mathrm{GeV}$ and $\sigma_y = 1\,\mu\mathrm{m}$. Another factor limiting the maximum value of b is the increase of the electron beam size, which leads to the increase of the required laser flash energy. The minimum laser spot size attainable, 20 μm, allowed $b \sim 10$ cm, which was sufficient for magnetic deflection. Later, in 1985, the chirped pulse amplification (CPA) laser technology emerged, which enabled production of laser beams of "diffraction" quality, allowing reduction of the spot sizes to their diffraction limits (we considered such beams as a limiting case). In the following year, the vertical beam sizes in LC projects decreased down to 3–5 nm. It became clear that on order to maximize the $\gamma\gamma$ luminosity, it is necessary to focus the beam both in the vertical and horizonal directions to the smallest possible spot cross section $\sigma_x \sigma_y$. Damping rings naturally produce beams with a vertical emittance that is much smaller than the horizontal emittance, so the resulting photon beams at the IP are flat (though not as flat as in e^+e^- collisons). For $\sigma_y = 3\,\mathrm{nm}$, the optimum $b \sim \gamma\sigma_y \sim 1.5\,\mathrm{mm}$ for $2E_0 = 500\,\mathrm{GeV}$. This space is way too small to fit any kind of a magnet. Therefore, since 1991 [33], we have been considering the scheme with no magnetic deflection, Fig. 4 (upper). In this case, there is a mixture of $\gamma\gamma$, γe and e^-e^- collisions,

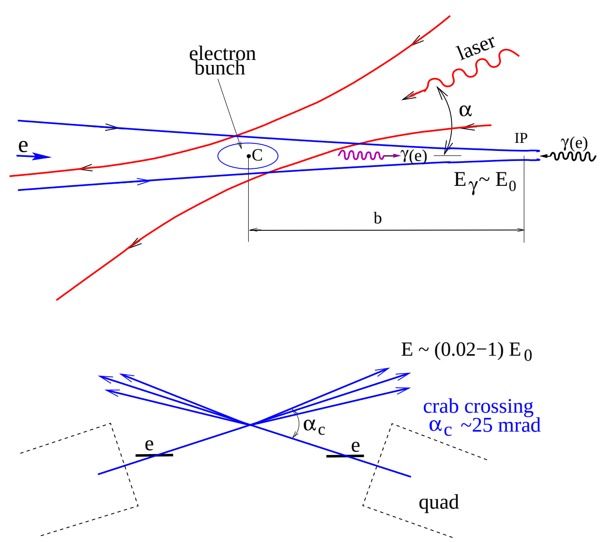

Fig. 4. Scheme of $\gamma\gamma$, γe collider.

beamstrahlung photons give a very large contribution to the $\gamma\gamma$ luminosity at the low and intermediate invariant masses, the backgrounds are larger, and the disruption angles are larger than in the scheme with magnetic deflection. However, there are certain advantages: the scheme is simpler, and the luminosity is larger. As for the backgrounds, they are larger but tolerable.

Note, that even without deflecting magnets there is the beam–beam deflections which suppress residual e^-e^- luminosity. Also at large CP–IP distances and a non-zero crossing angle the detector field serves as the deflecting magnet and allows to get more or less clean and monochromatic $\gamma\gamma, \gamma e$ collisions with reduced luminosity which will be useful for QCD studies [34].

4.2. The removal of beams

After crossing the conversion region, the electrons have a very broad energy spectrum, $E = (0.02\text{–}1)E_0$, and so the removal of such a beam from the detector is far from obvious. In the scheme with magnetic deflection, all charged particles travel in the horizontal plane following the conversion. At the IP, they get an additional kick from the oncoming beam, also in the horizontal plane. This gave us a hope that the beams can be removed through a horizontal slit in the final quadrupoles; that was a feasible, but a difficult-to-implement solution.

In 1988, Palmer suggested the crab-crossing scheme for e^+e^- collisions at the NLC in order to suppress the multi-bunch instabilities [35], Fig. 4 (bottom). In the crab-crossing scheme, the beams are collided at a crossing angle, $\alpha_{\rm c}$. In order to preserve the luminosity, the beams are tilted by a special cavity by the angle $\alpha_{\rm c}/2$. This scheme solves the problem of beam removal at photon colliders [18]: the disrupted beams just travel straight outside the quadrupoles.

In the scheme without magnetic deflection (which is now the primary scheme), the disrupted beams have an angular spread of about $\pm$ 10 mrad after the IP [26, 36]. The required crossing angle is determined by the disruption angle, the outer radius of the final quadrupole (about 5 cm), and the distance between the first quad and the IP (about 4 m), which gives $\alpha_{\rm c} \approx 25$ mrad.

4.3. Luminosity

In e^+e^- collisions, the maximum achievable luminosity is determined by beamstrahlung and beam instabilities. At first sight, in $\gamma\gamma$,γe collisions at least one of the two beams is neutral, and so the beams do not influence each other; however, it is not so. Beam-collision effects at photon colliders were considered in Refs. [18, 19]. The only effect that restricts the $\gamma\gamma$ luminosity is the conversion of the high-energy photons into e^+e^- pairs in the field of the opposing beam, that is, coherent pair creation [37]. The threshold field for this effect $\kappa = (E_\gamma/mc^2)(B/B_0) \sim 1$, where $B_0 = \alpha e/r_e^2 = 4.4 \times 10^{13}$ Gauss is the Schwinger field and B is the beam field. For γe collisions, the luminosity is determined by beamstahlung, coherent pair creation and the beam displacement during the collision. All these processes, and a few others, were included into the software codes for simulation of beam collisions at linear colliders by Yokoya [38], Telnov [19] and Schulte [39]. The code [19] was used for optimization of the photon colliders both at NLC [21] and TESLA [26, 79].

It is interesting to note that at the center-of-mass energies below 0.5–1 TeV and for electron beams that are not too short, the coherent pair creation is suppressed due to the broadening and displacement of the electron beams during the collision [40, 41]: the beam field becomes lower than the threshold for e^+e^- production. So, one can even use infinitely narrow electron beams. Simulated $\gamma\gamma$ and γe luminosities (in the high energy peak) for TESLA (and, similarly, for ILC) are shown in Fig. 5 [55, 56]. This figure shows how the luminosity depends on the horizontal beam size. One can see that all $\gamma\gamma$ luminosity curves follow their natural behavior: $L \propto 1/\sigma_x$. Note that for e^+e^-, the minimum horizontal beam size restricted by beamstrahlung is about 500 nm, while the photon collider can work even with $\sigma_x \sim 10$ nm at $2E_0 = 500$ GeV, delivering a luminosity that is several times higher than that in e^+e^- collisions! In fact, the $\gamma\gamma$ luminosity is simply proportional to the *geometric* e^-e^- luminosity.

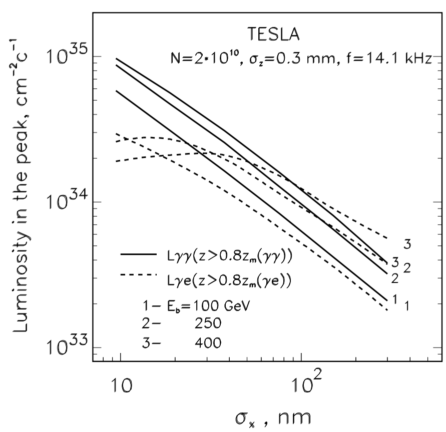

Fig. 5. Dependence of $\gamma\gamma$ and γe luminosities in the high energy peak on the horizontal beam size for TESLA–ILC at various energies.

Unfortunately, the beam emittances in the damping-ring designs currently under consideration do not allow beam sizes that are smaller than $\sigma_x \sim 250$ nm and $\sigma_y \sim 5$ nm, though a reduction of σ_x by a factor of two seems possible. In principle, one can use electron beams directly from low-emittance photo-guns, avoiding the need for damping rings altogether, but at present they offer a product of the transverse emittances that is noticeably larger than can be obtained with damping rings (note: the beams should be polarized).

To further reduce the beam emittances downstream of the damping rings or photo-guns, one can use the method of laser cooling of the electron beams [42–44]. This method opens the way to emittances that are much lower than those obtainable at damping rings, however, this method requires a laser system that is much more powerful than the one needed to achieve the $e \to \gamma$ conversion. So, laser cooling of electron beams at linear colliders is a technology for use in a $\gamma\gamma$ factories in the distant future.

The typical $\gamma\gamma$, γe luminosity spectra for the TESLA–ILC(500) parameters are shown in Fig. 6 [26]. They are decomposed to states with different spins J_z of the colliding particles. The luminosity spectra and polarizations can be measured using various QED processes [45, 46]. At the nominal ILC parameters (foreseen for e^+e^- collisions), the expected $\gamma\gamma$ luminosity in the high-energy peak of the luminosity spectrum $L_{\gamma\gamma} \sim 0.15$–$0.2\, L_{e^+e^-}$ [36]. By reducing emittances in the damping rings (which is not easy but possible by adding wigglers), $L_{\gamma\gamma} \sim (0.3$–$0.5)\ L_{e^+e^-}$ can be acieved. Note that cross sections for many interesting processes in $\gamma\gamma$ collisions (*e.g.*, charged pairs, Higgs bosons, *etc.*) are higher than those in e^+e^- collisions by about one order of magnitude (see [26] and references therein), so in all cases the number of events in $\gamma\gamma$ collisions will be greater than in e^+e^-.

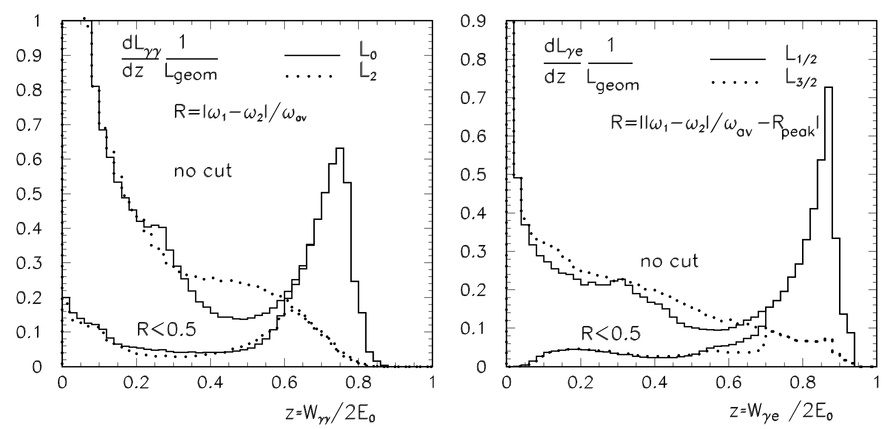

Fig. 6. The $\gamma\gamma$ (left) and γe (right) luminosity spectra for typical TESLA (ILC) parameters at $2E_0 = 500$ GeV. Solid lines for J_z of two colliding photons equal to 0, dotted lines for $J_z = 2$ (1/2 and 3/2, respectively, in the case of γe collisions). The total luminosity is the sum of the two spectra. The residual e^-e^- luminosity (not shown) is one order of magnitude smaller due to beam repulsion.

A few words about multi-TeV energies. Due to beamstrahlung, the maximum energy of a e^+e^- linear collider of a reasonable luminosity is $2E_0 \sim 5$ TeV [48], which can be reached with the CLIC technology. At high-energy photon colliders with short bunches, coherent pair creation plays a role that is similar to the role of beamstahlung in e^+e^-. In the high-energy limit, $\sigma_\gamma/\sigma_{e^+e^-} = 3.8$ [49, 50], which means that the energy reach of the photon colliders is approximately the same as in the e^+e^- case [41, 49–51]. In principle, one can imagine rather long electron bunches with a special transverse shape, such that in the process of beam collision the electrons are spread by the opposing beam in a more-or-less symmetrical fashion, so that the beam field near the axis (where the photons travel) is small, and so there is no coherent pair creation [49]. In this case, photon colliders can reach much higher energies; alas, this is quite an unrealistic dream.

4.4. The laser schemes and technologies

The photon collider at the ILC(500) requires a laser system with the following parameters (see Sec. 3.1): the flash energy $A \sim 10$ J, $\sigma_t \sim 1.5$ ps, $\lambda \sim 1\ \mu$m, and the following ILC pulse structure: 3000 bunches within a 1 ms train and 5 Hz repetition rate for the trains, the total collision rate being 15 kHz. These parameters are quite similar to those discussed for VLEPP, only the collision rate has increased by a factor of a thousand.

As has already been mentioned above, in 1981 the short-pulse Terawatt lasers required by a photon collider were just a dream. A breakthrough in laser technologies, the invention of the chirped pulse amplification (CPA) technique [52], occurred very soon, in 1985. In this case, "Chirped" means a time–frequency correlation within the laser pulse. The main problem in obtaining short pulses was the limitation of the peak power imposed by the nonlinear refractive index of the medium. This limit on intensity is about 1 GW/cm^2; the CPA technique successfully overcame it.

The principle of CPA is as follows. A short, ∼100 fs low-energy pulse is generated in an oscillator. Then, this pulse is stretched by a factor of 10^4 by a pair of gratings, which introduces a delay that is proportional to the frequency. This several-nanosecond-long pulse is amplified, and then compressed by another pair of gratings into a pulse of the initial (or somewhat longer) duration. As nonlinear effects are practically absent in the stretched pulses, the laser pulses obtained with the CPA technique have a quality close to the diffraction limit. This technique now allows the production of not merely TW, but even PW laser pulses, and in several years the Exawatt level will be reached. Fig. 7 [53] shows the increase of the laser energy density in W/cm^2 *versus* year for table-top laser systems. In 1981, the corresponded power was about ∼10 GW. The minimum power required by the photon collider was achieved roughly in 1992.

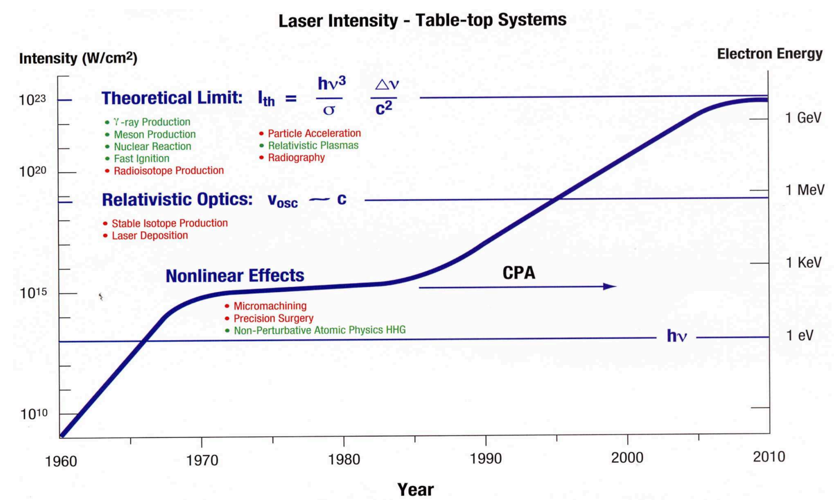

Fig. 7. Laser intensity *versus* year for table-top system. The progress in 1960s and 1970s was due to Q-switching and mode locking; after 1985, owing to the chirped-pulse technique.

The next, very serious problem was the laser repetition rate. The pumping efficiency of traditional flash lamps is very low; the energy is spent mainly on heating of the laser medium. In addition, the lifetime of flash lamps is too short, less than 10^6 shots. Semiconductor diode lasers solved these problems. The efficiency of diode laser pumping is very high, and heating of the laser medium is low. The lifetime of the diodes is sufficient for the photon collider.

In addition to the average repetition rate, the time structure is of great importance. The average power required of each of the two lasers for the photon collider at the ILC is $10\,\mathrm{J} \times 15000\,\mathrm{Hz} \sim 150\,\mathrm{kW}$; however, the power within the 1 msec train is $10\,\mathrm{J} \times 3000/0.001 \sim 30$ MW! The cost of diodes is about $\mathcal{O}(1\$)/\mathrm{W}$, the pumping efficiency is about 25%, so the cost of just the diodes would be at least $\mathcal{O}(100)\mathrm{M}\$$, and the size of the facility would be very large.

Fortunately, there is a solution. A 10 J laser bunch contains about 10^{20} laser photons, only about 10^{11} of which are knocked out in a collision with the electron bunch. So, it is natural to use the same laser bunch multiple times. There are at least two ways to achieve this: an optical storage ring and an external optical cavity.

In the first approach, the laser pulse is captured into a storage ring using thin-film polarizers and Pockels cells [21, 26, 55]. However, due to the nonlinear effects that exist at such powers, it is very problematic to use Pockels cells or any other materials inside such an optical storage ring.

Another, more attractive, approach is an "external" optical cavity that is pumped by a laser via a semi-transparent mirror. One can create inside such a cavity a light pulse with an intensity that is by a factor of Q (the quality factor of the cavity) greater than the incoming laser power. The value of Q achievable at such powers is 100–200. The optical-cavity principle is illustrated in Fig. 8. The cavity should also include adaptive mirrors and other elements for diagnostic and adjustment.

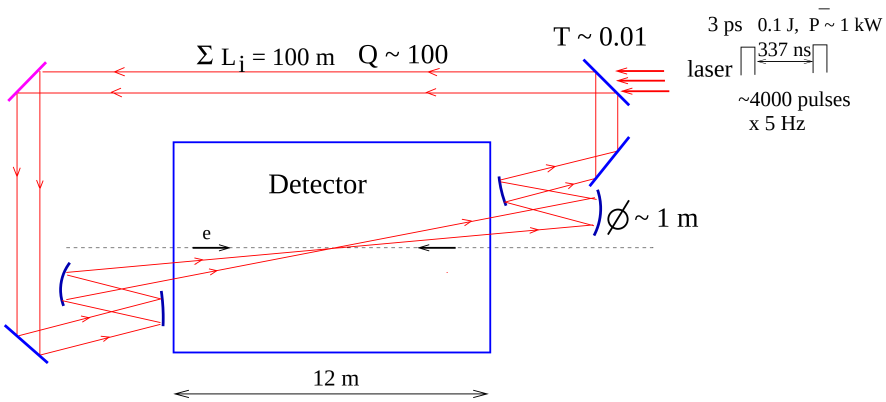

Fig. 8. External optical ring cavity for the photon collider.

While working on photon colliders, I was in contact with many laser experts; incredibly, no one ever said a word about "external" optical cavities. It was in early 1999 [54, 57, 58] that I came to the idea of such a cavity from first principles, checked the literature, and found that such cavities already existed, were used in a FEL experiments, in the gravitational-wave experiment LIGO, and in the optical laboratories. Only then did I finally come to believe in the technical feasibility of the photon collider with TESLA–ILC pulse structure and started to push it vigorously [26, 55, 59]. Working on the TESLA TDR at DESY in 1999–2000, I got the people from the Max Born Institute (Berlin) involved in the work on the optical cavity, and they further advanced this scheme [60, 61]; now, it is the baseline approach for the laser system at the ILC.

Advancements in laser technologies is being driven by several large, well-funded programs, such as inertial-confinement fusion. This is a very fortunate situation for photon colliders as we would benefit from the last two decades of laser-technology developments that have cost hundreds of millions of dollars each year. They are: the chirped-pulse technique, diode pumping, laser materials with high thermo-conductivity, adaptive optics (deformable mirrors), disk amplifiers with gas (helium) cooling, large Pockels cells, polarizers, high-power and high-reflectivity multi-layer dielectric mirrors; anti-reflection coatings, *etc.* Now, practically the all laser technologies and components required for a photon collider are in existence; nevertheless, the construction of such a state-of-the-art laser system would not be an easy task.

One should not forget free-electron lasers either. These might be single-pass SASE FEL lasers or amplifiers [14, 62], though they require an excessively high electron current. More attractive is an FEL amplifying a chirped laser pulse [33] that is then compressed by grating pairs, as in solid-state lasers. In this case, one can use much longer electron bunches. Such FELs with CPA were considered in Ref. [21, 63] (single-pass) and in Ref. [64] (a multi-pass regenerative amplifier). FEL facilities are much larger than the "table-top" solid-state lasers, but FELs have certain advantages for trains with small inter-bunch spacing; in particular, they have no problems with pumping and overheating of the laser medium.

5. Physics

The $\gamma\gamma$ and γe capabilities can be added to a high-energy e^+e^-linear collider at a small fraction of the cost of the entire project. Although the $\gamma\gamma$ luminosity in the high-energy part of the spectrum will be lower than in e^+e^- by a factor of 3–5, the cross sections in $\gamma\gamma$ collisions are typically greater by a factor of 5–10, so the number of "interesting" events would surpass that in e^+e^- collisions. Moreover, a further increase of the achievable $\gamma\gamma$ luminosity by up to one order of magnitude cannot be excluded.

Since the photon couples directly to all fundamental charged particles– leptons, quarks, W's, supersymmetric particles, *etc.* — the photon collider provides a possibility to test every aspect of the Standard Model, and beyond. Besides, photons can couple to neutral particles (gluons, Z's, Higgs bosons, *etc.*) through charged-particle box diagrams. See Brodsky's review talk at this conference for more details [1].

Many theorists took part in the development of the physics program for the photon collider; the total number of publications has surpassed the 1000 mark.

The physics program of the photon collider is very rich and complements in an essential way the physics in e^+e^- collisions under any physics scenario. In $\gamma\gamma$, γe collisions, compared to e^+e^-:

- the energy is smaller only by 10–20%;
- the number of interesting events is similar or even greater;
- access to higher particle masses (single resonances in H, A, *etc.*, in $\gamma\gamma$, heavy charged and light neutral (SUSY, *etc.*) in γe);
- at some SUSY parameters, heavy H/A-bosons will be seen only in $\gamma\gamma$;
- higher precisions for some phenomena;
- different types of reactions;
- highly polarized photons.

So, the physics reach of a $\gamma\gamma$, γe and e^+e^- colliders is comparable. The only advantage of e^+e^- collisions is the narrower luminosity spectrum, the feature that is of rather limited use.

The photon collider can be added to the linear e^+e^- collider at a very small incremental cost. The laser system and modification of the IP and one of the detectors would add about 3–4% to the total ILC cost. Some decrease of the e^+e^- running time is a negligible price to pay for the opportunity to look for new phenomena in other types of interactions.

More about physics at $\gamma\gamma$ colliders can be found in reviews [1, 26, 65–70], references therein, and many other papers.

6. Studies, projects, politics

Photon colliders were discussed at the series of LC, LCWS and PHOTON workshops/conferences, and at many others. In the beginning, these were single talks, then working groups formed, and then International Workshops on Photon Colliders took place in Berkeley in 1994 (Sessler) [71]; at DESY in 2000 (Heuer, Telnov) [59]; at FNAL in 2001 (Velasco) [77]; in Warsaw, 2005 (Krawczyk) [78], as well many smaller meetings.

Several LC projects have been in existence: VLEPP, NLC, JLC, TESLA, SBLC, CLIC — and each one of them foresaw the $\gamma\gamma$, γe option. In 1996–1997, three LC projects published their Conceptual Designs with chapters or appendices describing a second IP, dedicated for a photon collider: NLC [21] (Ed. K.-J. Kim), TESLA/SBLC [79] (Ed. V. Telnov), JLC [80, 81] (Ed. T. Takahashi, I. Watanabe). In February 1999, at the $\gamma\gamma$ mini-workshop on photon colliders in Hiroshima, it was decided to organize an International Collaboration on Photon Colliders. This was announced at LCWS1999, and approximately 150 physicists signed up. The work was done, presumably, within the framework of regional studies.

All that time, photon colliders were considered first and foremost as a natural additions to the e^+e^- collider projects. However, there were several short-lived suggestions to build dedicated photon colliders with no e^+e^- collisions at all: a 10 GeV $\gamma\gamma$ collider for study of b-quark resonances [72], a 100–200 GeV $\gamma\gamma$ collider for "Higgs hunting" [73], a "proof-of-principle" photon collider at the SLC [74], a photon collider on the basis of the CLIC test facility [75]. In my mind, suggesting a linear collider with no e^+e^- collisions when most people dream about e^+e^- is just not serious. "Test" colliders with low energy or luminosity would be a waste of resources.

A few words about dedicated $\gamma\gamma$ workshops. At LC92, I spoke to Andy Sessler about photon colliders and asked him to give a talk on the possible application of FELs for photon colliders. He did so, and "in addition" organized the first workshop on $\gamma\gamma$ colliders (Berkeley, 1994 [71]), gave a talk on photon colliders at PAC95, and wrote a paper on photon colliders for Physics Today [76].

The second International Workshop on the High Energy Photon Colliders [59] (GG2000) was organized at DESY as a part of work on the Photon Collider for the TESLA TDR [26]. Together with accelerator physicists, we found that after some optimization of the damping rings and the final focus system, $L_{\gamma\gamma}(z > 0.8z_m) \sim 0.3L_{e^+e^-}$ can be achieved. Now, even some of the past opponents of photon colliders agreed that $\gamma\gamma$, γe should be built. As for the technical feasibility, the very attractive idea of an external optical cavity was already in existence in 2000.

The primary motivation behind GG2001 [77] at FNAL was the idea of $e \to \gamma$ conversion using crystals instead of lasers. It was rejected, completely and outright, due to the destruction of crystals by the very dense electron beams, large photo-nuclear backgrounds and defocusing by the beam produced plasma; this was quite obvious from the very beginning [4, 18].

Now, let me discuss the present situation. Due to the high costs of building a high-energy linear collider, the international HEP community agreed to build one collider for the energy $2E_0 = 0.5$–1 TeV instead of three (TESLA, NLC and JLC). In 2004, the ILC project, based on the superconducting TESLA-like technology, was inaugurated. According to the consensus document titled "Understanding matter: ... the case for the Linear Collider" [82], which was signed by three thousands supporters, the ILC should have an interaction region compatible with the photon collider. So, the next steps are the ILC design, cite selection, obtainig government approval and funding, and the construction. Under the best-case scenario, ILC operation may start in 2015. "To be or not to be" for the sub-TeV linear collider depends both on the energy scale of new physics, which should become known soon after the start of experiments at the LHC, and on multiple other scientific and political factors.

If the ILC is built, in the first few years it will operate in the e^+e^- mode in all (1 or 2) of its detectors. Then, one of the IPs would be modified for the $\gamma\gamma$, γe mode of operation.

Unfortunately, life is not easy for the advocates and supporters of the photon collider at the ILC. For many years, the photon collider has been considered an "option" in the "baseline" e^+e^- collider design. In real life, "option" meant no support, and no money. Nevertheless, the interest of the physics community in having the photon collider built is tremendous. For example, the number of articles in the SPIRES database (publications only) that mention linear colliders or photon (gamma) colliders in their titles are, respectively, approximately 2950 and 600. These numbers speak for themselves.

In the conclusion of my sermon, let me share with you an instructive story from the very early days of collider physics. When G. Budker proposed to build the first e^+e^- storage ring in Novosibirsk, responses of all three referees were negative. However, I. Kurchatov, head of the USSR nuclear program, overruled the skeptics: "If the referees are so unanimously against it, it means that the project is really interesting" — and gave the green light to e^+e^- colliding beams. So, nothing new is ever easily done.

In summary: the physics expected in the 0.1–1 TeV region is very exciting, there is a big chance that a linear collider will be built somewhere in the world, and then the photon collider will inevitably happen.

I am very grateful to D. Asner, V. Balakin, T. Barklow, K. van Bibber, R. Brinkmann, S. Brodsky, D. Burke, H. Burkhardt, S. Chattopadhyay, P. Chen, J.P. Delahaye, A. De Roeck, K. Geissler, I. Ginzburg, J. Gronberg, A. Finch, R. Heuer, C. Heusch, G. Jikia, K-J.Kim, G. Kotkin, M. Krawczyk, D. Meyerhofer, D. Miller, G. Mourou, V. Serbo, K. Mönig, O. Napoli, R. Palmer, M. Peskin, F. Richard, B. Richter, A. Seryi, A. Sessler, S. Söldner-Rembold, J. Spenser, A. Skrinsky, T. Takahashi, T. Tauchi, D. Trines, A. Undrus, N. Walker, I. Watanabe, K. Yokoya, P. Zerwas for useful discussions and joint efforts in the study of photon colliders, and to all the people who have contributed to the development of the photon collider and its physics program.

REFERENCES

[1] S. Brodsky, *Acta Phys. Pol. B* **37**, 619 (2006) these Proceedings.

[2] I.F. Ginzburg, *Acta Phys. Pol. B* **37**, 657 (2006) these Proceedings, [`hep-ph/0512235`].

[3] G.S. Abrams *et al., Phys. Rev. Lett.* **43**, 477 (1979).

[4] Proc. of the Workshop on the Program of Experiments on Colliding Electron–Positron Beams (VLEPP), 1–5 Dec. 1980, Novosibirsk (in Russian), Ed. A. Grozin, V. Fadin.

[5] F.R. Arutyunian, V.A. Tumanian, *Phys. Lett.* **4**, 176 (1963); F.R. Arutyunian, I.I. Goldman, V. A. Tumanian, *Zh. Eksp. Teor. Fiz. (USSR)* **45**, 312 (1963).

[6] R.H. Milburn, *Phys. Rev. Lett.* **10**, 75 (1963).

[7] O.F. Kulikov *et al., Phys. Lett.* **13**, 344 (1964).

[8] J. Ballam *et al., Phys. Rev. Lett.* **23**, 498 (1969).

[9] I.F. Ginzburg, G.L. Kotkin, V.G. Serbo, V.I. Telnov, Preprint INP 81-50, Novosibirsk, Feb. 1981 (in English); *Pisma Zh. Eksp. Teor. Fiz.* **34**, 514 (1981); *JETP Lett.* **34**, 491 (1982).

[10] I.F. Ginzburg, G.L. Kotkin, V.G. Serbo, V.I. Telnov, *Nucl. Instrum. Methods* **205**, 47 (1983) (Prep. INP 81-92, Novosibirsk, Aug. 1981, in English).

[11] I.F. Ginzburg, G.L. Kotkin, S.L. Panfil, V.G. Serbo, V.I. Telnov. *Nucl. Instrum. Methods* **A219**, 5 (1984).

[12] C. Akerlof, Preprint UMHE 81-59, Univ. of Michigan, 1981.

[13] V.E. Balakin, V.A. Sidorov, A.N. Skrinsky, The VLEPP Project Status Report, in Bonn 1981, Proc. Lepton and Photon Interactions At High Energies, 944–956.

[14] A. Kondratenko, E. Pakhtusova, E. Saldin, *Dokl. Akad. Nauk* **264**, 849 (1982).

[15] S.I. Vavilov, *Phys. Rev* **36**, 1590 (1930).

[16] P.L. Csonka, *Phys. Lett.* **B24**, 625 (1967).

[17] R. Blankenbecler, S.D. Drell, *Phys. Rev. Lett.* **61**, 2324 (1988); Erratum **62**, 116 (1989).

[18] V.I. Telnov, *Nucl. Instrum. Methods* **A294**, 72 (1990).

[19] V.I. Telnov, *Nucl. Instrum. Methods* **A355**, 3 (1995).

[20] D.Y. Ivanov, G.L. Kotkin, V.G. Serbo, *Eur. Phys. J.* **C40**, 27 (2005).

[21] The NLC Design Group, Zeroth-Order Design Report for the NLC, LBNL-5424, SLAC-474, UCBL-ID-124161, UC-414. SLAC, 1996.

[22] V.B. Berestetskii, E.M. Lifshitz, L.P. Pitaevskii, *Quantum Electrodynamics*, Pergamon Press, Oxford 1982.

[23] I.F. Ginzburg, G.L. Kotkin, S.I. Polityko, *Sov. J. Nucl. Phys.* **37**, 222 (1983); *Yad. Fiz.* **40**, 1495 (1984); *Phys. Atom. Nucl.* **56**, 1487 (1993).

[24] M.V. Galynskii, S. Sikach, *Adv. Synerg.* **8**, 60 (1997).

[25] M. Galynskii, E. Kuraev, M. Levchuk, V.I. Telnov, *Nucl. Instrum. Methods* **A472**, 267 (2001).

[26] B. Badelek *et al., Int. J. Mod. Phys.* **A30**, 5097 (2004).

[27] D.Y. Ivanov, G.L. Kotkin, V.G. Serbo, *Eur. Phys. J.* **C36**, 127 (2004).

[28] G.L. Kotkin, V.G. Serbo, *Phys. Lett.* **B413**, 122 (1997).

[29] G.L. Kotkin, H. Perlt, V.G. Serbo, *Nucl. Instrum. Methods* **A404**, 430 (1998).

[30] V.I. Telnov, *Acta Phys. Pol. B* **37**, (2006) these Proceedings, Part II.

[31] V.E. Balakin, G.I. Budker, A.N. Skrinsky, Proc. of All-Union Conf. on Charged Part. Accelerators, Dubna 1978; A.N. Skrinsky, *Sov. Phys. Usp.* **25**, 639 (1982).

[32] SLAC Linear Collider, SLAC-Report-229, 1980.

[33] V.I. Telnov, *Physics and Experiments with Linear Colliders*, Saariselka, Finland 1992, Ed. R. Orava *et al.*, World Scientific, vol. 2, pp. 739–775.

[34] V.I. Telnov, the 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`

[35] R.B. Palmer, in DPF Summer Study Snowmass '88: High Energy Physics in the 1990's, Snowmass, Colorado, June 27 – July 15, 1988, SLAC-PUB 4707.

[36] V.I. Telnov, "Physics options at the ILC. GG6 summary at Snowmass2005", Proc. of 2005 Intern. Linear Collider Physics and Detector Workshop and 2nd ILC Accelerator Workshop, Snowmass, Colorado, 14–27 Aug. 2005, [physics/0512048].

[37] P. Chen, V.I. Telnov, *Phys. Rev. Lett.* **63**, 1796 (1989).

[38] P. Chen, G. Horton-Smith, T. Ohgaki, A.W. Weidemann, K. Yokoya, *Nucl. Instrum. Methods* **A355**, 107 (1995).

[39] D. Schulte, CERN-PS-99-014-LP.

[40] V.I. Telnov, Proc. of Workshop "Photon 95", Sheffield, UK, April 8–13, 1995, Ed. D. Miller *et al.*, World Scientific, 1995, p. 369.

[41] V.I. Telnov, Proc. of ITP Workshop "Future High Energy Colliders", Santa Barbara CA, USA, 1996, *AIP Conf. Proc.* **397**, 259 (1997), [physics/9706003].

[42] V.I. Telnov, *Phys. Rev. Lett.* **78**, 4757 (1997); Erratum **80**, 2747 (1998).

[43] V.I. Telnov, *Nucl. Instrum. Methods* **A455**, 80 (2000).

[44] V.I. Telnov, Requirements to beam sizes at photon colliders and problems of realization, http://icfa-nanobeam.web.cern.ch/icfa-nanobeam/slides/telnov_gg.pdf.

[45] A.V. Pak, D.V. Pavluchenko, S.S. Petrosyan, V.G. Serbo, V.I. Telnov, *Nucl. Phys. Proc. Suppl.* **126**, 379 (2004).

[46] V. Makarenko, K. Monig, T. Shishkina, *Eur. Phys. J.* **C32**, SUPPL1143 (2003).

[47] V.I. Telnov, Proc. of 2005 Intern. Linear Collider Physics and Detector Workshop and 2nd ILC Accelerator Workshop, Snowmass, Colorado, 14–27 August 2005, http://alcpg2005.colorado.edu:8080/alcpg2005/program/accelerator/GG6/agenda

[48] V.I. Telnov, *Critical Issues in Linear Colliders*, World Scientific, Hiroshima 2003, pp. 413–430, [hep-ex/0306044].

[49] V. Telnov, *Nucl. Instrum. Methods* **A472**, 280 (2001).

[50] V. Telnov, Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001), Ed. N. Graf, eConf **C010630**, E3026 (2001).

[51] H. Burkhardt, V. Telnov, CERN-SL-2002-013-AP.

[52] D. Strickland, G. Mourou, *Opt. Commun.* **56**, 219 (1985). M. Perry, G. Mourou, *Science* **264**, 917 (1994).

[53] Final report from the OECD Workshop on Compact High-Intensity Short-Pulse Lasers, JAERI, Kyoto, Japan, May 28–30, 2001.

[54] V.I. Telnov, *Nucl. Phys. Proc. Suppl.* **82**, 359 (2000).

[55] V.I. Telnov, *Nucl. Instrum. Methods* **A472**, 43 (2001).

[56] V.I. Telnov, *Nucl. Instrum. Methods* **A494**, 35 (2002).

[57] V.I. Telnov, Optics at the interaction region of photon colliders, Talk at the Int. meeting on Gamma-Gamma Collider, Hiroshima, Japan, Feb. 10–12, 1999, http://photon.hepl.hiroshima-u.ac.jp/lab/jlc/mini-ws/agenda.html

[58] V.I. Telnov, *Int. J. Mod. Phys.* **A15**, 2577 (2000).

[59] Proc. of Intern. Workshop On High-Energy Photon Colliders (GG 2000), Hamburg, Germany, June 14–17, 2000, Ed. R.D. Heuer, V.I. Telnov, N.J. Walker, *Nucl. Instrum. Methods* **A472**, pp. 1–321 (2001).

[60] I. Will, T. Quast, H. Redlin, W. Sandner, *Nucl. Instrum. Methods* **A472**, 79 (2001).

[61] G. Klemz, K. Monig, I. Will, `physics/0507078`.

[62] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, *Nucl. Instrum. Methods*, **A472**, 94 (2001).

[63] K.J. Kim, M. Xie, A.M. Sessler, *Nucl. Instrum. Methods* **A375**, 523 (1996).

[64] K.C.D. Chan, J.C. Goldstein, D.C. Nguyen, H.Takeda, Proc. of the 16th IEEE Part. Accel. Conf. (PAC95), Texas, 1–5 May 1995, vol. 1, p. 228.

[65] E.E. Boos,*Nucl. Instrum. Methods* **A472**, 22 (2001).

[66] M.M. Velasco *et al.*, Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001), eConf **C010630**, E3005 (2001).

[67] A. De Roeck, DESY-04-123GF, DESY-PROC-2004-01F, Nov. 2003; Proc. of the ECFA/DESY Study on Physics and Detectors at a Linear Collider, [`hep-ph/0311138`].

[68] M. Krawczyk, *Eur. Phys. J.* **C33**, S638 (2004).

[69] S.J. Brodsky, *Int. J. Mod. Phys.* **A20**, 7306 (2005).

[70] M.M. Muhlleitner, P.M. Zerwas, *Acta Phys. Pol. B* **37**, (2006) these Proceedings, Part II, [`hep-ph/0511339`].

[71] Proc. of Workshop on Gamma–Gamma Colliders, Berkeley CA, USA, 1994, Ed. S. Chattopadhyay and A.M. Sessler, *Nucl. Instrum. Methods* **A355**, pp. 1–194 (1995).

[72] D.A. Bauer, D.L. Borden, D.J. Miller, J. Spencer, SLAC-PUB-5816, presented at 9th Int. Workshop on Photon–Photon Collisions, San Diego, CA, March 22–26, 1992.

[73] V.E. Balakin, I.F. Ginzburg, Proc. of the 2nd Intern. Workshop on Physics and Experiments with Linear e^+e^- Colliders, Waikoloa, Hawaii 26–30 April, 1993.

[74] J. Gronberg, *Int. J. Mod. Phys.* **A18**, 2921 (2003).

[75] D. Asner *et al., Eur. Phys. J.* **C28**, 27 (2003).

[76] A.M. Sessler, *Phys. Today* **51**, 48 (1998).

[77] The Second International Workshop on High Energy Photon Colliders, FERMILABes, March 14–17, 2001, `http://diablo.phys.northwestern.edu/ggws/`

[78] PLC2005, Kazimierz, Poland, 5–8 Sept. 2005, `http://photon2005.fuw.edu.pl/plc2005`

[79] R. Brinkmann *et al.*, *Nucl. Instrum. Methods* **A406**, 13 (1998).

[80] N. Akasaka *et al.*, JLC Design Study, KEK-REPORT-97-1.

[81] I. Watanabe, *et al.*, $\gamma\gamma$ Collider as an Option of JLC, KEK-REPORT-97-17.

[82] Understanding Matter, Energy, Space and Time: The Case for the e^+e^- Linear Collider, `http://www-flc.desy.de/lcsurvey/`