Two photon physics. Personal recollection

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The term two–photon processes is used for the reactions in which some system of particles is produced in collision of two photons, either real or virtual. In the study of these processes the main goal is to describe principal features of proper two–photon process separating them from mechanism which responsible for the production of photons.

Here I present my view for history of two–photon physics in the topics in which I took part (and some related topics).

I don't try to give complete review, concentrating mainly on works of our team (which cover essential part of general field).

I cite here only papers which were essential in our understanding of problem in the work. The more or less complete citation can be found in the original papers and special reviews.

The choice of published details was result of my discussions with Gleb Kotkin and Valery Serbo.

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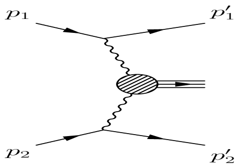

The processes which called now as two-photon ones were discussed first in 1934. That was e^+e^- pair production in collision of ultrarelativistic charged particles

1. L.D. Landau, E.M. Lifshitz, *Sow. Phys.* **6** (1934) 244
2. H.A. Bethe, W. Heitler, *Proc. Roy. Soc.* **A146** (1934) 85

After that these processes were included in the theory of wide atmospheric showers in cosmic rays and in the description of the energy losses of fast muons in matter.

The hadron production by two photons was considered by H. Primakoff (1951), suggested to measure the π^0 life-time in the $\gamma Z \to \pi^0 Z$.

The new interest to such processes appeared when the construction of e^+e^- colliders become close to a reality. In 1960 F.E. Low pointed out that the π^0 life-time can be measured also in the $e^+e^- \to e^+e^- \pi^0$ process. Simultaneously the two–photon reaction $e^+e^- \to e^+e^- \pi^+\pi^-$ (for point–like pions) was considered by F. Calogero, C. Zemach.
In 1969–1970 new generation of papers appeared with the goal to cover possible set of final states of e^+e^- colliders as complete as possible. Paris (Kessler et al., 1969-1971) and Novosibirsk BINP (Baier, Fadin, 1971) groups considered e^+e^- collisions with final states $e^+e^- + e^+e^-, +\mu^+\mu^-, +\pi^0, +\eta, +\pi^+\pi^-, +K^+K^-$ (in the latter two cases for the point-like pions and kaons).
These papers were in line with numerous calculations of various processes at e^+e^- colliders don't pretend for obtaining of new information except new tests of QED. That is why they did not provoke high interest in particle physics community

End of 60-th. Popular problems.

In the 60-th the study of different processes of hadron collisions was of main interest for community. In addition to the collisions initiated by proton and deuton beams, the processes, initiated by pion beams, kaon beams, antiproton beams, hyperon beams (experiment and theory) were of great interest for community providing new types of final states and new field for the Regge theory developed at that time. In this respect the study of deep inelastic ep scattering was a hot point in particle physics provided new type of collided hadron (photon) with variable mass and helicity.

One more popular field of studies was the coupled channel problem in the low energy scattering – description of $\pi\pi \to \pi\pi$ and $\pi\pi \to KK$ scattering.

Two photon processes at e^+e^- colliders

- **Novosibirsk. 1969-1970**. Once in the winter 1969-1970 my PhD student Victor Budnev was informed me about observation in Novosibirsk BINP the process $e^+e^- \to e^+e^-e^+e^-$ in the group of my former student Balakin. Relatively high cross section of this 4-th order process of QED was explained by small virtuality of photons coupled initial and scattered electrons.
  I understood that similar mechanism is suitable also for the production of hadron systems. Few months I reported in different groups in Moscow and JINR about "new opportunity found by experimentalists of BINP". My first proposal was to study process $\gamma\gamma \to \pi\pi$ by using of methods developed for the $\pi\pi \to KK$. I have not received a response for these proposals. And once somehow told me –
  you find new opportunity .

After that I understand that high energy e^+e^- colliders really provide us opportunity to study new type of processes, yet unknown for community – production of particles in the collisions of two photons. The study of such process continues studies of deep inelastic ep scattering to the absolutely new region of parameters and final states with two variable parameters – virtualities of each photon in addition to the cms energy of $\gamma\gamma$ system.
I invite for writing paper my PhD student V. Budnev and experimentalist V. Balakin.
Fortunately, I had no experience in the QED calculations and don't know well developed approximate Weizsacker-Williams method (it had to the moment mainly qualitative explanations). We start our calculations from Feynman diagrams, from the very beginning. This way allow us to skip inaccuracies widely spread in the description of similar processes even many years later.

We understand that the study of cross sections is more preferable than calculation of amplitudes. We find that the differential distribution is roughly $\propto \frac{dq_1^2}{q_1^2}\frac{dq_2^2}{q_2^2}\sigma_{\gamma\gamma}^{exp}(\hat{s}, q_1^2, q_2^2)$ (more accurate form is (**??**)) with kinematically determined lower limits $q_{i,min}^2 \sim m_e^2(m_e/E)^2$. The developed conception of two-photon processes make clear for us that one should to consider same scale Λ of dependence of this $\sigma_{\gamma\gamma}^{exp}$ on virtualities, similar to form-factor (Unfortunately many physicists skip this simple fact.). In the most of cases of hadron production $\Lambda \sim m_\rho \sim 750$ MeV. For the production of kaons $\Lambda \sim m_\phi \sim 1$ GeV, for the production of $\mu^+\mu^-$ pairs $\Lambda \sim m_\mu \sim 100$ MeV, for the production of discovered later charmed particles $\Lambda \sim m_\Psi \sim 3$ GeV, etc. In our estimates we take into account that at $q_i^2 \ll \Lambda^2$ the dependence of virtualities q_i^2 is negligible and at $q_i^2 \gg \Lambda^2$ cross section falls rapidly.

Письма в ЖЭТФ, том 11, стр. 559 – 562 *5 июня 1970 г*

ВОЗМОЖНОСТЬ ЭКСПЕРИМЕНТА ПО РОЖДЕНИЮ АДРОНОВ ДВУМЯ ФОТОНАМИ ОТ ПОРОГА ДО ПРЕДЕЛЬНО БОЛЬШИХ ЭНЕРГИЙ

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Литература

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Paper V.E. Balakin, V.M. Budnev, I.F. Ginzburg, "Possible experiment of hadron production by two photons from threshold to extremely high energies"was published in *Pis'ma ZhETF* at June 5, 1970 after submitting at May 4, it was translated in English (*JETP Lett*) soon; the paper was reported in August by Budnev at XV Rochester in Kiev (I cannot took part in that conference since I was in the hospital after a heavy car accident in the beginning of July in Yakutia.).

The paper contains also estimate of high energy total cross section $\sigma(\gamma\gamma \to hadrons) \sim \sigma^2(\gamma p)/\sigma(pp) \sim (0.3\div 1)\mu$b, which is in accord with modern (2015) measurements, and the equations for extraction of two-photon cross sections from the data at small electron scattering angles in the form which is used for this aim up to now. The numerical estimates of anticipated cross sections were done and it was found that the cross section grows fast with beam energy. Besides, the sketch of experimental program was formulated. More detail calculations were published soon in Phys. Lett.

In fact, this paper also open door for correct writing of the Weizsacker–Williams (equivalent photon) approximation.

This paper contains also Balakin's proposal to supplement future detectors by transverse magnetic field in the collision region to bent and observe scattered electrons for the detail observation of $e^+e^- \to e^+e^- f$ process. This idea was realized later, on detectors MD-1 and KEDR of BINP.

Three month later after our publication and after Rochester-Kiev

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DOMINANT COLLIDING-BEAM CROSS SECTIONS AT HIGH ENERGIES*

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(Received 11 August 1970)

Conference S. Brodsky, T. Kinoshita & S. Terazawa have submitted to Physical Review Letters their paper. They calculated processes $e^{\pm}e^{-} \to e^{\pm}e^{-} + \pi^0, +\eta, +e^{+}e^{-}, +\pi^{+}\pi^{-}$ for point-like pions. They found that these cross sections grow fast with beam energy and described some features of the angular distributions of pions.

These results allow them to conclude that two-photon processes provides a large field for theoretical studies and experimentation. Unfortunately they based on the Weizsacker–Williams method without analysis of its ability, with essential mistake. At the language of virtualities they don't take into account decreasing of cross sections of subprocess due to formfactor, and used in fact for the scale Λ, mentioned above, the kinematical limit $\Lambda \sim E$. It enhances spectra of equivalent photons by factor about 2 for each photon. Many authors of subsequent papers reproduced this inaccuracy.

After these theoretical studies the papers of BINP and Frascati with observation $e^+e^- \to e^+e^- e^+e^-$ were considered as first observations of two-photon processess.

- V.E. Balakin et al. *Phys. Lett.* **34 B** (1971) 320; *Yad. Fiz.* **16** (1972) 729,
- C. Bacci et al. *Lett. Nuovo Cim.*, **3** (1972) 709; G. Barbellini et al., *Phys. Rev. Lett.*, **32** (1974) 385.

5 mentioned papers open doors for stream of publications devoted two–photon physics.

70-th. Our group continue basic analysis to understand main features of two-photon processes which are independent on the nature of produced system. In this stage the important member of our team becomes V. Serbo. The first results were summarized in Physics Report review (1974) containing all necessary equations for data preparation and set of equations useful for different estimates. This review contains also detail description of equivalent photon (Weizsacker–Williams) method, including estimate of its accuracy in different situations. The physical problems related to the separate $\gamma\gamma$ processes, details of data extraction, backgrounds, QED processes were discussed by many authors of that time. Most of papers of 70-th devoted to hadron physics in $\gamma\gamma$ collisions were reproductions of results and ideas considered earlier for other hadronic systems.

In 1973 series of conferences devoted these processes was started in Paris. I cannot took part in the 8 first conferences. My first visit was in 1992 at 9-th San Diego conference from modern Russia.
The real experimental activity in this field started in 1979 by SLAC experiment in which it was demonstrated that two–photon processes can be successfully studied at the modern detectors without recording of the scattered electron – via the separation of events with the small total transverse momentum of produced system. After that, the study of two–photon processes become regular component of physical program at each e^+e^- collider. One of the first review of these results was done in the book of Kolanoski. A number of results obtained till now are summarized in the Particle Data Review.
At May 2 of 1980 Budnev died during rafting at Kazakhstan. Since that our two-photon team contains 3 key persons – Valery Serbo, Gleb Kotkin and me.

Two-photon physics at e^+e^- colliders. My general view for two-photon studies at e^+e^- colliders was formulated in the report at the first workshop devoted to the Linear e^+e^- colliders in the winter 1980-1981. It does not changed till now.

In my opinion, the standard two-photon studies in the processes $e^+e^- \to e^+e^- f$ will give substantial supplement to the future hadron and e^+e^- data with improved values of parameters but without discovery of really new phenomena of the first line, except two points in which two-photon mechanism can provide information unavailable in other processes.

(a) The most important seemed to me the study of the structure function of the photon. Witten found that it is an unique quantity in particle physics which can be determined from QCD at large enough Q^2 and s completely without phenomenological parameters, it is determined by point-like component of photon (1977). The checking up this result in future experiments is necessary to verify that the QCD is indeed a theory of strong interactions. Unfortunately, the hadron-like component of photon dominates at modern parameters of e^+e^- machines.

(b) The interference between two-photon and bremsstrahlung mechanism of production of simple systems like $\pi^+\pi^-$ allow to measure relative phases of s- and p-waves (d- and p-waves) of $\pi\pi$ scattering, not available in other approaches (Chernyak, Serbo (1973). However that is the problem of relatively low energy physics – for modern generation of e^+e^- colliders.

Photon colliders. I

Important fact from the past. In 1970 we read with great interest about experiments in SLAC. The laser photons were scattered on electrons of SLAC beam giving via backward Compton scattering photons of relatively high energy which value was determined by production angle. Than these *tagged photons* collide with target. Thus it is appeared an opportunity to study collisions of photons having high and precisely known energy with target proton. The typical conversion coefficient (ratio of number of high energy photons to the number of incident electrons) was about 10^{-7}. The typical photon energy was about 10% from an initial electron energy.

Working group at Workshop 1981

In the winter 1980-1981 the Budker INP was organized first workshop devoted to the Linear e^+e^- colliders (LC) with beam energy $E = 100$ GeV, named as VLEPP.

In the working group at the two-photon section Valery Telnov proposed very new idea.

In the LC each electron is used only once. Therefore it can be useful to convert almost each electron into the high energy photon to obtain and use beams of high energy photons.

Unfortunately specific ideas suggested for realization of this proposal gave bad perspectives for realization.

We discussed there

$\Diamond$ Bremsstrahlung on a solid target.

$\Diamond$ The radiation in the undulator (wiggler).

$\Diamond$ Beamstrahlung Radiation in the collision with strong electromagnetic field of collided beam.

Common feature of all these proposals giving large number of produced photons was very soft energetic spectrum of these photons, large background and relatively wide angular distribution. These roads were recognized as unpromising in the discussion of the working group.

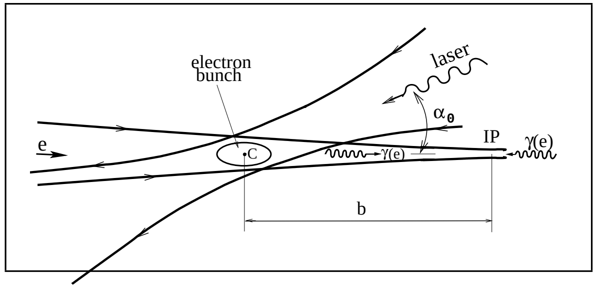
Laser photon backscattering. First Proposal. In the end of discussions of working group Gleb Kotkin remind us about laser photon backscattering on the electron of LC beam in spirit of forgotten ideas of 60-th. This idea meet no support among participants which remember a small conversion coefficient in these experiments. Nevertheless Serbo and me suggested Kotkin to discuss with laser experimentalists this opportunity. At that moment we (Serbo and me) recognize that in our case photons will move mainly along initial electron direction and their energy will be high enough but we don't expect big conversion coefficient. In few days Kotkin told us that laser specialists told him that the necessary laser flush energy is unacceptably high. We decide that this idea seem also hopeless.

Next day during our walking with Serbo I told: "Let us check statements of Gleb"(we know that he may be impressed by this statement and give up after the first objection). During walk we estimated necessary laser flash energy. Our estimate was very simple. We were known the size of electron beam of VLEPP near the collision point S. For complete conversion of electrons to photons the laser target should be opaque for electrons. Therefore, the necessary number N of laser photons in flash is S/σ_C, where σ_c is Compton cross section. For the first estimate we took σ_C to be as the Tomson limit value. For the laser photon energy $\omega_0 \sim$ few eV (visible light) we estimated necessary laser flash energy $\omega_0 N \sim 1 \div 10$ J. This value seemed realistic for us. One half hour later Serbo at home reproduced this estimate with paper. (In what follows we distinguish laser photon γ_0 with energy $\omega_0 \sim$ few eV and high energy photon γ with energy $\omega \sim E$.)

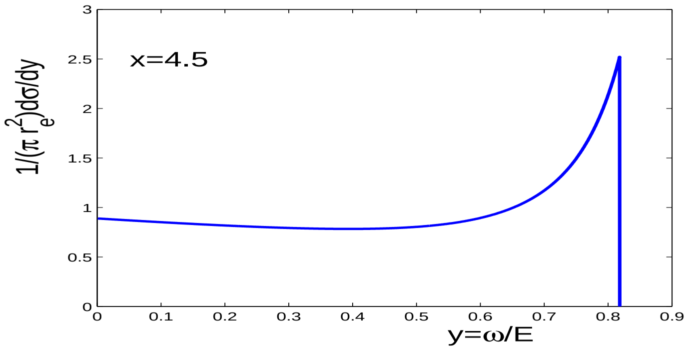
After that we three were connected with laser specialist Folin about possible type of laser suitable for our problem. He showed us laser from neodimium glass or garnet with laser photon energy $\omega_0 = 1.17$ eV. To that moment one can find such lasers with necessary flash energy and (separately) necessary repetition rate. He told us that with suitable budget even middle laser group can construct laser with necessary flash energy and repetition rate for about 3 year. We understood that the desirable conversion can be possible.
To describe phenomenon we introduce variables $x = 4E\omega_0/m_e^2$ and $y = \omega/E$, so the squared Compton cms energy $\hat{s}_C = (x+1)m_e^2$. Simple kinematic calculation for the first year student showed that y is limited from above by quantity $y_m = x/(x+1)$. The using of well known QED results for the considered case showed us that the energy spectrum of photons is concentrated near upper bound y_m.

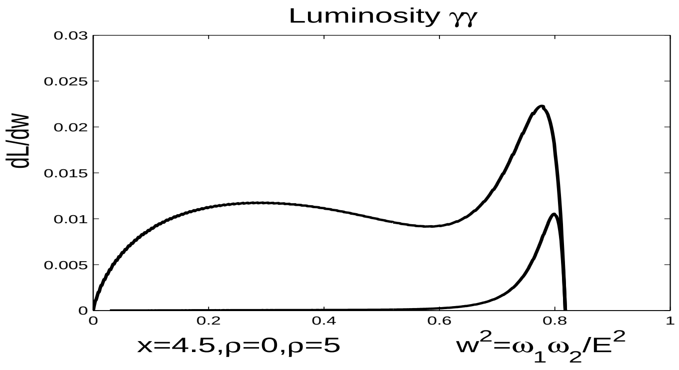
After that the important problem was – what is the length of photon beam of high enough density near the focus – it was necessary to determine laser flash energy which is sufficient for conversion of almost each electron from the beam having known length of VLEPP project to photon. Kotkin brought us idea of Gaussian laser beams, giving simple estimate with the optimistic result and then Serbo confirmed it by calculation with the these beams. It transforms our preliminary estimates into modern accurate calculation. It become clear that the opportunity is realizable and the paper with proposal should be written as soon as possible. In this stage we invite Valery Telnov, author of basic idea about conversion of each electron to photon, to join us. We prepare together preprint (1981), paper in "Pis'ma ZhETF"(1981) and paper in *Nuclear Instruments and Methods (1983).*

When we report results of our working group at the final session of Workshop, some participants were sceptic in our proposal. They refer to the old experiments in which the photon energy was much lower than E and the corresponding conversion coefficient was small. The fate was favorable to us in the choice of numbers. At considered $E = 100$ GeV we find $x \approx 1.8$. Therefore maximal photon energy reach $\omega_m = 0.64E$ (while at earlier experiments, for example at $E = 10$ GeV we had $x = 0.18$ and $\omega_m = 0.15E$, as what mentioned by participant). The special choice of lasers allows in principle to reach conversion coefficient ~ 1, in contrast with 10^{-7} in the old experiments.



The scheme of $e \to \gamma$ conversion was evident for us from the very beginning. At the conversion point C, preceding the interaction point IP, the electron (e^- or e^+) beam of basic linear collider (LC) meets the photon flash from powerful laser. The Compton backscattering of laser photons on electrons from LC produces high energy photons with energy spectrum peaked at $y = y_m$. With the suitable choice of laser one can obtain the photon beam with the photon energy close to that of the basic electron and conversion coefficient close to 1. These photons are focused at the approximately the same spot, as it was expected for electrons without laser conversion. In the IP the obtained photon beam collides with either opposite non-converted electron beam ($e\gamma$ collisions) or with photon beam ($\gamma\gamma$ collisions).
Soon after these papers this scheme was called **Photon Linear Collider** with abbreviation PLC.





The differential luminosity spectrum is given by convolution of individual photon spectra with geometric factor determined by the known energy dependent angular spread. At the shift of conversion point C from collision point IP for the distance b the photons of smaller energies spread for more wide region, and their contribution into luminosity become relatively lower – luminosity spectra become more monochromatic. For the round electron beam with radius in IP without conversion σ, the dependence on the distance b is determined by parameter $\rho = \dfrac{bm_e}{\sigma E}$.

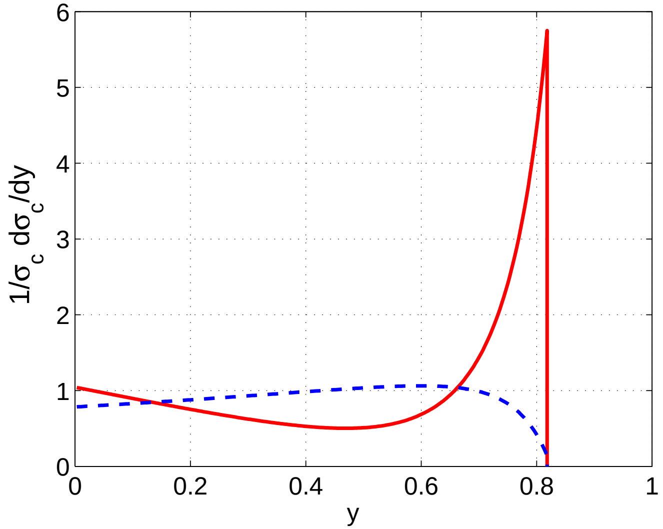
We note in this basic paper that the quality of $\gamma\gamma$ collisions (degree of monochromaticity) improves with growth of ρ and x.
However with the growth of x the new phenomenon stops improvements. At $x > 2(1+\sqrt{2}) \approx 4.8$ the number of output high energy photons is diminishes due to process $\gamma\gamma_0 \to e^+e^-$ (production of e^+e^- pairs in the collision of produced high energy photons with residual photons from the tail of laser flash). Therefore, the "optimal"laser photon energy gives $x \approx 4.8$ (for the considered laser at $E = 250$ GeV we have almost optimal $x = 4.5$).

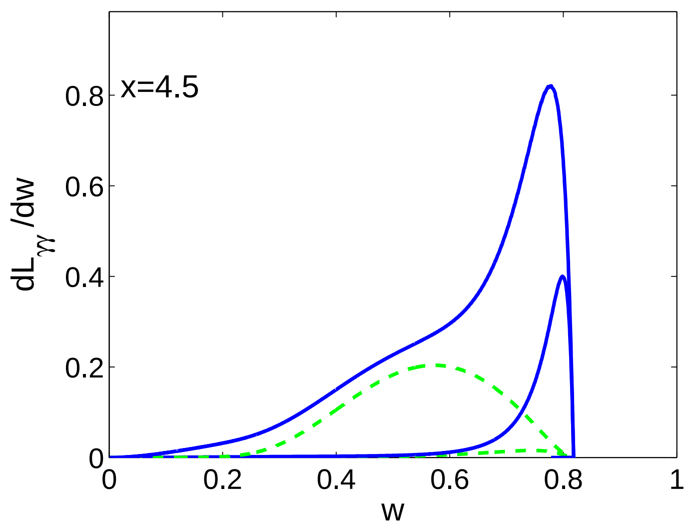
Polarization

The opportunity to have longitudinally polarized electrons in the project of LC looks very natural and attractive. Laser light is easily polarized. The study of polarization look us at the moment desirable only for completeness.

Our theory group (GKS) started study polarization effects. The first analysis of equations give us surprising result. *The energy spectrum of photons and total Compton cross section depends strong on only product of transverse polarization of electron (helicity)* λ_e *and degree of laser circular polarization* λ_L. In the range of parameters of interest this dependence is weak for total cross section and strong for differential distribution. At $2\lambda_e\lambda_L = -1$ the number of photons with greatest energy is almost doubled as compare with the case of nonpolarized photons. On the other hand, at $2\lambda_e\lambda_L = 1$ this number almost disappear.

This observation was the reason for more detail study of problem. First, we observe that the circular polarization of laser photons is transferred to high energy photons with degree, dependent on both y and incident $2\lambda_e\lambda_L$. Therefore it is useful to consider two different luminosities, dependent on initial laser photon polarization – the luminosity L_0 for photons having identical helicity (total helicity of final state 0) and L_2 for photons having opposite helicity (total helicity of final state ± 2). At the suitable choice of initial helicities $L_0 > L_2$.





Case $x = 4.5$.

Left: Photon energy spectra, $2\lambda_e\lambda_L = -1$ (full) and $2\lambda_e\lambda_L = 1$ (dotted).

Right: Luminosity spectra at L_0 (full) and $L = 2$ (dotted) for $\rho = 1$ (upper) and $\rho = 5$ (lower).

The natural next problem was to study linear polarization of photons. To the moment we don't know equation for Compton effect with all polarization. We invite my PhD student Shimon Panfil to take part in the obtaining these equations. At the subsequent stage we meet important technical difficulty. The scattering planes, which are useful for description of linear polarizations in the individual Compton process, are different for each process. In the description of beam polarization suitable averaging become necessary. Some delicate effects appear at this averaging. The result of these calculations was published in the paper of Ginzburg, Kotkin, Panfil, Serbo *Sov. Yad. Fiz. (1983)*. These results were used for complete description of polarization phenomena in the differential luminosity in the paper prepared together with V. Telnov – Ginzburg, Kotkin, Panfil, Serbo, Telnov (*Nucl. Instr. Meth. 1984*).

The mentioned papers gave complete description of basics of PLC. Beginning from 90-th many physicists consider different problems related construction of PLC but in fact that were details which change basic results only weakly.

After these basic studies, our team (GKS) studied the physical processes at PLC with some works devoted to PLC itself, while Telnov concentrate efforts on the technical problems of PLC (see report at this session). His activity in many meetings ensured the inclusion of PLC mode in all projects of LC's. The challenges for the PLC project were given by strong increasing of repetition rate as compare with VLEPP, strong decreasing of beam size of LC and corresponding electromagnetic field of laser bunch, choice of geometry of collision, etc. Telnov answer most of these challenges with the goal to obtain the highest $\gamma\gamma$ luminosity of the best quality.

Photon Collider II. Additional points

1. New useful estimates for elliptic beams (Ginzburg, Kotkin).

2. The unsuccessful attempt to use powerful infrared lasers (Ginzburg, Kotkin, Polityco).

Non-linear QED effects (D.Ivanov, Kotkin, Serbo).

Notes on physical program for PLC