объединенный
институт
ядерных
исследований
дубна

E9-93-254

E.L.Saldin*, V.P.Sarantsev, E.A.Schneidmiller*,
M.V.Yurkov

ON A POSSIBILITY TO CONSTRUCT A HIGH LUMINOSITY 2x5 GeV PHOTON COLLIDER AT SLC

Submitted to «Nuclear Instruments and Methods A»

*Automatic Systems Corporation, Smyshlyaevskoe Shosse 1a, 443050 Samara, Russia

1993

1. Introduction

An activity around a future generation of electron-positron linear colliders in the earliest 80-th gave birth to an idea of a photon linear collider (PLC). It was proposed to generate high energy photon colliding beams by means of the Compton backscattering of laser light on electron beams of the linear collider [1]. Since that time the idea of the PLC has been widely spreaded over the world and is considered now as a unique possibility to study physical processes in the center-of-mass energy region of $0.5 \div 1$ TeV [2, 3].

There are a lot of technical problems to be solved prior the constructing future linear colliders. To construct the PLC on the base of the linear collider, once more problem should be solved, namely that of a laser with sufficient parameters: peak output power about 1 TW, pulse duration of an order of several picoseconds and repetition rate of an order of several hundreds cycles per second. It is likely that the laser should be tunable, so as an optimal wavelength range depends on the collider energy and spans from the infrared up to UV ranges. Analysis of the state of art with conventional lasers shows that there are unsolvable technical problems to achieve the required parameters. It is evident now that the only candidate for the PLC laser is a free-electron laser (FEL). For the first time an idea to use the FEL in the PLC scheme was proposed in ref. [4]. Later this idea was developed in ref. [5], a two-stage FEL scheme for a 2×1 TeV PLC was proposed consisting of a tunable FEL master oscillator (wavelength ~ 4 μm, peak power ~ 10 MW) and FEL amplifier with tapered undulator (peak output power ~ 1 TW).

A construction of the TeV-range PLC will be possible in far future, but the PLC with the center-of-mass energy $3 \div 10$ GeV may be constructed at the present level of acceleration technique R&D. It will be a unique instrument to study charmonium C = + 1 states (η and χ) in two-photon reactions. The $q\bar{q}$ wave function could be studied via $\eta, \chi \rightarrow 2\gamma$ which constitute direct test of $q\bar{q}$ models. Moreover, a huge amount of η and χ events at the PLC could be used to study many hadronic decays of these states. The PLC would make a systematic search for gluonia and hybrids in a gluonrich environment: $\eta, \chi \rightarrow gg$, $q\bar{q}g$. The η and χ are the preeminent experimental tools for gluonium spectroscopy and the PLC should be able to shed fresh light on the important problem in QCD concerning the dearth of gluonic matter.

Two-photon physics is studied now experimentally at electron-positron storage rings. It is well known that the shape of the electromagnetic field of the ultrarelativistic electron is close to the shape of a plane wave. One may consider the field of the ultrarelativistic electron to be composed of "equivalent" photons and the most fraction of them has low energy. Integral luminosity of these "equivalent" photons for the energy region $\hbar\omega \simeq \mathcal{E}_0/2$, where $\mathcal{E}_0$ is the electron (positron) energy, is equal to $L_{\gamma\gamma} \sim 10^{-3} L_{e^+e^-}$ and is much less than the e^+e^- luminosity.

In the present paper we point at the possibility to construct a high luminosity, $L_{\gamma\gamma} \simeq 10^{34}\text{cm}^{-2}\text{s}^{-1}$, photon collider with the center-of-mass energy $3 \div 10$ GeV. Its luminosity will be by six order of magnitude greater than the luminosity of "equivalent" photons at existent electron-positron colliders. The PLC with such a luminosity will reveal a novel direction of fundamental research, namely a precision study of τ-lepton physics. It is well known that the $\tau^+\tau^-$ pair production cross-section $\sigma_p(\gamma\gamma \rightarrow \tau^+\tau^-)$ near the threshold is of the order of 10^{-32}cm^2 and exceeds the value of the corresponding cross-section $\sigma_p(e^+e^- \rightarrow \tau^+\tau^-)$ by an order of magnitude. Thus, at the luminosity $L_{\gamma\gamma} \simeq 10^{34}\text{cm}^{-2}\text{s}^{-1}$, $\tau^+\tau^-$ pairs will be produced at a rate of several hundreds per second which exceeds by a two orders of magnitude the corresponding rate at future τ-charm factories [6]. A possibility to steer the polarization of colliding photon beams reveals additional perspectives for a wide range of experiments. For instance, two photons with opposite helicities will product the $\tau^+\tau^-$ pair with a high polarization degree (see section 4). So, such a photon collider may be considered as a polarized τ-lepton factory.

In the earliest 80-th it was pointed at a possibility to use the FEL amplifier for the colliding photon beams production [4]. At that time a project of 2×50 GeV photon collider was under study. It was assumed to use the electron beam of the main accelerator as the driving beam for the FEL amplifier operating in a superradiant mode. Since that time the FEL reputation have achieved an appropriate level. The main principles of the FEL operation are widely known. A possibility to increase the FEL amplifier efficiency was demonstrated experimentally, an efficiency ~ 30 % was achieved [7]. Successful experiments with the FEL amplifier operating in the infrared wavelength range have been performed [8].

A problem of an optimal FEL configuration choice is somewhat complex one. To describe physical processes occurring in the FEL, one should solve self-consistent field equations taking into account such effects as diffraction of radiation, space charge fields, energy spread of the electrons in the beam, electron beam profile, etc. Computer codes play an important role here allowing one to perform a set of numerical experiments to get an optimal choice of parameters. All the results presented in this paper are obtained with the FS2R code package which provides a possibility to perform an overall analysis of the FEL amplifier including optimization of the FEL amplifier with the tapered undulator [9, 10].

There is an attractive idea to use the existent Stanford Linear Collider (SLC) facility as a basis for construction of the photon collider with the center-of-mass energy $3 \div 10$ GeV. It may be realized with additional installation of a tunable ($\lambda \sim 10 \div 30$ μm) laser with a peak output power $W \simeq 3 \cdot 10^{11}$ W, pulse duration ~ 10 ps and repetition rate about of $100 \div 200$ Hz. The laser radiation should have an ideal (i.e. diffraction) dispersion, otherwise the laser radiation power should be much more. We suppose that the required laser for the proposed PLC should be the free electron laser. It has a high efficiency, it is tunable and capable to generate powerful coherent radiation which always has minimal (i.e. diffraction) dispersion. A driving accelerator for the FEL may be a modification of the main SLAC linac, thus providing the required high repetition rate. At a sufficient driving electron beam quality, the FEL peak output power is defined by the peak power of this driving beam. At the electron beam energy $\mathcal{E} \sim 1$ GeV and the peak beam current $I \sim 1$ kA, this power achieves a TW level.

A thorough analysis of the possibility to build the photon collider at the SLC facility

has led us to an optimistic conclusion that it is quite possible at the present level of acceleration technique R&D, we have not faced any unresolvable problem. The key element of our proposal is two-stage infrared free electron laser as a source of primary photons. The first stage of this device is a tunable FEL master oscillator and the second stage is the FEL amplifier. The main feature of the proposed scheme is that it based totally on the acceleration technique.

To provide the physical investigation program at a photon collider with the center-of-mass energy $3 \div 10$ GeV, its luminosity should be not less than $L_{\gamma\gamma} \simeq 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [11]. If we consider a minor modifications of the SLC, namely additional installation of the FEL system only, then at the electron-positron luminosity $L_{e^+e^-} \simeq 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, the $\gamma\gamma$ luminosity $L_{\gamma\gamma} \simeq 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ may be achieved. It should be noted that the value of $L_{\gamma\gamma}$ is greater than the value of $L_{e^+e^-}$ due to the process of multiple photon production (in the case considered the number of γ-quantums produced by each electron is of the order of 4).

There is principal difference between the photon collider and electron-positron collider is that there is no need in positrons for the PLC. As a result, the injection system, the main elements of which are the damping rings, may be simplified and optimized for the PLC operation. The achievements in the field of photoinjectors make it possible to achieve this goal at the present level of acceleration technique. Estimations shows that special modification of the SLC for operation in the photon collider mode will provide the luminosity of colliding γ beams $L_{\gamma\gamma} \simeq 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

2. Luminosity of photon beams

The most optimal way to produce high energy γ - quantums is the Compton backscattering of the laser photons by the high energy electrons [1]. The frequencies of the incident and scattered photons, ω and ω_γ, are connected by the relation (in the small-angle approximation):

$$\hbar\omega_\gamma = \frac{\mathcal{E}\chi}{1+\chi+\gamma^2\theta^2}, \qquad (1)$$

where θ is the scattering angle, $\chi = 4\gamma\hbar\omega/m_e c^2$, m_e and $\mathcal{E}$ are the electron mass and energy, respectively, and $\gamma = \mathcal{E}/m_e$ is relativistic factor. To obtain an effective conversion of the primary laser photons into the high energy photons, the laser beam should be focused on the electron beam. It may be performed, for instance, by means of a metal focusing mirror (see Fig.1). Electrons move along the z axis and pass through the mirror focus S. To calculate the conversion coefficient, it is necessary to know the distribution of the optical field intensity in the focal spot. One can easily obtain that the focusing will be optimal when the following conditions are fulfilled:

$$\sigma_F^2 \ll \lambda^2 F^2/4a_0^2, \qquad F^2 \ll a_0^2 l_b/2\lambda, \qquad l_b \le l_w, \qquad (2)$$

where λ is the laser light wavelength, F is the focus distance of the mirror, a_0 is the characteristic size of the laser beam on the mirror surface, σ_F is the transverse dimension of the electron beam in the conversion region, and l_b and l_w are the lengths of the electron beam and the laser beam, respectively. The first condition (2) assumes that the transverse dimension of the electron beam in the conversion region is much less than the dimension of the laser beam. So, when calculating the probability of the Compton scattering, it is sufficient to take into account the variation of the optical field amplitude along the z axis only. The second condition (2) assumes that the characteristic axial size of the region with a high optical field, along the z axis in the focus vicinity, is much more than the electron and laser beams lengths.

When conditions (2) are fulfilled, the probability P of the electron scattering by the incident optical beam is given with the expression [4]:

$$P = 1 - \exp[-(2\sigma_c c/4\pi\hbar\omega)\int_{-\infty}^{\infty}|E|^2 dz], \qquad (3)$$

where

$$\sigma_c = 2\pi r_e^2[\frac{1}{\chi}\ln(1+\chi) - \frac{8+4\chi}{\chi^3}\ln(1+\chi) + \frac{8}{\chi^2} + \frac{2+\chi}{2(1+\chi)^2}] \qquad (4)$$

is the total Compton cross section on unpolarized electrons, $r_e = e^2/m_e c^2$ and $|E|$ is the amplitude of the optical wave. It is assumed here that the laser beam is circularly polarized. Remembering that the field of the optical beam is decreased quickly with the removal from the focus (it vanishes almost completely at $|z| > 4\pi c F^2/\omega a_0^2$, so we calculate the integral in expression (3) the limits $-\infty < z < \infty$. Using the Huygens-Fresnel integral, we may write

$$\int_{-\infty}^{\infty}|E|^2 dz = 4\pi\omega W/c^2, \qquad (5)$$

where W is the total power of the optical beam. Substituting expression (5) into expression (3), we obtain [4]:

$$P = 1 - \exp(-\delta), \qquad \delta = 2W\sigma_c/\hbar c^2. \qquad (6)$$

Let us point at the important feature of this result. Under the conditions (2), the expression for the probability of the Compton scattering (6) does not depend on the details of the optical field distribution on the focusing mirror and is defined by the total power of the laser beam.

The main characteristic of the colliding beams is the luminosity L which is defined as

$$L = 2fN^{(1)}N^{(2)}\int\rho^{(1)}(\vec{r},t)\rho^{(2)}(\vec{r},t)d\vec{r}dt, \qquad (7)$$

where $N^{(1,2)}\rho^{(1,2)}$ are the densities of the colliding beams ($\int\rho d\vec{r} = 1$) and f is the collision repetition rate. In the axisymmetric case, for the beams with the Gaussian distribution of the beam density we have:

$$\rho^{(1,2)}(r,z,t) = [(2\pi)^{3/2}\sigma_z\sigma_t^2(z)]^{-1}\exp[-\frac{r^2}{2\sigma_t^2(z)} - \frac{(z\mp Vt)^2}{2\sigma_z^2}], \qquad (8)$$

where

$$\sigma_t(z) = \sigma_t(0)\sqrt{1+\frac{z^2}{\beta_0^2}}, \qquad \sigma_t(0) = \sqrt{\epsilon\beta_0/\pi},$$

ϵ is the electron beam emittance, σ_z is the width of the longitudinal distribution and β_0 is the beta-function at the interaction point. Substituting expression (8) into expression (7) we obtain:

$$L_{ee} = \frac{\sqrt{\pi}N_e^2 f}{8\epsilon\sigma_z}\exp(H^2)[1 - \frac{2}{\sqrt{\pi}}\int_0^H \exp(-x^2)dx], \qquad (9)$$

where $H = \beta_0/\sigma_z$.

To calculate the luminosity of the colliding $\gamma\gamma$ - beams, one should calculate the distribution of the secondary γ - quantums $\rho_\gamma(\vec{r},t)$. In this paper we study the case of small values of parameter χ. In this classical limit, $\chi \ll 1$, using ultrarelativistic approximation $\gamma \gg 1$, we may write differential Compton cross-section on unpolarized electrons in the following form:

$$\frac{d\sigma_c}{\gamma^2 d\theta^2} = 4\pi r_e^2 \frac{1+\gamma^4\theta^4}{(1+\gamma^2\theta^2)^4}.$$

When optimal conditions of focusing are fulfilled:

$$\sigma_z \ll z_0, \qquad z_0 \ll \gamma\sigma_t^{(0)}, \tag{10}$$

where z_0 is the distance between the conversion point and interaction point, then γ - quantum beam density becomes proportional to the electron beam density:

$$N_\gamma\rho_\gamma = \eta N_e\rho_e(\vec{r},t),$$

and the luminosity of the colliding $\gamma\gamma$ beams may be written in the form:

$$L_{\gamma\gamma} = \eta^2 L_{ee}. \tag{11}$$

Here η is the conversion factor, i.e. the total number of γ - quantums produced by the single electron. In classical limit, when probability of the Compton backscattering $P \sim 1$ (i.e. at $\delta \sim 1$), the processes of the multiple photon production should be taken into account to calculate the conversion factor η. From the practical point of view it is sufficient to consider the region of parameters

$$1 \leq \delta \leq 1/\chi,$$

when the electron energy losses in the field of incident laser wave are relatively small. In this approximation conversion factor is equal to δ and may be done much more than unity.

Integral luminosity is not an exhaustive characteristic of the photon collider. From the practical point of view, the spectral luminosity, i.e. the luminosity calculated per unity

frequency interval $\omega_0 = \sqrt{\omega_1\omega_2}$ of the colliding γ - quantums, is of a significant interest. At small value of z_0 when

$$z_0 \ll \gamma\sigma_t^{(0)}\frac{\nu}{1-\nu}, \qquad \nu = \frac{\hbar\omega_\gamma(1+\chi)}{\mathcal{E}\chi},$$

in classical limit we obtain [4]:

$$\omega_0\frac{dL_{\gamma\gamma}}{d\omega_0} = \frac{9}{2}\eta^2 L_{ee}[\nu^2(\ln\frac{1}{\nu^2}-2) + 4\nu^2(\ln\frac{1}{\nu^2}-1) + 2\nu^6(2\ln\frac{1}{\nu^2}+3)]. \tag{12}$$

The value of $dL_{\gamma\gamma}/d\omega_0$ achieves its maximum at $\nu = 0.22$:

$$(\frac{dL_{\gamma\gamma}}{d\omega_0})_{max} \simeq 1.45\eta^2 L_{ee}/\omega_{max}, \tag{13}$$

where $\hbar\omega_{max} = \mathcal{E}\chi/(1+\chi)$ is maximal energy of the backscattered γ - quantum.

An application of the FEL as a laser for PLC reveals wide possibilities to steer the polarization of the colliding photon beams. In the FEL amplifier, the polarization of the amplified wave is defined by the undulator magnetic field configuration. For instance, in the case of the helical undulator, the output FEL radiation is circularly polarized. As a result, one can easily steer the polarization of the colliding $\gamma\gamma$ - beams. Let us consider the practically important case when the FEL optical beam is circularly polarized. At the given helicities of the optical beams $\xi_{opt}^{(1)}$ and $\xi_{opt}^{(2)}$, the helicities of the backscattered γ - quantums may take the values ± 1. As a result, the total luminosity may be presented as a sum of partial luminosities corresponding to the different helicity combinations of colliding γ - quantums. In the classical approximation and at small distance between the conversion and interaction point (see relations (10)), we obtain the following expression [4]:

$$\omega_0\frac{dL_{\gamma\gamma}}{d\omega_0} = \frac{9}{2}\eta^2 L_{ee}\nu^2 f(\nu,\xi^{(1)},\xi^{(2)}), \tag{14}$$

where $\xi^{(1,2)} = \xi_{opt}^{(1,2)}\xi_\gamma^{(1,2)}$ are the products of the helicities of incident and scattered photons. Function $f(\nu,\xi^{(1)},\xi^{(2)})$ is given with the following expressions:

$$\begin{aligned} f(\nu,1,1) &= (1+4\nu^2+\nu^4)\ln\frac{1}{\nu^2} - 3(1-\nu^4), \\ f(\nu,1,-1) &= f(\nu,-1,1) = \frac{1}{2}(2\nu^4\ln\frac{1}{\nu^2} + 1 - 4\nu^2 + 3\nu^4), \\ f(\nu,-1,-1) &= \nu^4\ln\frac{1}{\nu^2} \end{aligned} \tag{15}$$

It is seen from the plots in Fig.2 that the photon collider may be easily tuned on the required partial luminosity maximum by steering of the FEL optical beam polarization.

3. A choice of the PLC parameters

In this section we will illustrate with the numerical example the results obtained in the previous section and discuss the main factors influencing the choice of the PLC parameters. For numerical example we have chosen a conceptual project of a collider with the parameters presented in Table 1.

Table 1. Main linear accelerator

Electron energy, $\mathcal{E}$	50 GeV
Number of electrons in the bunch, N_e	$4 \cdot 10^{11}$
Repetition rate, f	150 Hz
Normalized emittance, ϵ_n	$\pi \cdot 10^{-3}$cm·rad
Electron bunch length, σ_z	0.1 cm
β - function at the interaction point, β_0	0.1 cm

We consider an axisymmetric case when $(\epsilon_n)_x = \pi\gamma x x' \simeq (\epsilon_n)_y \simeq \pi\gamma y y'$ and $(\beta_0)_x = (\beta_0)_y = \beta_0$. In accordance with expression (9), the luminosity of such a collider is equal to $L_{ee} \simeq 7 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1}$.

Principal difference between the electron-positron collider and photon collider is that there is no need in positrons for the latter one. So, the injection system based on the damping ring technique is not optimal for the PLC. We suppose that the injection system based on a photoinjector technique will be the most appropriate. The photoinjector technique has been developed intensively during last years, mainly due to the needs of the FEL technique. Significant achievements has been obtained in this field. For instance, constructed at the Brookhaven National Laboratory photoinjector electron gun provide the electron beam with the normalized brightness $B_n \simeq 8 \cdot 10^8\text{A}\cdot\text{cm}^{-2}\text{rad}^{-2}$ ($B_n = I/\epsilon_n^2$,

where I is the beam current) and pulse duration $\sim$ 5 ps. Cathode lifetime of this gun was 700 hours [12]. The results obtained reveal a possibility of application of the photoinjector technique for the PLC. In the example considered the electron beam is produced by a photoinjector gun (normalized beam brightness $B_n \simeq 8 \cdot 10^8\text{A}\cdot\text{cm}^{-2}\text{rad}^{-2}$). The photoinjector with such parameters may be constructed at the present level of the accelerating technique R&D.

Another key element of the project is the optical system providing the required parameters of the laser beam at the conversion point. Let us consider the photon collider optimized to operate at the center-of-mass energy 10 GeV which corresponds to the maximal energy of the secondary γ - quantums $(\hbar\omega_\gamma)_{max} \simeq 5$ GeV. In this case the laser wavelength should be chosen to be $\lambda \simeq 10$ μm. We let the peak laser power to be $W \simeq 3 \cdot 10^{11}$ W, laser pulse duration $l_w/c \simeq 15$ ps and radius of the laser beam at the focusing mirror $a_0 \simeq 3$ cm (we will show below that free electron laser with such parameters may be constructed at the present level of acceleration technique R&D). Assuming the focus distance of the mirror to be equal to $F = 10$ cm and the distance between the conversion and interaction point - $z_0 = 5$ cm, we find that the conditions of optimal focusing (2) and condition (10) on z_0 are fulfilled. Using the parameters of the chosen optical system we find the conversion coefficient to be $\eta \simeq \delta \simeq 4$ (see expression (6)). Using formulae (11) and (13) we obtain that the integral and spectral luminosities are roughly equal with each other:

$$L_{\gamma\gamma} \simeq \omega_0 (\frac{dL_{\gamma\gamma}}{d\omega_0})_{max} \simeq 10^{34}\text{cm}^{-2}\text{s}^{-1}. \qquad (16)$$

Let us discuss briefly a potential of the existent Stanford Linear Collider facility to be a base of the PLC. Nowadays the SLC operates successfully in a e^+e^- collider mode with the center-of-mass energy about 100 GeV. The intensive low-emittance electron bunches with the number of particles $N_e \sim 4 \cdot 10^{10}$ are accelerated routinely in the main SLC accelerating structure and an attaining of the luminosity level $L_{ee} \sim 10^{30}$ cm^{-2}sec^{-1} is considered to be the nearest goal of the SLC team [13]. So, taking into account these parameters, one may expect to achieve the luminosity level $L_{\gamma\gamma} \sim 10^{31}$ cm^{-2}sec^{-1} after installation of the FEL optical system with the mentioned above parameters. Radical optimization of the SLC facility, namely the injection system, for operation in the PLC mode will enable to attain the luminosity level $L_{\gamma\gamma} \sim 10^{34}$ cm^{-2}sec^{-1}.

To begin precision physical experiments at the PLC with the center-of-mass energy 3 $\div$ 10 GeV, the value of the luminosity $L_{\gamma\gamma} \simeq 10^{31}$cm^{-2}s^{-1} is quite sufficient. The program of the possible physical investigations was discussed widely elsewhere (see, e.g. ref. [11]). Here we should point at a novel possibility of the PLC operation as a polarized τ - lepton factory.

4. Photon collider as intensive source of polarized τ - leptons

The process of lepton pairs production by two photons with the opposite helicities was studied in ref. [14]. A system of two photons with opposite helicities can be only in the states with a positive parity and total angular momentum $j \geq 2$, and projection of $\vec{j}$ on the direction of photon beams propagation is equal to $j_z = 2$. Due to the parity conservation, the $\tau^+\tau^-$ - pairs can be produced only in the states with an odd orbital momentum l. Near the threshold, due to the nonrelativistic motion of the produced particles, the pair production with the orbital momentum $l = 3$ is suppressed with respect to the $l = 1$ case and with an accuracy of an order of $(v/c)^4$, all the pairs are produced in the state j =2, l =1, j_z = 2.

Differential cross-sections of the $\tau^+\tau^-$ - pair production in the collision of two photons with the same and opposite helicities are equal to (in the center-of-mass system) [14]:

$$\frac{d\sigma_{\uparrow\uparrow}}{d\Omega} = \frac{r_\tau^2}{2\gamma^2}\frac{\beta(1-\beta^4)}{(1-\beta^2 cos^2\theta)^2},$$
$$\frac{d\sigma_{\uparrow\downarrow}}{d\Omega} = \frac{r_\tau^2}{2\gamma^2}\frac{\beta^3 sin^2\theta(2-\beta^2 sin^2\theta)}{(1-\beta^2 cos^2\theta)^2}, \qquad (17)$$

where $d\Omega$ is the solid angle differential, $r_\tau = e^2/m_\tau c^2$, m_τ is the τ - lepton mass, $\gamma = (1-\beta^2)^{-1/2}$ is the relativistic factor and θ is the angle between the τ - lepton velocity and the photon wave vector.

The polarization degree of the produced τ - leptons is equal to [14]:

$$\vec{\xi} = [\vec{k} + \frac{\vec{P}(\vec{k}\cdot\vec{P})}{m_\tau c(\hbar\omega_\gamma/c + m_\tau c)}][m_\tau c + \frac{P^2}{2m_\tau c}(1+cos^2\theta)]^{-1} \qquad (18)$$

where ω_γ is the frequency of the colliding photons, $\vec{k}$ is the wave vector of the photon with the positive helicity ($|\vec{k}| = \omega_\gamma/c$) and $\vec{P}$ is the momentum of τ - lepton. It is important to note that near the threshold, the projection of $\xi_{\vec{k}} = (\vec{\xi}\cdot\vec{k})/|\vec{k}|$ is close to the unity. For instance, at P = 0.6 (i.e. at $\hbar\omega_\gamma = 1.25 m_\tau c^2$), the polarization degree $\xi_{\vec{k}} \geq 0.98$ in the whole angle region. The total cross-sections of the τ - leptons pair production are equal to [14]:

$$\sigma_{\uparrow\uparrow} = \frac{\pi r_\tau^2}{\gamma^4}(1+\beta^2)[\beta\gamma^2 + \frac{1}{2}\ln\frac{1+\beta}{1-\beta}],$$
$$\sigma_{\uparrow\downarrow} = \frac{\pi r_\tau^2}{\gamma^2}[\beta^3 - 5\beta + \frac{5-\beta^4}{2}\ln\frac{1+\beta}{1-\beta}], \qquad (19)$$

In the case of the photons with different frequencies ω_1 and ω_2, ω_γ in the above formulae should be substituted by $\omega_\gamma = \sqrt{\omega_1\omega_2}$. The cross-section σ_n for the case of unpolarized photons may be expressed via $\sigma_{\uparrow\uparrow}$ and $\sigma_{\uparrow\downarrow}$ [15]:

$$\sigma_n = \frac{1}{2}(\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}).$$

In conclusion of this section we should note that near the threshold, for instance at $\hbar\omega_\gamma = 1.25 m_\tau c^2$, the cross-section $\sigma_{\uparrow\uparrow}$ is equal to

$$\sigma_{\uparrow\uparrow} \simeq 2\cdot 10^{-32}\text{cm}^2. \qquad (20)$$

Thus, when the helicities of the primary laser photons are equal to $\xi_{opt}^{(1)} = \xi_{opt}^{(2)}$ = -1 and $\hbar(\omega_{gamma})_{max} \simeq 1.25 m_\tau c^2$, then at the luminosity of the photon collider $L_{\gamma\gamma} \simeq 10^{34}$cm^{-2}s^{-1}, one obtains an intensive source of the polarized τ - leptons which yields $\sim 10^2$ particles per second.

5. A choice of the FEL parameters

5.1. Preliminary remarks

In this section we will discuss a problem of an optimal choice of the FEL parameters for application in the PLC scheme. Prior a detailed discussion, we should like to present a simple estimation of energetic characteristics of the FEL driving electron beam. To attain an output radiation power W, one should use the driving beam with the following parameters:

$$I\mathcal{E}_0/e = W/\eta, \tag{21}$$

where I is the peak beam current, $\mathcal{E}_0$ is the electron energy and η is the FEL efficiency. As a rule, a TW level of the radiation power is required for the PLC applications. So, to attain the output radiation power $W \simeq 3 \cdot 10^{11}$ W at the FEL efficiency $\eta \simeq 10$ %, one should use, for instance, the electron beam with the peak current $I \simeq 1.5$ kA and the electron energy $\mathcal{E}_0 \simeq 2$ GeV. At the same time, the driving electron beam must be of high quality, it should have low emittance and small energy spread.

Thus, this simple energetic estimation shows that the problem of the driving beam for the PLC FEL is extremely severe one. To reduce the requirements on the FEL driving electron beam parameters, one should choose an optimal FEL configuration providing the highest possible efficiency. There are two FEL configurations: the FEL amplifier and the FEL oscillator. There are evident advantages of the FEL amplifier against the FEL oscillator. It is well known that the efficiency of the FEL oscillator with untapered undulator is of an order of $\eta \sim 0.3/N_u$, where N_u is the number of undulator periods [16, 17]. So as N_u is usually of the order of several tens, this results in a low efficiency, less or of an order of one percent. An application of additional methods, such as undulator tapering and using of a prebuncher, allows one to increase an efficiency up to the value about several percents [18]. As for the FEL amplifier, undulator tapering allows one to increase the efficiency up to a value of several tens of percents [7]. Such a difference

between these devices means that the choice of the FEL amplifier is more preferable, so as it requires less powerful (by an order of magnitude) driving electron beam to attain the required output radiation power level.

There is another disadvantage of the FEL oscillator connected with the average required power of the driving electron beam. Indeed, one should take into account the time during which the FEL oscillator attains a saturation level. In a general case this time is rather large, so as the radiation should perform several hundreds of resonator rounds-trips till it achieves a saturation level. As a result, the average driving beam power of the FEL oscillator should be greater by about three orders of magnitude than the corresponding one for the FEL amplifier case.

The above mentioned consideration has been referred to a possibility of using the FEL oscillator active power. To overrun these difficulties, some authors propose to use a reactive power of the FEL oscillator, i.e. to use the radiation power stored in the optical resonator, so as it is much more than the active one [2, 11]. It is proposed to place the conversion and interaction region inside the optical resonator. Such a solution of the problem seems to be elegant, but significant technical problems are arisen. First, a lot of small-aperture magnetic elements of the final focus system (mini-β quadrupoles, separation magnets, etc.) should be placed as close as possible to the interaction point. Second, the optical resonator should be placed inside the detector. Third, a problem of optimal focusing of the laser beam on the electron beam becomes extremely difficult, etc. We think that the idea of using the reactive FEL oscillator power is possessed significant technical disadvantages with respect to that of using the FEL amplifier. The latter approach assumes to place only two relatively small focusing mirrors in the vicinity of the interaction region, thereby letting more wide possibilities for an arrangement of experimental facility.

So, preliminary analysis indicates that the FEL amplifier is the most appropriate source of primary photons for the photon collider. That is why we confine the further consideration with the case of the FEL amplifier.

Let us now perform a detailed analysis of an optimal FEL amplifier parameters choice.

In the case under consideration, the FEL amplifier operating in the $10 \div 30$ μm wavelength range should be optimized providing an output peak radiation power $\sim 3 \cdot 10^{11}$ W. Here we find that there is no a wide region for an optimization of the driving beam energy and current. Indeed, the electron beam energy of the order of one hundred MeV is desirable for a such FEL wavelength range. Nevertheless, such a choice results in the peak current of an order of 10 kA. It seems a difficult task to construct an accelerator with such parameters providing a high quality electron beam. To attain a compromise, we should fix our choice on the energy of an order of one GeV and the beam current of an order of $1 \div 3$ kA. Such a value of the beam current may be provided with a future generation photoinjector gun.

Now we proceed with the choice of the FEL magnetic system parameters, namely the undulator magnetic field H_w and undulator period λ_w. These parameters are not independent and are connected with each other by the resonance condition:

$$\lambda \simeq \lambda_w/2\gamma_z^2 = \lambda_w(1+Q^2)/2\gamma^2, \qquad (22)$$

where $Q = eH_w\lambda_w/2\pi mc^2$ is the undulator parameter (here and below all the formulae are written for the case of the helical undulator). We will show below that the increment of radiation instability is defined with the electron energy $\mathcal{E}_0$, beam peak current I, radiation wavelength λ and electron rotation angle in the undulator $\theta_w = Q/\gamma$. Here we obtain that almost all the parameters, except the rotation angle θ_w, are already chosen. As for the choice of the θ_w value (or, to be more strict, of the undulator parameter Q value), it should be chosen as large as possible. Thus, the only thing is left to do is to maximize the product $H_w\lambda_w$ keeping in mind that the resonance condition (22) must be fulfilled. There are also other restrictions of technical matter on the values of H_w and λ_w. For instance, during the amplification process, the radiation spans in outer beam space due to the diffraction. It means, that the undulator aperture should be made rather large to avoid the radiation losses in the vacuum chamber walls. As a result, the required size of the undulator aperture impose technical restrictions on the values of H_w and λ_w. A more detailed analysis shows that the values of $H_w \simeq 10 \div 15$ kG and $\lambda_w \simeq 15 \div 20$ cm are quite attainable.

When using the FEL amplifier, the problem of a master oscillator is usually arisen. It should be tunable and provide the amplitude of input signal above the FEL amplifier noise. In the present paper we propose a two-stage FEL scheme for the photon linear collider. Such an approach is based totally on the acceleration technique providing natural matching of the optical system with the systems of the main accelerator. For instance, the problem of synchronization of the laser and electron pulses is solved by means of standard methods used for accelerators. The sketch of the proposed scheme is presented in Fig.3. The tunable FEL oscillators ($\lambda \simeq 10 \div 30$ μm) with moderate peak output power $W \simeq 10$ MW serve as master oscillators for the FEL amplifiers with the tapered undulator. The radiation from the amplifiers ($W \simeq 3 \cdot 10^{11}$ W) is focused on the electron beams by means of metal mirrors. To illustrate the consideration, we have chosen the FEL facility with parameters presented in Tables 2 and 3.

Table 2. FEL amplifier parameters

Electron energy, $\mathcal{E}_0$	1 GeV
Beam current, I	2.5 kA
Radiation wavelength, λ	10 μm
Undulator period, λ_w	18 cm
Undulator field, H_w	12.26 kG
FEL amplifier efficiency, η	12 %

Table 3. FEL master oscillator

Electron beam	
Energy, $\mathcal{E}_0$	35 MeV
Peak current, I	50 A
Energy spread, $\Delta\mathcal{E}/\mathcal{E}$	0.5%
Normalized emittance, ϵ_n	100π mm·mrad
Micropulse duration	15 ps
Macropulse duration	10 μs
Repetition rate	150 Hz
Undulator	
Undulator period, λ_w	4 cm
Undulator field, H_w	3 kG
Number of undulator periods, N_w	40
Optical resonator	
Radiation wavelength, λ	10 μm
Resonator length	6 m
Curvature radius of mirrors	3.2 m
Radiation power losses	6 %

In the case under consideration the FEL amplifier noise is defined mainly by random fluctuations of the electron beam density and effective power of the noise signal at the FEL amplifier entrance is given with the expression [4]:

$$W_{sh} \simeq eI\omega\gamma_z^2\theta_w^2/c \tag{23}$$

For the FEL amplifier parameters presented in Table 2, the effective power of shot noise at the FEL amplifier entrance is equal to $W_{sh} \simeq 2$ W, so the chosen value of the master oscillator power is much more than this value.

5.2. FEL amplifier model

To describe the FEL amplifier operation we use the model of the FEL amplifier with the "open" axisymmetric beam when the external material structure (waveguide walls, etc.) does not influence significantly on the processes in the FEL [9, 10]. Such a model, allowing a wide application of analytical techniques, enables one not only to get a deeper insight into the FEL physics, but also to take into account almost all main physical effects influencing the FEL amplifier operation, namely the radiation diffraction effects, space charge fields and energy spread of electrons in the beam. To be more strict, we should point at a peculiar feature of this model. Physical approximations are chosen in such a way that the undulator field variation in the transverse plane is neglected. As a result, the electron motion in the undulator is assumed to be one-dimensional (after averaging over constrained motion). The physical sense of this approximation consists in neglecting the transverse betatron oscillations due to the natural focusing forces of the undulator field. Nevertheless, such a model is valid in the following practical situation. One should remember that a scaling hierarchy of physical effects of the problem under consideration takes place. In the linear high gain limit, the radiation field changes significantly at a scale of the growth length l_g. At the same time the particles in the beam perform full betatron oscillation at the betatron wavelength λ_b

$$\lambda_b = \sqrt{2}\,\lambda_w/\theta_w. \tag{24}$$

Thus, one can conclude that the model is valid when a characteristic length of the radiation field growth l_g is much less than $\bar{\lambda}_b = \lambda_b/2\pi$, i.e. at $l_g \ll \bar{\lambda}_b$. Another constrain supposes that the size of the radiation field spot should be much more than the transverse size of the matched electron beam $\sigma_d = \sqrt{\bar{\lambda}_b\epsilon/\pi}$. When these conditions are fulfilled, the influence of the finite value of the electron beam emittance on the FEL amplifier operation may be taken into account in the following way. The angle spread of the matched electron beam in the undulator is equal to:

$$<(\Delta\theta)^2> = \epsilon/\pi\bar{\lambda}_b. \tag{25}$$

This angle spread results in an additional longitudinal electron velocity spread which is taken into account by introducing an additional effective energy spread:

$$<(\Delta\mathcal{E}/\mathcal{E})^2>_{eff} \simeq \gamma_z^4 <(\Delta\theta)^2>^2 /4. \tag{26}$$

One can easily find that in the case under consideration, when the radiation of the infrared wavelength range is generated by the drive beam with the energy of an order of one GeV, the above mentioned conditions are fulfilled.

So, we consider the axisymmetric electron beam of radius r_0 having the bounded gradient profile of current density:

$$\begin{aligned} j_0(r) &= IS(r/r_0)[2\pi \int_0^{r_0} rS(r/r_0)dr]^{-1} \qquad \text{at } r < r_0 \\ j_0(r) &= 0 \qquad \text{at } r > r_0, \end{aligned} \tag{27}$$

where I is the beam current and $S(r/r_0)$ is the function describing the gradient profile. The beam moves in the magnetic field of the helical undulator along the z axis:

$$H_w = H_x + iH_y = H_w \exp(-i \int \kappa_w dz), \tag{28}$$

where $\kappa_w = 2\pi/\lambda_w$ is the undulator wavenumber. The rotation angle $\theta_w = Q/\gamma$ of the electron in the undulator is considered to be small and the electron longitudinal velocity v_z is close to the velocity of light, i.e.

$$\gamma_z^2 = 1/(1 - v_z^2/c^2) = \gamma^2/(1 + Q^2) \gg 1.$$

5.3. Linear mode of the FEL amplifier operation

Let us begin with the analysis of the linear mode of the FEL amplifier operation. In the linear high gain limit, the radiation of the FEL amplifier may be presented as a set of modes. Each mode is characterized with the eigenvalue and the eigenfunction of the transverse radiation field distribution. During the amplification process the transverse

field distribution of the mode remains intact while its amplitude grows with the length exponentially with the increment equal to the real part of the eigenvalue. In the case of the electron beam with the stepped profile of the beam current density, the eigenvalue equation of the TEM_{mn} mode is of the form [9]:

$$\mu J_{n+1}(\mu)K_n(g) = gJ_n(\mu)K_{n+1}(g), \tag{29}$$

where n is azimuthal index of the mode, $g = -2iB\hat{\Lambda}$, $\mu = -2i\hat{D}/(1 - i\hat{\Lambda}_p^2\hat{D}) - g^2$, $\hat{\Lambda} = \Lambda/\Gamma$ is the reduced eigenvalue, $B = \Gamma r_0^2\omega/c$ is the diffraction parameter, $\hat{\Lambda}_p^2 = \Lambda_p^2/\Gamma^2 = 4c^2/(\omega^2 r_0^2\theta_s^2)$ is the space charge parameter, $\Gamma = [I\omega^2\theta_s^2/(I_A\gamma_z^2\gamma c^2)]^{1/2}$ is the gain parameter and $I_A = m_e c^3/e$. In the case of the Gaussian energy spread, function $\hat{D}$ is given by

$$\hat{D} = i\int_0^\infty \xi \exp[-\hat{\Lambda}_T^2\xi^2 - (\Lambda + i\hat{C})\xi]d\xi,$$

where $\hat{C} = C/\Gamma = (2\pi/\lambda_w - \omega/2\gamma_z^2 c)/\Gamma$ is the reduced detuning from the resonance of the particle with the nominal energy $\mathcal{E}_0$, $\hat{\Lambda}_T^2 = \sigma_E^2\omega^2/(2c^2\gamma_z^4\mathcal{E}_0^2\Gamma^2)$ is the energy spread parameter and $\sigma_E = [<(\Delta\mathcal{E}/\mathcal{E})^2> + \gamma_z^4 <(\Delta\theta)^2>^2 /4]^{1/2}$ is the width of the energy distribution.

The analysis presented in ref. [9] had shown that the choice of the FEL amplifier parameters, providing the amplification of the ground TEM_{00} mode, is the most appropriate with respect to attaining of maximal increments and reducing sensitivity to the energy spread. Moreover, the field distribution of this mode is optimal with respect to the problem of laser beam focusing on the electron beam at the conversion point. So, we consider below the FEL amplifier tuned to amplify the ground TEM_{00} mode.

Analyzing the linear mode of the FEL amplifier operation, it is interesting to trace the dependence of the increment on the values of emittance and energy spread of electron beam. Fig.4 presents the dependency of the reduced increment versus the beam emittance. It is seen from this plot that there is a region of optimal values of emittance when increment achieves its maximal value. At large emittance values, $\epsilon \sim 3\cdot 10^{-3}$ cm·rad, there is drastical drop of the increment due to the large spread of the longitudinal velocities of the beam electrons. At small emittance values, at $\epsilon \sim 10^{-6}$ cm·rad, a decrease of increment is connected with the growth of the space charge fields, so as transverse size of the matched electron beam is decreased while the beam emittance is decreased. The behaviour of increment in the intermediate region is defined with diffraction effects due to the change of the transverse size of matched electron beam. For the further consideration we have chosen the value of the electron beam emittance $\epsilon = 10^{-4}$ cm·rad. One should note that such a value of the emittance does not correspond to the optimum for the linear high gain limit. An actual reason of such a choice of the emittance value is a consequence of an overall optimization of the FEL amplifier parameters.

Another important factor influencing significantly on the FEL amplifier operation is the energy spread of the electrons in the beam. The plot presented in Fig.5 presents the dependence of the increment on the energy spread. It is seen that increment drops drastically at $\Delta\mathcal{E}/\mathcal{E} \geq 0.3\%$.

Thus, the analysis of the eigenvalue equation of the FEL amplifier provides a possibility to obtain restrictions on the values of the electron beam emittance an energy spread. For the FEL amplifier parameters presented in Table 2, these values should be as follows: $\epsilon \sim 10^{-4}$ cm·rad and $\Delta\mathcal{E}/\mathcal{E} \leq 0.3\%$.

To attain minimum of the undulator length, one should provide an optimal focusing of the master oscillator radiation on the electron beam at the undulator entrance. It is natural to assume that the radiation from the master oscillator has a form of the Gaussian laser beam:

$$E_x + iE_y = \frac{-iE_0 w_0^2 k}{2(z-z_0) - i w_0^2 k} exp[-i\omega t + ik(z-z_0) + \frac{2ik(z-z_0)r^2 - r^2 k^2 w_0^2}{4(z-z_0)^2 + w_0^4 k^2}] \qquad (30)$$

where $k = \omega/c$, w_0 is size of the Gaussian beam waist and z_0 is its coordinate. A criterion of optimization consists in such a choice of w_0 and z_0 which provides maximal preexponential factor for the ground symmetrical TEM_{00} beam radiation mode. This problem has been studied in details in ref. [9] using the solution of the initial-value problem. It was found that the results of optimization do not depend significantly on the value of z_0 and it may be chosen equal to zero. The plot in Fig.6 presents the dependence of the optimal value

of w_0 on the beam diffraction parameter B. For the considered numerical example B = 0.46 and the size of the matched electron beam in the undulator is equal to $r_0 = 0.11$ cm, so from the plot in Fig.6 we find the optimal value of the Gaussian beam waist size: w_0 = 0.2 cm.

5.4. Nonlinear mode of the FEL amplifier operation

The results presented in the previous section refer to the linear mode of the FEL amplifier operation when the output signal amplitude is proportional to the input one. During the process of the radiation amplification the electrons lose their energy which leads to desynchronism of the electrons an the electromagnetic wave. In the case of the undulator with the fixed parameters these results in a situation when at some undulator length the most fraction of electrons shifts to an accelerating phase of the ponderomotive well and the electron beam begins to take off the energy from the electromagnetic wave. The radiation power at the saturation is of an order of

$$W_{sat} = \rho \mathcal{E}_0 I/e, \qquad (31)$$

where

$$\beta = \lambda_w \Gamma / 4\pi. \qquad (32)$$

Usually the gain length $l_g = 1/\Gamma$ is much more than the undulator period which results in a low saturation efficiency. In the case under study $\Gamma^{-1} = 165$ cm and $\beta = 0.0086$.

To describe nonlinear mode of the FEL amplifier operation, analytical techniques have limited possibilities and numerical simulation codes should be used. In the present paper we use computer code FS2RN [10] for the FEL amplifier simulations. The FEL amplifier parameters are presented in Table 2. The electron beam has emittance $\epsilon = 10^{-4}$ cm·rad and energy spread $\sigma_E = 0.3\%$ (see section 5.3). The FEL amplifier amplifies the radiation from the FEL master oscillator (see Table 3). It is assumed that the master oscillator radiation has the form of the Gaussian laser beam and is focused optimally on the electron beam at the FEL amplifier entrance.

The calculations for the case of the untapered undulator have shown that the saturation of the amplification occurs at the undulator length $L = 13.6$ m. The FEL amplifier efficiency is equal to $\eta_{sat} = 0.009$ which is by 13 times less than the required efficiency $\eta = 0.12$.

The method of the FEL amplifier efficiency increase by the undulator parameters tapering is a widely known one [7, 19, 20]. There is a lot of possibilities of undulator tapering and here we have chosen for numerical example only one of them, namely the undulator tapering at the constant undulator parameter Q. We have performed a set of calculations to obtain optimal conditions of the tapering. As a result, a linear law of tapering has been chosen. The variation of the undulator parameters turn on at the undulator length $L = 11.3$ m. At the undulator length $L = 39.8$ m the required efficiency $\eta = 0.12$ is achieved which corresponds to the FEL amplifier output power $W = 3 \cdot 10^{11}$ W (see Fig.7). At the undulator exit, the undulator field and period are equal to $H_w = 15.12$ kG and $\lambda_w = 14.6$ cm, respectively. A phase analysis shows that about 75 % of the electrons trap in the regime of coherent deceleration.

The transverse distribution of the radiation field amplitude at the undulator exit is shown in Fig.8. This plot enables one to impose restriction on the vacuum chamber radius, it should not be much less than 2 cm.

Fig.9 presents the dependence of the FEL amplifier output power on the reduced detuning $\hat{C} = C/\Gamma = (2\pi/\lambda_w - \omega/2\gamma_z^2 c)/\Gamma$. This plot enables one to find restrictions on the values of systematical drifts: frequency of the master oscillator $\Delta\omega/\omega = 2\beta \cdot \Delta\hat{C}$; energy deviation $\Delta\mathcal{E}/\mathcal{E} = \beta \cdot \Delta\hat{C}$; undulator field $\Delta H_w/H_w = \beta(1+Q^2) \cdot \Delta\hat{C}/Q^2$ (here the reduced bandwidth of the amplifier $\Delta\hat{C}$ is determined by the requirements on the stability of the output power level). It is seen from the plot in Fig.9 that systematical drifts ~ 1 % of the above mentioned parameters do not influence significantly on the FEL amplifier output power.

Another important problem is that of an accuracy of the undulator manufacturing. A

detailed analysis of this problem shows that the requirements on the random fluctuations of the undulator field and period should be of the order $[< (\Delta H_w/H_w)^2 >^{1/2}, < (\Delta\lambda_w/\lambda_w)^2 >^{1/2}] \leq \beta$.

To take a right choice of the driving electron beam pulse duration, one should take into account the slippage of the electron beam with respect to the amplified electromagnetic wave. So as this slippage is equal to the radiation wavelength at each undulator period, then at the undulator length $l \sim 40$ m it results in total slippage ~ 2 mm. Thus, the electron pulse duration should be by 10 ps larger than the required laser pulse duration.

It should be noted that the electrons, moving in the undulator, radiate incoherent synchrotron radiation, too. This process results in additional losses of the electron energy and increase of the energy spread of electrons in the beam due to the quantum fluctuations of radiation. In the numerical example these effects are negligibly small and should not be taken into account.

6. Discussion

Let us discuss a possibility of technical realization of the proposed photon linear collider with the center-of-mass energy $3 \div 10$ GeV.

The main essence of our proposal consists in the usage of the electron beam with a relatively high energy ($\mathcal{E} \sim 50$ GeV) and infrared laser beam ($\lambda \sim 10 \div 30$ μm) to generate relatively low energy ($\hbar\omega_\gamma \sim 2 \div 5$ GeV) colliding $\gamma\gamma$ beams. Such an approach enables one to increase significantly, by an order of magnitude with respect to the ee case, the luminosity of the colliding $\gamma\gamma$ - beams due to the multiple Compton backscattering.

There are two main problems to be solved prior the construction of such a photon collider. The first one is the problem of the electron accelerator providing two intensive and low-emittance electron bunches ($N \sim 10^{11}$ e^-/bunch, $\epsilon_n \sim 10^{-3}$cm·rad, $\mathcal{E} \sim 50$ GeV). It seems attractive to use the existent Stanford Linear Collider facility for this purpose. Nowadays the SLC operates successfully in a e^+e^- collider mode with the center-of-mass energy about 100 GeV [13]. A lot of scientific and technical problems was solved to achieve the designed SLC parameters. The intensive bunches with the number of particles $N_e \sim 4 \cdot 10^{10}$ are accelerated routinely in the main SLC accelerating structure. So, it seems to us that the required increase in the electron beam intensity by a factor of two is quite attainable and works in this direction are under the way at SLAC [13]. On the other hand, the SLC injection system may be simplified and optimized for the goals of the photon linear collider, so as there is no need in positrons. It will be natural to construct specialized photoinjector gun providing intensive and low-emittance electron beams for an injection immediately into the main accelerating structure, thus removing damping rings. Another modification of the SLC facility is connected with a necessity to install the separation kicker magnet providing separation of two electron bunches at the entrance into arcs. This problem may be resolved, so as the existing kicker magnet of the positron production system has the close parameters to those required [13].

The key problem of the design is the problem of the powerful infrared free electron laser. We propose to build a two-stage FEL. The FEL oscillator serves as a master oscillator for the FEL amplifier which produces a required level of the radiation power.

The FEL master oscillator, providing an output power W $\sim$ 10 MW, may have relatively moderate parameters (see Table 3). Devices with parameters close to those presented in Table3, are operating successfully nowadays at many accelerating centers [21, 22, 23]. The driving beam from a conventional S-band linear accelerator may be used for such a FEL oscillator.

The driving beam for the FEL amplifier may be generated by an S-band linear accelerator, too. Here the main problem will be to construct an injector. Nevertheless, we think that it may be solved with application of the photoinjector gun technique. The parameters close to those required ($B_n \simeq 10^6$ A $\cdot$ cm$^{-2} \cdot$ rad^{-2}, pulse duration $\tau \sim 10$ ps) are obtained at many laboratories (see, e.g. ref. [12, 24, 25]).

Another problem to be solved prior the construction of the FEL amplifier for the PLC applications, is that of the undulator. It is necessary to construct the undulator

with the period $\lambda_w \sim 10 \div 20$ cm and the undulator field $H_w \sim 10 \div 15$ kG. There is a severe constrain on the undulator aperture, it should be rather large in order that vacuum chamber walls should not influence on the FEL amplifier operation (see Fig.8). Taking into account these requirements, it seems natural to construct a superconducting undulator. It should be noted that the first FEL lasing was obtained with the superconducting undulator [26, 27]. That undulator had the period $\lambda_w = 3.2$ cm and total length 5 m. Amplitude of the magnetic field $H_w = 10$ kG was attained at the current density in superconducting windings $j_s = 700$ A/mm^2. Bifilar windings were mounted on the tube with diameter 1 cm. To scale these parameters to the case under consideration, we use the following expression for the magnetic field at the undulator axis [28]:

$$H_w = \frac{I_w}{\pi R_w}[\alpha^2 K_0(\alpha) + \alpha K_1(\alpha)], \tag{33}$$

where $\alpha = \kappa_w R_w$, $\kappa_w = 2\pi/\lambda_w$, I_w is the current in the winding, R_w is the winding radius and K_0 and K_1 are the modified Bessel functions (here it is assumed that the transverse dimensions of the winding Δ and δ are much less than the winding radius R_w). The extrapolation of the results of ref. [27] to the case under study may be performed by the increase of the winding current I_w and all geometrical dimensions, namely R_w, λ_w, Δ and δ by $6 \div 7$ times. So as the winding current is equal to $I_s = j_s\delta\Delta$, one can see that the requirement on the value of the critical current is diminished significantly and there is a reserve to increase the winding current. Thus, the undulator of the first SLAC free-electron laser may be considered as a scaled model of the undulator for the PLC FEL amplifier.

So, we have found that all systems of the proposed photon linear collider with the center-of-mass energy $3 \div 10$ GeV may be constructed using the present day level of the acceleration technique R&D and the usage of the existing SLC facility will make the PLC idea to be a reality in the nearest future. As a result, the physical community will possess a novel and unique instrument to study the structure of matter.

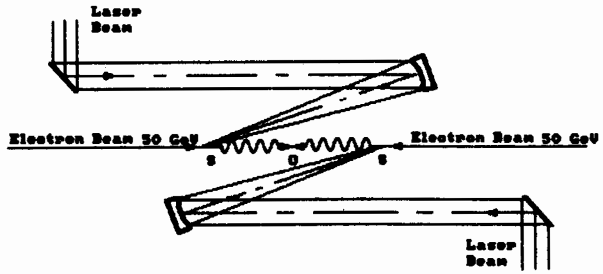

Fig.1 Photon collider

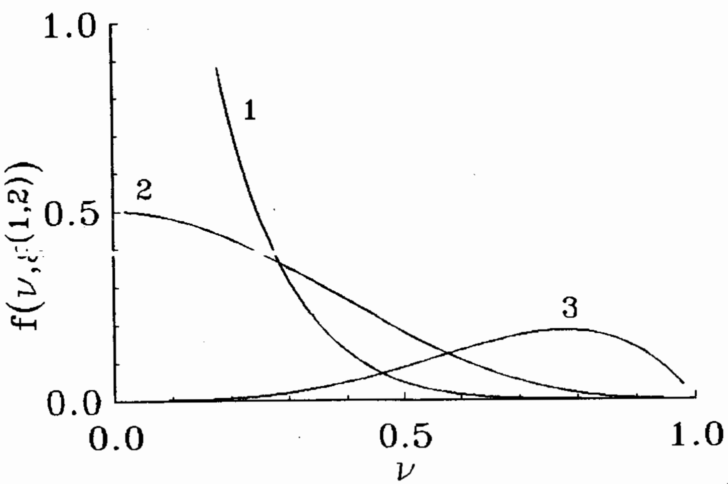

Fig.2 Dependency of function $f(\nu, \xi^{(1)}, \xi^{(2)})$ on energy:

(1) – $f(\nu, 1, 1)$;

(2) – $f(\nu, 1, -1)$ & $f(\nu, -1, 1)$;

(3) – $f(\nu, -1, -1)$.

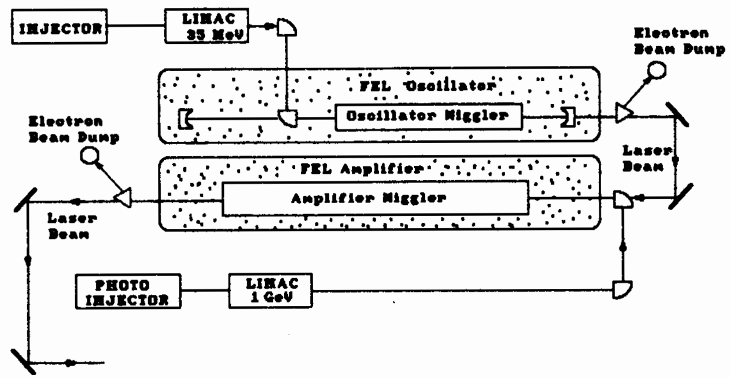

Fig.3 Two-stage FEL scheme for a photon collider

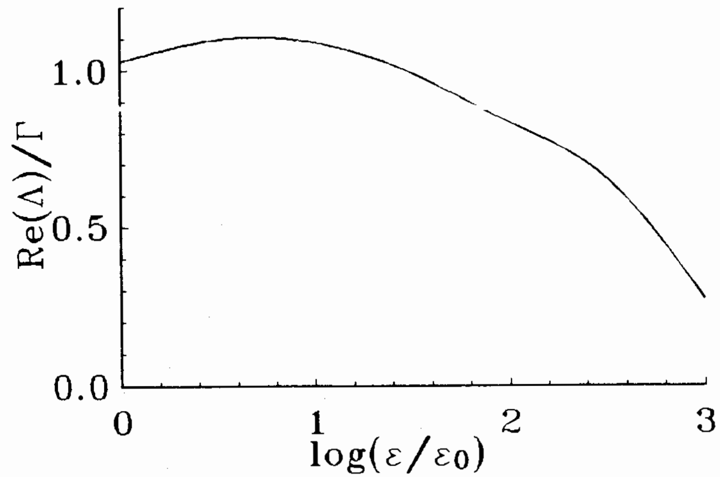

Fig.4 Dependency of the FEL amplifier increment on emittance ($\varepsilon_0 = 10^{-6}$cm·rad)

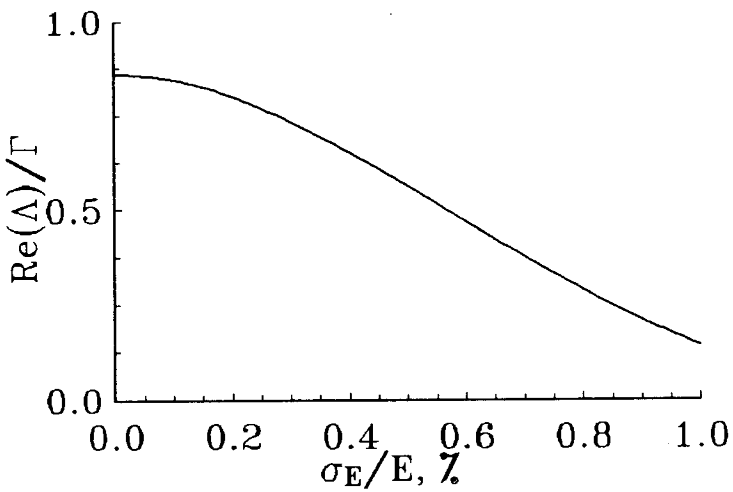

Fig.5 Dependency of the FEL amplifier increment on energy spread

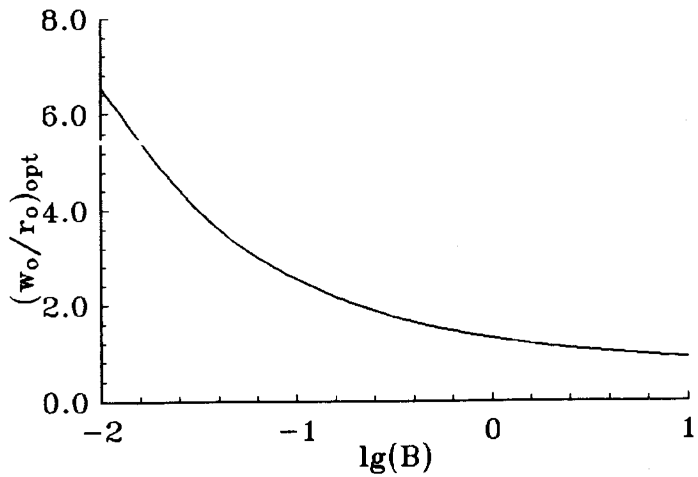

Fig.6 Dependency of the optimal value of the Gaussian beam waist on the beam diffraction parameter

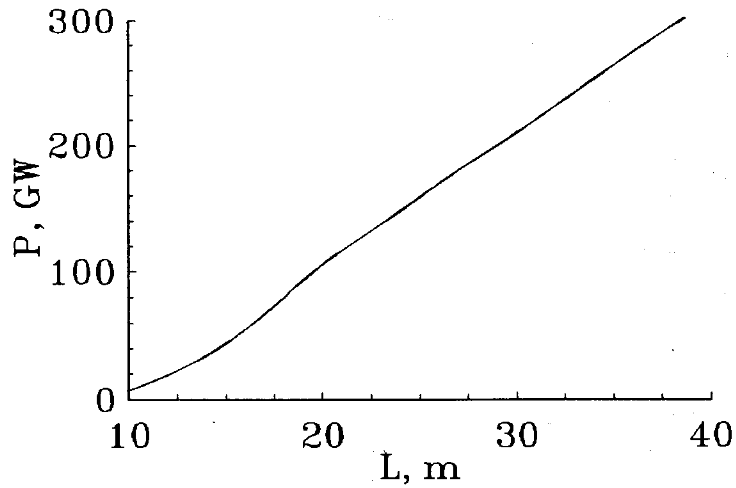

Fig.7 Output FEL amplifier power versus undulator length

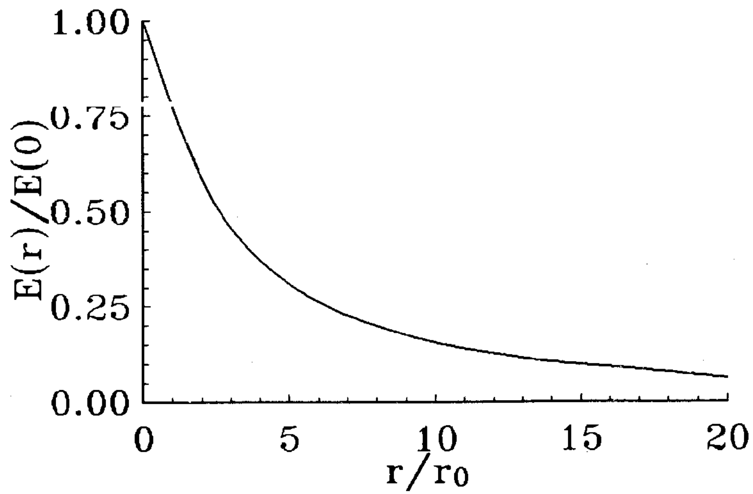

Fig.8 Radiation field distribution versus radius at the FEL amplifier exit

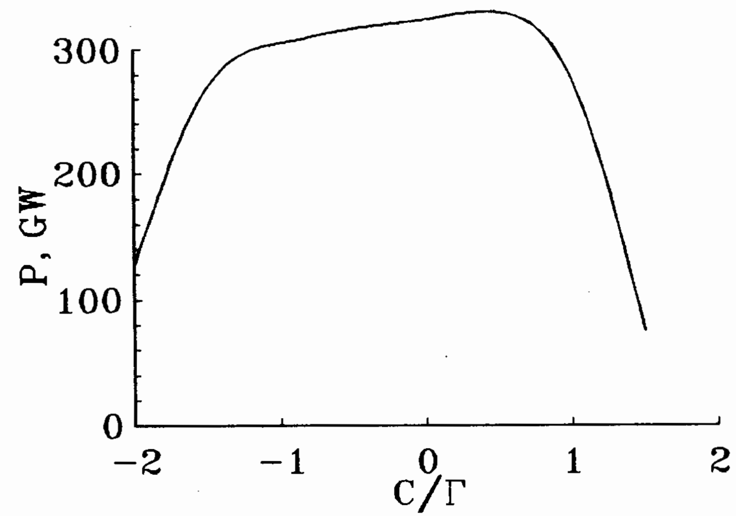

Fig.9 Output FEL amplifier power versus detuning

Acknowledgments

The authors should like to thank Yu.N. Ulyanov for many useful discussions and recommendations. We also should like to thank V.E. Balakin and G.V. Dolbilov for a kind interest in our work.

References

[1] I.F. Ginzburg et al., Pis'ma v ZhETF **34**(1981)514, Preprint INF 81-50, Novosibirsk (1981), in Russian

[2] V.I. Telnov, Nucl. Instr. and Methods **A294**(1990)72

[3] D.L. Borden, D.A. Bauer and O. Caldwell, SLAC-PUB-5715 (January, 1992)

[4] A.M. Kondratenko, E.V. Pakhtusova and E.L. Saldin, Dokl. Akad. Nauk **264**(1982)849, Preprint INF 81-130, Novosibirsk (1981), in Russian

[5] E.L. Saldin, V.P. Sarantsev, E.A. Schneidmiller and M.V.Yurkov Proceedings of the 2nd Workshop "Physics on VLEPP" (2 - 4 June, 1992, Protvino, Russia), Vol.2, page 96, in Russian

[6] S.M. Bilenky, Proceedings of the Workshop on JINR c-tau Factory (29–31 May, 1991, Dubna, Russia), page 27

[7] T.J. Orzechowski et al., Phys. Rev. Lett. **57**(1986)2172

[8] T.J. Orzechowski et al., Proc. 1988 Linear Accelerator Conf., CEBAF Report 89–001, Newport news, 1988

[9] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Optics Communications, **97**(1993)272

[10] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Optics Communications, **95**(1993)141

[11] D. Bauer et al., SLAC-PUB-5816 (June, 1992)

[12] K. Batchelor et al., Nucl. Instrum. and Methods **A318**(1992)372

[13] J.T. Seeman, SLAC-PUB-5607 (July, 1991), SLAC-PUB-5748 (June, 1992)

[14] E.L. Saldin, Dokl. Akad. Nauk **244**(1979)570, in Russian

[15] V.B. Berestecky, E.M. Lifshitz and L.P. Pitaevsky, Quantum Electrodynamics (nauka, Moscow, 1989)

[16] B.W.J. McNeil, Nucl. Instrum. and Methods **A296**(1990)388

[17] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, "Similarity techniques in a one-dimensional theory of a FEL oscillator", Optics Communications, 1993

[18] D.W. Feldman et al., Nucl. Instrum. and Methods **A285**(1989)11

[19] N. Kroll, P. Morton and M. Rosenbluth, SRI Rep. JSR-79-01; IEEE J. Quant. Electr. **QE-17**(1981)1436

[20] P. Sprangle, C.M. Tang and W.M. Manheimer, Phys. Rev. **A21**(1980)302

[21] P.W. van Amersfoort et al., Nucl. Instrum. and Methods **A318**(1992)42

[22] F. Glotin et al., Proceedings of the Third European Particle Accelerator Conference (EPAC 92), Vol.1, p.620, Berlin, 1992

[23] P.G. O'Shea et al., Nucl. Instrum. and Methods **A318**(1992)52

[24] G. Travier, Nucl. Instrum. and Methods **A304**(1991)285

[25] T. Tsang, T.Srinivasan and J. Fischer, Proceedings of the Workshop "Prospects for a 1Å Free-Electron Laser" (Sag Harbor, New York, April 22 – 27, 1990), BNL 52273, page 161.

[26] D.A.G. Deacon et al., Phys. Rev. Lett. **38**(1977)892

[27] L.P. Elias and J.M.J. Madey, Rev. Sci. Instr. **50**(1979)1335

[28] H. Buchholz, Elektrische und magnetische Potetialfelder (Berlin – Göttingen – Heidelberg, Springer – Verlag, 1957)

Received by Publishing Departmen on September 11, 1993.

Салдин Е.Л. и др. E9-93-254

О возможности создания фотонного коллайдера с высокой светимостью в области энергий 2x5 ГэВ на базе SLC

Рассмотрены физические принципы работы фотонного линейного коллайдера (ФЛК), в котором жесткие фотоны получаются путем обратного комптоновского рассеяния лазерных фотонов на высокоэнергетичном электронном пучке. Основной упор сделан на анализе возможности создания ФЛК с энергией в центре масс 3+10 ГэВ на базе стэнфордского линейного коллайдера SLC. Показано, что современный уровень развития ускорительной техники позволит создать на базе SLC фотонный коллайдер со светимостью $L_{\gamma\gamma} \sim 10^{34}$ cm^{-2}s^{-1} путем модификации инжекционной части ускорителя, установкой дополнительных кикер-магнитов и двухкаскадного лазера на свободных электронах, в котором задающий сигнал ЛСЭ-генератора ($\lambda \sim$ 10+30 μm, W $\sim$ 10 MW) усиливается в ЛСЭ-усилителе до мощности $\sim 3\cdot10^{11}$ W. Отмечено, что такая установка откроет уникальные перспективы изучения физики c- и B-кварков, а также физики τ-лептонов, производя $\sim 10^2$поляризованных τ-лептонов в секунду. В то же самое время фотонный коллайдер на базе SLC будет служить надежной экспериментальной базой, на основе которой станет возможным проектирование фотонных коллайдеров ТэВ-ного диапазона энергий.

Работа выполнена в Лаборатории сверхвысоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 1993

Saldin E.L. et al. E9-93-254

On a Possibility to Construct a High Luminosity 2x5 GeV Photon Collider at SLC

Physical principles of operation of the high energy photon linear colliders (PLC) based on the Compton backscattering of laser photons on high energy electrons are discussed. The main emphasis is put on the analysis of a possibility to construct the PLC with the center of mass energy 3+10 GeV at the Stanford Linear Collider (SLC) facility. It is shown that such a collider, providing luminosity of colliding $\gamma\gamma$ beams $L_{\gamma\gamma} \sim 10^{34}$ cm^{-2}s^{-1}, may be constructed at the present level of acceleration technique R&D with moderate modifications of the existing SLC facility by installation of new injector, kicker magnet and two-stage free electron laser consisting of a FEL oscillator ($\lambda \sim$ 10+30 μm, output power ~10 MW) with subsequent amplification of the master signal in a FEL amplifier up to the power $\sim 3\cdot10^{11}$ W. It is emphasized that such a collider will be a unique instrument for precision study of the charmonium and bottomonium physics as well as τ-lepton physics providing $\sim 10^2$ polarized τ-leptons per second. At the same time the Photon Linear Collider at SLC will serve as a reliable test base for constructing of future TeV-range photon linear colliders.

The investigation has been performed at the Particle Physics Laboratory, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 1993