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дубна

E9-94-70

E.L.Saldin[1], V.P.Sarantsev, E.A.Schneidmiller[1],
M.V.Yurkov

FEL BASED PHOTON COLLIDER OF TEV ENERGY RANGE

Submitted to «Particle Accelerators»

[1]Automatic Systems Corporation, Smyshlyaevskoe Shosse 1a, 443050, Samara, Russia

1994

1 Introduction

It was realized in the beginning of the 80s that peculiar feature of the future generation e^+e^- linear colliders, namely that bunches are used only once, reveals a possibility to construct high luminosity 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]. When laser light intensity is rather large, then significant fraction of electrons scatters the laser photons which enables one to obtain high luminosity colliding gamma quantum beams.

There are a lot of technical problems to be solved prior the constructing of future linear colliders. To construct the PLC on the base of the linear collider, one 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 [2]. The laser pulse should be synchronized precisely with respect to the electron pulse with accuracy of an order of one picosecond. Finally, to provide a more reach program of physical experiments, the laser should provide a possibility to steer the polarization of the laser light. 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).

When considering the FEL as a source of primary photons for the PLC, one should pay attention at several evident advantages of the FEL against conventional quantum laser. Indeed, the FEL can provide 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 linear accelerator, 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. One should remember that the laser and electron beams should be synchronized with a high accuracy at the conversion point (timing jitter should be of an order of one picosecond). This problem seems to be unsolvable for powerful quantum lasers, but it may be solved by standard methods for the FEL so as it is totally based on accelerator technique. There is another decisive factor in favor of the FEL choice. When performing physical program at the photon colliding beam facility, it will be necessary to steer the helicity of colliding beams. This problem seems to be unsolvable with quantum lasers, while the FEL output radiation is totally polarized: circularly or linearly for the case of helical or planar undulator, respectively. Use this feature of the FEL radiation together with the possibility to use polarized electron beams, reveals wide possibilities to steer the helicity and energy spectrum of colliding gamma quantums.

We should notice, however, that there is one visible disadvantage of the FEL, namely that it should be rather bulky device. As we will show below, the FEL for the PLC requires separate linear accelerator with energy about 1 – 2 GeV and the total length of the FEL system is of an order of several tens of meters. Nevertheless, comparing the FEL system dimensions and cost with the overall dimensions and cost of the linear collider, one can obtain that the FEL equipment will constitute only small fraction of total linear collider equipment.

For the first time an idea to use the FEL in the PLC scheme was proposed in ref. [3]. At that time a conceptual project of 2×50 GeV PLC was under study. The project was based on the parameters of the first VLEPP project [4]. It was assumed to use the beam of the main linear accelerator at the intermediate phase of acceleration ($\mathcal{E} = 10$ GeV, $I =$ 5 kA) as the driving beam for the FEL amplifier (undulator period $\lambda_w = 20$ cm, undulator field $H_w = 20$ kG and undulator length $L = 40$ m) operating in a superradiance mode. Output radiation with the wavelength $\lambda = 0.4$ μm and peak power about 2.5×10^{11} W was obtained at the undulator exit. Then the optical beam and the electron beam were separated and the latter was accelerated up to the final energy 50 GeV. At the conversion point the optical beam was focused on the electron beam. Conversion efficiency $\eta \sim 70$ % has been obtained resulting in the luminosity $L_{\gamma\gamma} \simeq 4 \times 10^{31}$ cm^{-2}s^{-1}.

Analyzing the approach proposed in ref. [3], we may conclude that it was a basic one in the main details. It was a right choice of the FEL amplifier configuration for use in the PLC design. Presented in ref. [3] numerical estimations of the FEL amplifier output parameters are in good agreement with the present-day numerical simulations. Moreover, the idea to use the beam of the main linear accelerator as the driving beam for the FEL amplifier may be of use for constructing relatively low energy photon colliders ($\mathcal{E}_{c.m.} \leq 200$ GeV).

Since that time significant experience in the field of linear collider design was accumulated by powerful research groups from SLAC, KEK, Novosibirsk/Protvino, CERN and DESY. Successful operation of the first linear collider SLC at Stanford has shown that it is quite feasible to build at the beginning of the next century a linear collider of TeV range [5]. Almost all leading accelerating centers develop national projects of such a collider: NLC/TLC (SLAC, USA), JLC (KEK, Japan), VLEPP (Novosibirsk/Protvino, Russia), CLIC (CERN) and DLC (DESY, Germany) [6]. On the other hand, it was realized by the physical community that the PLC may serve as a unique tool to study matter in the energy region $0.2 - 2$ TeV. For instance, PLC may serve as a Higgs boson factory providing

a branch of the Higgs boson production $\gamma\gamma \to H$. Even in the case when Higgs boson will be found at another type of accelerator, its properties may be studied in details only at the photon linear collider [7].

During last decade the FEL reputation have achieved an appropriate level, too. The main principles of the FEL operation are widely known now. A possibility to increase the FEL amplifier efficiency was demonstrated experimentally, an efficiency ~ 30 % was achieved [8]. Successful experiments with the FEL amplifier operating in the infrared wavelength range have been performed [9].

Thus, nowadays there is an urgent necessity to consider once more the problem to construct the FEL based PLC.

In the present paper we will not touch the general problems of the linear collider design and will consider the problems of the optimal choice of the FEL configuration and problems of optimal conversion of laser photons to high energy photons. Here we should note only that there are some peculiarities of the PLC which should be taken into account at a design stage of the linear collider. First, there is no need in positrons for the PLC operation, so injection system may be simplified and optimized for the PLC mode of operation. Second, there is no need to produce flat electron beams and round beams may be more preferable. Third, a single bunch mode of operation (as accepted in the VLEPP project) is more preferable to reduce requirements on the FEL system parameters.

The paper proceeds as follows. In section 2 we study the problem of the optimal focusing of laser radiation on the electron beam and discuss the problem to calculate the luminosity of colliding $\gamma\gamma$ beams. In sections 3 and 4 we study the problem to construct the FEL for the PLC. We suppose that the optimal FEL configuration for the PLC application is a two-stage FEL scheme consisting of a tunable FEL master oscillator (peak power $\sim 1 - 10$ MW) as the first stage and the FEL amplifier with tapered undulator (peak output power ~ 1 TW) as the second stage [10, 11]. Though our paper does not pretend to be universal with respect to the choice of the FEL parameters, nevertheless, as we show below, there is no a wide possibility for optimization of these parameters, almost all of them have to be chosen simple. To give the reader a more full notion about the range of the FEL parameters required, we illustrate our consideration with numerical examples for the PLC schemes with the center-of-mass energy 0.5, 1 and 2 TeV, respectively. Requirements on the parameters of the FEL system (i.e. on energy, current, emittance and energy spread of the driving electron beam, parameters of the undulator etc.) are formulated. It is shown that construction of such a FEL system is quite possible at the present level of accelerator technique R&D.

All the numerical results of the FEL amplifier simulations, presented below, are obtained with the FS2R computer code package [12, 13].

2 Obtaining of colliding $\gamma\gamma$ beams

The most optimal way to produce high energy γ - quantums is the Compton backscattering of the laser photons by the high energy electrons [2]. The frequencies of the incident and scattered photons, ω and ω_γ, are connected by the relation (in the small-angle approximation):

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

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 $\gamma = \mathcal{E}/m_e c^2$ is relativistic factor.

Focusing of laser beam

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 find the distribution of the optical field intensity in the focal spot. We assume the focus distance and aperture of the focusing mirror to be F and a, respectively. All the calculations will be performed using paraxial approximation, i.e. it means that the angle of incident laser beam α with respect to the mirror normal and $\theta_{max} \simeq a/F$ are much less than unity.

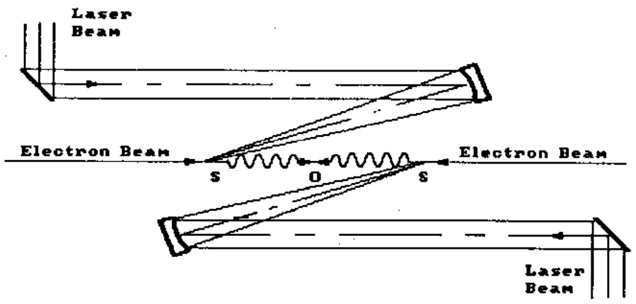

Figure 1: Photon collider scheme

First we consider the case of infinitely long laser pulse. To be concrete, we assume the laser radiation to be circularly polarized. Electric field of the laser electromagnetic wave is presented in the following complex form:

$$E_x + iE_y = \tilde{E}(x,y,z)\exp[i\omega(z/c-t)].$$

In axisymmetric case, the expression for the optical field distribution on the mirror surface may be written in the form:

$$\tilde{E}(x,y,z)|_{z=F} \simeq \tilde{E}_0(r),$$

where $r = (x^2+y^2)^{1/2}$ (it is assumed that the coordinate system origin is placed in the geometrical focus of the mirror). Thus, using Huygens-Fresnel integral, one can find distribution of the optical field in the focus vicinity [14]:

$$E = |\tilde{E}(z,r)| = \frac{\omega}{cF}\left|\int_0^a \tilde{E}_0(\rho)J_0(v\rho)\exp(-iu\rho^2)\rho d\rho\right|, \tag{2}$$

where $v = \omega r/cF$ and $u = \omega z/2cF^2$. Let us perform physical analysis of this expression. When the optical field intensity on the mirror surface is uniform one:

$$\tilde{E}_0(r) = A = const \qquad \text{at} \qquad 0 < r < a, \tag{3}$$

then intensity distribution in the focal plane $I(0,r)$ is given with the expression:

$$I(0,r) = |\tilde{E}(0,r)|^2/4\pi c = I_0\left[\frac{2J_1(v_a r)}{v_a r}\right]^2, \tag{4}$$

where $I_0 = A^2\omega a^2/2$ is the optical field intensity in the geometrical focal point and $v_a = \omega a/cF$. It is seen from expression (4) that the optical field intensity takes the first zero value at $v_a r = 3.88$, i.e at

$$r = 3.88cF/\omega a. \tag{5}$$

and more than 80% of the total optical power is passed inside the first diffraction maximum.

The distribution of the optical field intensity along z axis is given with expression:

$$I(z,0) = I_0[2\sin(ua^2/2)/ua^2]^2. \tag{6}$$

The optical field intensity takes its first zero value at the distance

$$z = \pm 4\pi cF^2/\omega a^2 \tag{7}$$

from the geometrical focus of the mirror. So, simple physical estimations show that characteristic dimensions of the region with strong optical field are od the order of:

$$r \lesssim 4cF/\omega a, \qquad |z| \lesssim 4\pi cF^2/\omega a^2. \tag{8}$$

When calculating the conversion efficiency, we assume transverse electron beam size at the conversion point σ_F to be small with respect to the laser beam spot size :

$$\sigma_F^2 \ll (4cF/\omega a_0)^2. \quad (9)$$

where a_0 is the characteristic size of laser beam on the focusing mirror. 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. When the electron transverse motion in the field of incident electromagnetic wave is nonrelativistic:

$$\frac{e^2}{m_e^2 c^4}|\tilde{E}|^2 \lambda\!\!\!^{-2} \ll 1, \quad (10)$$

the probability P of the electron scattering by the incident optical beam is given with the expression [3]:

$$P = 1 - \exp[-(2\sigma_c/4\pi\hbar\omega)\int_{-\infty}^{\infty}|\tilde{E}(z,0)|^2 dz], \quad (11)$$

where

$$\sigma_c = 2\pi r_e^2[\frac{1}{\chi}\ln(1+\chi) - \frac{8+4\chi}{\chi^3}\ln(1+\chi) + \frac{8}{\chi^2} + \frac{2+\chi}{2(1+\chi)^2}] \quad (12)$$

is the total Compton cross section on unpolarized electrons and $r_e = e^2/m_e c^2$. Remembering that the field of the optical beam is decreased quickly with the removal from the focus (it vanishes almost completely at $|z| > 4\pi cF^2/\omega a_0^2$), we calculate the integral in expression (11) the limits $-\infty < z < \infty$. Substituting expression (2) into expression (11) and using integral representation of the δ function:

$$\delta(y) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\exp(iky)dk,$$

we obtain:

$$\int_{-\infty}^{\infty}|\tilde{E}(z,0)|^2 dz = 2\pi\omega\int_0^a \rho|\tilde{E}_0(\rho)|^2 d\rho = 4\pi\omega W/c^2, \quad (13)$$

where W is the total power of the optical beam. Thus, expression (11) for the probability of Compton scattering takes the form [3]:

$$P = 1 - \exp(-\delta), \qquad \delta = 2W\sigma_c/\hbar c^2. \quad (14)$$

Let us point at the important feature of this result. Under the condition (9), the expression for the probability of the Compton scattering (14) 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. Applicability region of this result (see relation (10)) imposes the following restriction on the peak power of the laser radiation:

$$W \ll \frac{m_e^2 c^5}{e^2}\frac{F^2}{a_0^2}\frac{1}{(1+\chi)^2}.$$

When deriving expression (14) we have assumed the laser pulse duration to be infinitely long. Nevertheless, this expression is valid for the case of approximately equal lengths l_b and l_w of electron and laser beams. Taking into account expression (8) for axial dimension of the region with strong optical field, we may conclude that it takes place when

$$l_w \gg 4\pi cF^2/\omega a_0^2, \qquad l_b \lesssim l_w. \quad (15)$$

Spatial distribution of gamma quantums

All the above mentioned considerations are valid for an arbitrary value of parameter $\chi = 4\gamma\hbar\omega/m_e c^2$. From practical point of view two situations are of interest: $\chi \ll 1$ and $\chi \gg 1$. The first one describes classical limit of the Compton scattering and has been studied in detail elsewhere [15]. In this paper we will study the case of essentially quantum region of the Compton scattering, $\chi \gg 1$, which is the most suitable to describe the PLC of TeV energy range. So, in all the formulae we will assume that $\chi \gg 1$ and $\gamma \gg 1$.

To calculate the luminosity of the colliding $\gamma\gamma$ - beams, one should calculate spatial and energy distributions of the secondary γ - quantums $\rho_\gamma(\vec{r},t)$. Differential cross-section of photon on unpolarized electron is of the form ($\gamma \gg 1$) [16]:

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

When $\chi \gg 1$ and $\gamma^2\theta^2 \ll \chi$), this expression is reduced to:

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

When parameter $\chi \gg 1$, the electron energy after the first scattering is of the order of $\mathcal{E}/\chi$, so we can neglect the process of multiple scattering and the spatial distribution of secondary gamma quantums may be written in the form:

$$dW \simeq \eta_{e\gamma}\frac{d\sigma_c}{\sigma_c d\theta^2}\frac{d\theta_x d\theta_y}{\pi},$$

where the conversion efficiency $\eta_{e\gamma}$ (i.e. the total number of γ - quantums produced by the single electron) is equal to:

$$\eta_{e\gamma} \simeq P = 1 - \exp(-\delta). \quad (16)$$

Interaction region

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

$$L = 2fN^{(1)}N^{(2)} \int \rho^{(1)}(\vec{r},t)\rho^{(2)}(\vec{r},t)d\vec{r}dt, \quad (17)$$

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:

$$\rho^{(1,2)}(r,z,t) = [(2\pi)^{3/2}\sigma_z\sigma_t^2(z)]^{-1}\exp[-\frac{r^2}{2\sigma_t^2(z)} - \frac{(z \mp Vt)^2}{2\sigma_z^2}], \quad (18)$$

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 (18) into expression (17) we obtain:

$$L_{ee} = \frac{\sqrt{\pi}N_e^2 f}{8\epsilon\sigma_z}\exp(H^2)[1 - \frac{2}{\sqrt{\pi}}\int_0^H \exp(-x^2)dx], \quad (19)$$

where $H = \beta_0/\sigma_z$.

To obtain colliding gamma-quantums, one should convert high energy electrons into high energy gamma quantums (see previous section). When the distance z_0 between conversion point and interaction point is satisfied to the conditions:

$$\sigma_z \ll z_0, \qquad z_0 \ll \gamma\sigma_t^{(0)}/(1+\chi)^{1/2}, \quad (20)$$

and the conditions of the optimal focusing (9) and (15) are fulfilled, then γ - quantum beam density becomes proportional to the electron beam density:

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

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

$$L_{\gamma\gamma} = \eta_{e\gamma}^2 L_{ee}. \quad (21)$$

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:

$$\frac{dL_{\gamma\gamma}}{d\omega_0} = 4fN_\gamma^{(1)}N_\gamma^{(2)}\omega_0\int_{\omega'}^{\omega''}\frac{d\omega_\gamma^{(1)}}{\omega_\gamma^{(1)}}\int d\vec{r}dt\frac{d\rho^{(1)}}{d\omega_\gamma^{(1)}}\frac{d\rho^{(2)}}{d\omega_\gamma^{(2)}}, \quad (22)$$

where $\omega_0 = \sqrt{\omega_\gamma^{(1)}\omega_\gamma^{(2)}}$, $\omega' = \omega_0^2/\omega_{max}$ and $\omega'' = \omega_{max} = \mathcal{E}\chi/(1+\chi)$. When the distance z_0 between the conversion and interaction point is rather small:

$$z_0 \ll \frac{\sigma_e^{(0)}}{\theta(\omega_\gamma)} = \frac{\gamma\sigma_e^{(0)}}{\sqrt{1+\chi}}\sqrt{\frac{\omega_0}{\omega_{max}-\omega_0}}, \quad (23)$$

then the spectral density of secondary gamma quantums becomes proportional to the electron density:

$$\frac{d\rho_\gamma}{d\omega_\gamma} \simeq \frac{\eta_{e\gamma}}{\sigma_c}\frac{d\sigma_c}{d\omega_\gamma}N_e\rho_e(\vec{r},t), \quad (24)$$

where $\theta(\omega_\gamma)$ is given with expression (1). Substituting expression (24) into expression (22), one can obtain [3]:

$$\omega_0\frac{dL_{\gamma\gamma}}{d\omega_0} = \eta_{e\gamma}^2 L_{ee}\frac{2\chi}{\ln^2\chi}\frac{\ln[1+2\chi(1-\nu)]}{1+\chi(1-\nu)}, \quad (25)$$

where $\nu = \omega_0/\omega_{max}$. It is seen from this expression that spectral luminosity has a sharp maximum in the vicinity of $(1-\nu) \sim 1/\chi$ which is achieved at $\nu \simeq 1 - 1.3/\chi$:

$$\omega_0\left(\frac{dL_{\gamma\gamma}}{d\omega_0}\right)_{max} \simeq 1.1 L_{ee}\frac{\eta_{e\gamma}^2\chi}{\ln^2\chi}. \quad (26)$$

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 and electron beam is unpolarized. In essentially quantum region, $\chi \gg 1$, the differential Compton cross section averaged over final polarization states of electron is given with the expression [3]:

$$\frac{d\sigma_c}{d\omega_\gamma} = \frac{\pi r_e^2\hbar}{\chi(\mathcal{E}-\hbar\omega_\gamma)}\left[1 + \xi_{opt}\xi_\gamma\left(1 - \frac{2\hbar\omega_\gamma}{\chi(\mathcal{E}-\hbar\omega_\gamma)}\right)\right].$$

At the given helicity of the optical beam ξ_{opt}, 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 essentially quantum region, $\chi \gg 1$, and at small distance between the conversion and interaction point (see relation (23)), we obtain the following expression for spectral luminosity [3]:

$$\omega_0 \frac{dL_{\gamma\gamma}}{d\omega_0} = \eta_{e\gamma}^2 L_{ee} \frac{2\chi}{\ln^2 \chi} f(\nu, \xi^{(1)}, \xi^{(2)}), \qquad (27)$$

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:

$$\begin{aligned} f(\nu,1,1) &= \frac{1}{(1+k)^2}\left[\left(2k+\frac{1}{1+k}\right)\ln(1+2k)-2k\right], \\ f(\nu,1,-1) &= f(\nu,-1,1) = \frac{1}{(1+k)^2}\left[\frac{k}{1+k}\ln(1+2k)+\frac{2k^2}{1+2k}\right], \\ f(\nu,-1,-1) &= \frac{1}{(1+k)^2}\left[\frac{\ln(1+2k)}{1+k}+\frac{2k}{1+2k}\right], \end{aligned} \qquad (28)$$

where $k = \chi(1-\nu)$. 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.

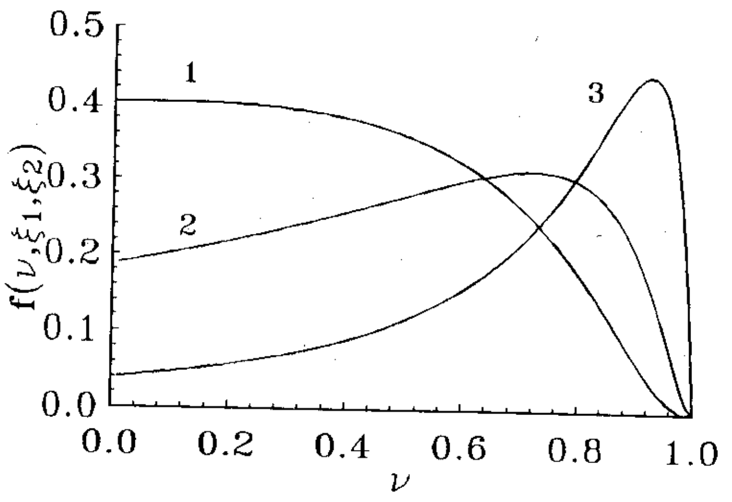

Figure 2: Dependency of function $f(\nu, \xi_1, \xi_2)$ on energy: (1) - $f(\nu,1,1)$; (2) - $f(\nu,1,-1)$ & $f(\nu,-1,1)$; (3) - $f(\nu,-1,-1)$

Final remark

In conclusion of this section it should be noted that all the presented above formulae refer to the case of the laser beam with ideal (i.e. diffraction limited) dispersion. In other words, the phase volume of the laser beam was assumed to be of the order of radiation wavelength λ. In the case when the laser beam phase volume exceeds significantly this value, the required laser power should be increased significantly to achieve a desired value of the conversion efficiency. In connection with this we should emphasize that the phase volume of radiation of powerful lasers usually exceeds by several tens of magnitude the value of λ. The main effect which determines the growth of the radiation dispersion is fluctuations of the active medium refractive index due to thermal effects. Contrary to this, the radiation of the FEL amplifier has always minimal phase volume because the process of the field amplification develops in vacuum.

3 On a choice of the PLC parameters

In the present paper we study the case of the PLC of TeV energy range aiming the goal to outline specific problems which will arise at the design stage of the PLC.

Main linear accelerator

There is no significant interdependence of the parameters of the key PLC systems: main linear accelerator, optical system, conversion region and interaction region. It was shown in the previous section that luminosity of $\gamma\gamma$ beams is growing when the ee - luminosity is growing. Nevertheless, when designing the PLC on the base of e^+e^- linear collider, some peculiarities of the PLC should be taken into account. First, there is no need in positrons for the PLC operation, so injection system may be simplified and optimized for the PLC mode of operation. 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 $B_n \simeq 8 \times 10^8$ A cm^{-2}rad^{-2} ($B_n = I/\epsilon_n^2$, where I is the beam current) and pulse duration ~ 5 ps. Cathode lifetime of this gun was 700 hours [17]. Significant experience in the development of the photoinjector technique has been stored at SLAC and KEK, too [6]. The results obtained reveal a possibility of application of the photoinjector technique for the PLC construction. Second, there is no need to produce flat electron beams and round beams may be more preferable. Third, a single bunch mode of operation (as accepted in the VLEPP project [6]) is more preferable to reduce requirements on the optical system parameters.

Table 1: Photon Linear Colliders of TeV Energy Range

	2×0.25 TeV	2×0.5 TeV	2×1 TeV
Main linear accelerator			
Electron energy $\mathcal{E}$, TeV	0.25	0.5	1
Number of electrons in the bunch N_e	2×10^{11}	2×10^{11}	2×10^{11}
Repetition rate f, Hz	150	150	150
Normalized emittance ϵ_n, cm·rad	$\pi\times10^{-3}$	$\pi\times10^{-3}$	$\pi\times10^{-3}$
Electron bunch length σ_z, cm	0.1	0.1	0.1
β - function at the interaction point β_0, cm	0.1	0.1	0.1
Luminosity L_{ee}, cm^{-2}s^{-1}	9.3×10^{32}	1.9×10^{33}	3.7×10^{33}
Optical System			
Laser power W, TW	0.3	0.3	0.3
Laser light wavelength λ, μm	1	2	4
Laser beam spot size at the mirror a_0, cm	2	2	2
Focus distance of the mirror F, cm	30	20	15
Conversion & Interaction Region			
χ parameter	4.75	4.75	4.75
Maximal energy of γ-quantums, GeV	206	413	826
Conversion efficiency $\eta_{e\gamma}$	0.7	0.7	0.7
Distance z_0 between CP and IP, cm	3	5	8
Luminosity $L_{\gamma\gamma}$, cm^{-2}s^{-1}	4.6×10^{32}	9.2×10^{32}	1.8×10^{33}

To illustrate the further consideration, we present three conceptual variants of the PLC with the center-of-mass energy 0.5, 1 and 2 TeV, respectively (see Table 1). The electron beams of the main linear accelerator are assumed to be round: $(\epsilon_n)_x = \pi\gamma x x' \simeq (\epsilon_n)_y \simeq \pi\gamma y y'$ and $(\beta_0)_x = (\beta_0)_y = \beta_0$.

Optical system

The laser light wavelength is chosen to be close to the optimal value given by the relation $\chi \simeq 4.8$ which correspond to [2]:

$$\lambda(\mu\mathrm{m}) \simeq 4.2\mathcal{E}(\mathrm{TeV}). \qquad (29)$$

The key element of the PLC project is the optical system providing the required parameters of the laser beam at the conversion point. For the numerical example we have chosen the value of the laser radiation power to be $W = 0.3$ TW which results in the conversion efficiency $\eta_{e\gamma} \simeq 0.7$ and in the ratio $L_{\gamma\gamma}/L_{ee} \simeq 0.5$. We should note that luminosity of gamma beams is extremely sensitive to the value of the laser radiation peak power. For instance, at $W = 0.1$ TW we obtain $\eta_{e\gamma} \simeq 0.33$ and $L_{\gamma\gamma}/L_{ee} \simeq 0.11$. At smaller values of W, the values of $\eta_{e\gamma}$ and $L_{\gamma\gamma}/L_{ee}$ may be approximated with simple formulae

$$\eta_{e\gamma} \simeq 4\times W, \qquad L_{\gamma\gamma}/L_{ee} \simeq 16\times W^2,$$

where W is expressed in TW units. On the other hand, at larger values of W, conversion efficiency quickly approaches to unity, for instance, at $W = 0.6$ TW we obtain $\eta_{e\gamma} \simeq 0.9$. So, when optimal conditions of focusing may be fulfilled, the value of $W \simeq 0.3$ TW may be considered as the required level of the laser radiation peak power.

Now we will show that the conditions of optimal focusing of the laser beam (9), (15) and (20) may be easily fulfilled at reasonable parameters of focusing system. To simplify these formulae, we assume the bunch length to be $l_b \simeq \beta_0$ and distance z_0 between the interaction and conversion points to be much larger than l_b. Under this approximations, relation (20) imposes an upper limit on the value of z_0:

$$z_0^2 \ll \frac{\epsilon_n\beta_0\gamma}{\pi(1+\chi)}.$$

Using this relation together with relations (9) and (15) we find that the ratio F/a_0 must obey the following relation:

$$\frac{4\epsilon_n^2}{\pi^2\lambda^2(1+\chi)} \ll \frac{F^2}{a_0^2} \ll \frac{\beta_0}{2\lambda}.$$

It is seen from Table 1 that all the conditions of the optimal focusing are achieved at reasonable values of the focusing system parameters.

Separation of electron beams

To avoid undesirable background due to collision of electron beams in the interaction region, one should separate them. The required value of the transverse magnetic field providing the separation of electron beams by $3\sigma_t(0) = 3\sqrt{\epsilon_n\beta_0/\pi\gamma}$ is given with the expression:

$$H(\text{kG}) \simeq 10^4 \frac{\sigma_t(0)}{z_0} \mathcal{E}(\text{GeV})$$

In the case under consideration this results in the values of the magnetic field 11.6 kG, 9.9 kG and 8.7 kG for 2×0.25 TeV, 2×0.5 TeV and 2×1 TeV collider projects, respectively (see Table 1).

Free electron laser for the PLC

The problem of optimal choice of the laser for the PLC has been discussed in details in ref. [15]. It was shown that the most optimal configuration of laser for the PLC is two-stage free electron laser (see Fig.3).

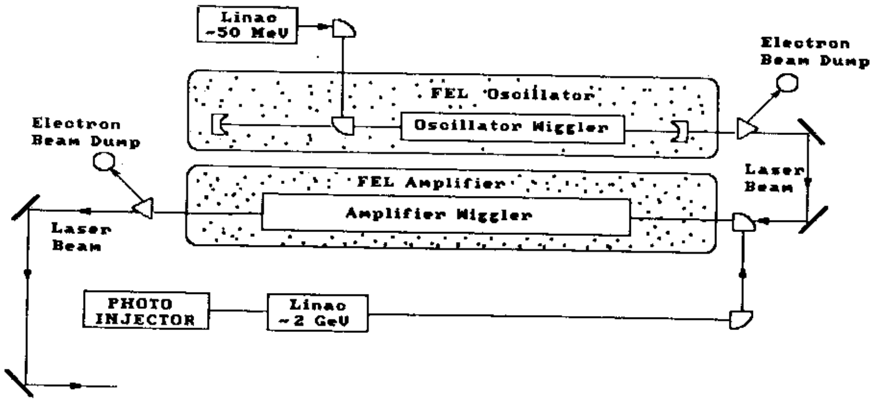

Figure 3: Two-stage FEL scheme for a photon collider

The first stage of laser is tunable FEL oscillator with moderate peak output power $W \sim 1 - 10$ MW and the second stage is an FEL amplifier with tapered undulator providing necessary peak output power about of a TW level. Such a FEL configuration meets all the requirements for the PLC laser. Indeed, it 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 radiation of the FEL amplifier is totally polarized and always has minimal, i.e. diffraction dispersion. At an appropriate parameters of the FEL driving electron beam, the required level of the FEL amplifier output radiation power may be achieved.

FEL master oscillator

The FEL master oscillator should provide tunable radiation with output power above the FEL amplifier noise. The effective value of the latter, as we will show below, is of an order of several Watts. On the other hand, the FEL oscillators of infrared wavelength range providing the output power W $\sim 1 - 10$ MW, are operating successfully nowadays at many locations [18, 19, 20]. So, the problem of the FEL master oscillator seems to be rather routine one.

4 FEL amplifier for the PLC

General remarks

A central problem to construct the photon collider on the base of e^+e^- linear collider will be the problem of the FEL amplifier with required parameters. Despite the fact that the FEL reputation has achieved an appropriate level during the last decade, devices which meet the requirements for the PLC application have not been constructed yet. Let us begin with the simple energetic estimations. To attain an output radiation power W, one should use the driving beam with the following parameters:

$$I\mathcal{E}_0/e = W/\eta, \tag{30}$$

where I is the peak beam current, $\mathcal{E}_0$ is the electron energy and η is the FEL efficiency. So, to attain the output radiation power $W \simeq 3 \times 10^{11}$ W at the FEL efficiency $\eta \simeq 6$ %, one should use, for instance, the electron beam with the peak current $I \simeq 2.5$ 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.

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 $1 - 4$ μm wavelength range should be optimized providing an output peak radiation power $\sim 3 \times 10^{11}$ 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 two hundreds 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 2 GeV and the beam current of an order of 2 kA.

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:

$$\lambda \simeq \lambda_w/2\gamma_z^2 = \lambda_w(1+Q^2)/2\gamma^2, \tag{31}$$

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 left to do is to maximize the product $H_w\lambda_w$ keeping in mind that the resonance condition (31) 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 imposes technical restrictions on the values of H_w and λ_w. A more detailed analysis shows that the values of $H_w \simeq 10 - 15$ kG and $\lambda_w \simeq 15 - 20$ cm are quite attainable.

Let us now to proceed with concrete numerical example. The parameters of the FEL amplifiers corresponding to the conceptual projects of the PLC of TeV energy range (see Table 1) are presented in Table 2.

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 [3]:

$$W_{sh} \simeq eI\omega\gamma_z^2\theta_w^2/c \tag{32}$$

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.

Energy spread and emittance of the driving electron beam

Analysis of the linear mode of the FEL amplifier operation enables one to impose restrictions on values of energy spread and emittance of the driving electron beam. In

Table 2: FEL amplifier parameters for the PLC

	2×0.25 TeV	2×0.5 TeV	2×1 TeV
Electron beam			
Electron energy $\mathcal{E}_0$, GeV	2	2	2
Beam current I, kA	2.5	2.5	2.5
Energy spread σ_E/E, %	0.3	0.3	0.3
Normalized emittance ϵ_n, cm·rad	1.3×10^{-2}	2.6×10^{-2}	5×10^{-2}
Undulator			
Undulator period λ_w, cm (entr./exit)	15 / 12.9	20 / 17.2	20 / 17.1
Undulator field H_w, kG (entr./exit)	10.2 / 11.9	9.34 / 10.9	13.2 / 15.44
Length of untapered section, m	11.7	15.6	14.0
Total undulator length, m	37.5	46.9	43.7
Radiation			
Radiation wavelength λ, μm	1	2	4
Input power W, MW	10	10	10
Output power W, TW	0.3	0.3	0.3
Efficiency η, %	6	6	6
Reduced parameters			
Diffraction parameter B	0.3	0.25	0.18
Energy spread parameter $\hat{\Lambda}_T^2$	0.1	0.1	0.1
Space charge parameter $\hat{\Lambda}_p^2$	0.08	0.1	0.14
Gain parameter Γ, cm^{-1}	5.1×10^{-3}	3.84×10^{-3}	3.84×10^{-3}
Saturation parameter $\beta = \lambda_w\Gamma/4\pi$	0.006	0.006	0.006

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 Λ and the eigenfunction of the transverse radiation field distribution $F(\vec{r})$. 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 axisymmetric electron beam with radius r_0, the eigenvalue equation of the TEM_{mn} mode is of the form [12]:

$$\mu J_{n+1}(\mu)K_n(g) = gJ_n(\mu)K_{n+1}(g), \qquad (33)$$

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, I is the beam current and $I_A = m_ec^3/e$. 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. We assume the electron beam to be matched with the magnetic system of the undulator which results in the following equilibrium radius r_0 and angle spread $(<(\Delta\theta)^2>)^{1/2}$ of the electron beam:

$$r_0 = (\beta_w\epsilon_n/\gamma\pi)^{1/2}, \qquad (<(\Delta\theta)^2>)^{1/2} = (\epsilon_n/\pi\beta_w\gamma)^{1/2}$$

where $\beta_w = \sqrt{2}\,\lambda_w/2\pi\theta_w$ is the beta-function of the electron beam in the undulator.

Detailed analysis of the FEL amplifier operation has 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 [12]. Moreover, the transverse 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.

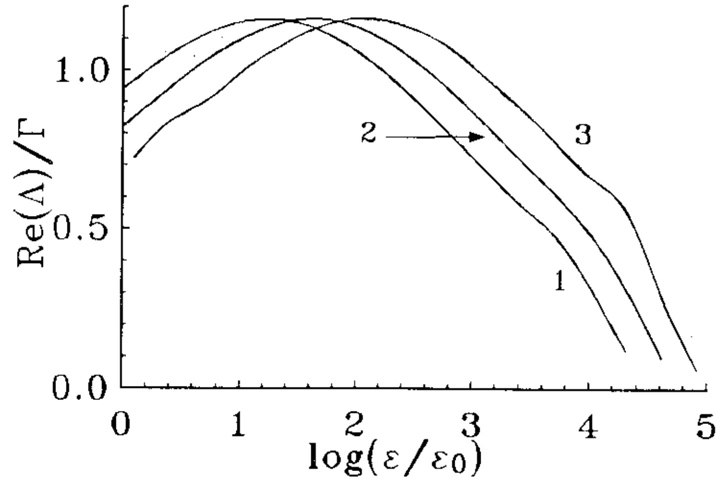

Figure 4: Dependency of the FEL amplifier increment on emittance ($\epsilon_0 = 10^{-6}$cm×rad): (1) - 2 × 0.25 TeV variant; (2) - 2 × 0.5 TeV variant; (3) - 2 × 1 TeV variant

Analysis of the eigenvalue equation (33) enables one to trace the dependence of the increment on the values of emittance and energy spread of the electrons in the beam. Fig.4 presents the dependencies of the reduced increment versus the beam emittance. It is seen from these plots that there is a region of optimal values of emittance when increment achieves its maximal value. At larger emittance there is drastical drop of the increment due to the large spread of the longitudinal velocities of the beam electrons. At small emittance values, 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. One can find from Table 2 that for the numerical examples we have chosen the values of the emittance which are slightly larger than those optimal given by plots in

Fig.4. The real reason of such a choice is based on the results of the overall optimization of the undulator length. Indeed, when one uses the electron beam with the emittance providing maximal increment in the linear mode of operation, this make it possible to reduce the length of this part of the amplifier. Then, at the nonlinear stage of the FEL amplifier operation, one should trap a significant fraction of electrons in the regime of coherent deceleration to obtain a high efficiency. Numerical simulations have shown that in this case the action of the space charge field forces to provide a more slow undulator tapering, which results in a more larger undulator length. An experience obtained on the base of numerical simulations has shown that one should choose such a value of the emittance which results in the value of the space charge parameter $\hat{\Lambda}_p^2 \lesssim 0.1$.

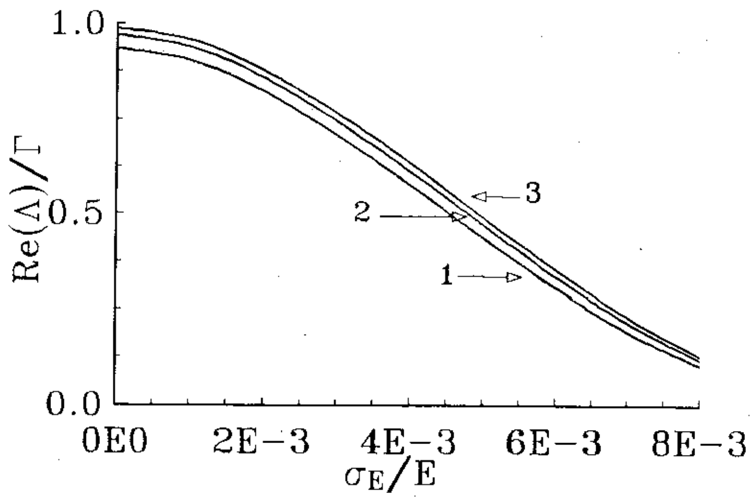

Figure 5: Dependency of the FEL amplifier increment on energy spread: (1) - 2 × 0.25 TeV variant; (2) - 2 × 0.5 TeV variant; (3) - 2 × 1 TeV variant

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 visibly drops at $\Delta\mathcal{E}/\mathcal{E} \gtrsim 0.3\%$. Numerical simulation of the nonlinear mode of the FEL amplifier operation have shown that the final FEL efficiency drastically drops when the energy spread exceeds this value.

Optimization of the undulator length and the FEL amplifier output characteristics

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:

$$E_x + iE_y = \frac{-iE_0 w_0^2 \omega/c}{2(z-z_0) - iw_0^2\omega/c} exp[-i\omega t + i(z-z_0)\omega/c + \frac{2i(z-z_0)r^2\omega/c - r^2 w_0^2\omega^2/c^2}{4(z-z_0)^2 + w_0^4\omega^2/c^2}] \qquad (34)$$

where 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. [12] 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. So, during numerical simulations we have assumed the input radiation to be optimally focused on electron beam.

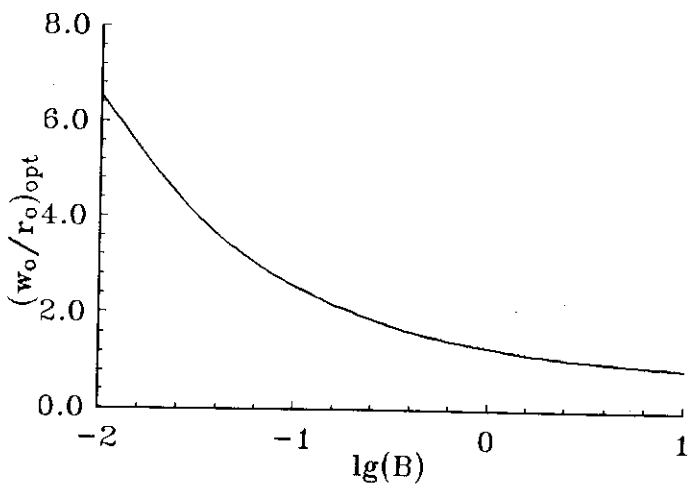

Figure 6: Dependency of the optimal value of the Gaussian beam waist on the beam diffraction parameter

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 [13]:

$$W_{sat} \simeq \beta \mathcal{E}_0 I/e, \tag{35}$$

where

$$\beta = \lambda_w \Gamma / 4\pi. \tag{36}$$

Usually the gain length $l_g = 1/\Gamma$ is much more than the undulator period which results in a low saturation efficiency

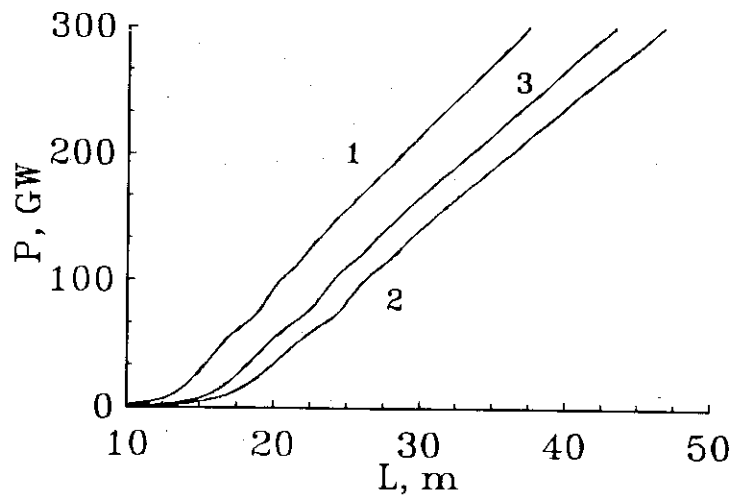

Figure 7: Output FEL amplifier power versus undulator length: (1) - 2×0.25 TeV variant; (2) - 2 × 0.5 TeV variant; (3) - 2 × 1 TeV variant

For the FEL amplifier parameters presented in Table 2 the saturation efficiency $\eta_{sat} \sim$ 0.6 % which is about 10 times less than the required level $\eta \sim 6$ %. The method of the FEL amplifier efficiency increase by the undulator parameters tapering is a widely known one [8, 21, 22]. 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. Fig.7 illustrates the dependencies on the undulator length of the FEL output power. It is seen that the required level of the radiation power is achieved at the undulator lengths

$L \sim 40$ m. A phase analysis shows that about 75 % of the electrons trap in the regime of coherent deceleration.

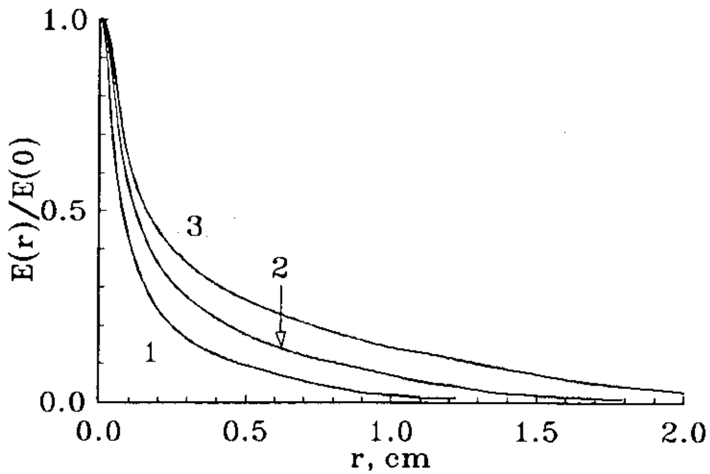

Figure 8: Radiation field distribution versus radius at the FEL amplifier exit: (1) - 2×0.25 TeV variant; (2) - 2 × 0.5 TeV variant; (3) - 2 × 1 TeV variant

The transverse distributions of the radiation field amplitude at the undulator exit are shown in Fig.8. This plot enables one to impose restriction on the vacuum chamber radius, it should be about 2 cm.

Fig.9 presents the dependencies 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.

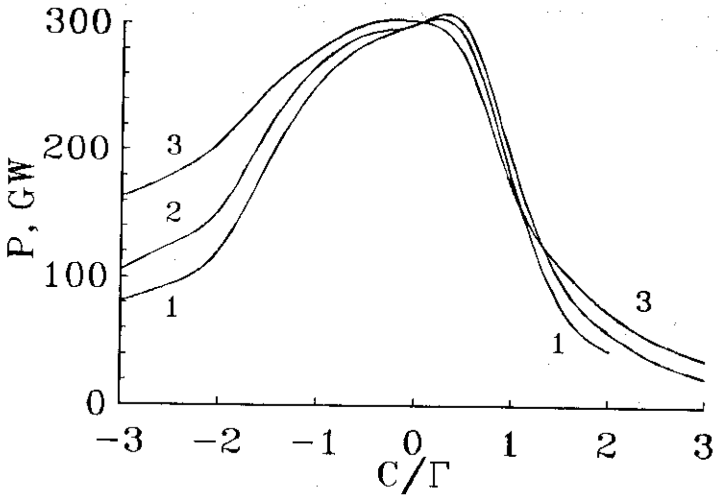

Figure 9: Output FEL amplifier power versus detuning: (1) - 2 × 0.25 TeV variant; (2) - 2 × 0.5 TeV variant; (3) - 2 × 1 TeV variant

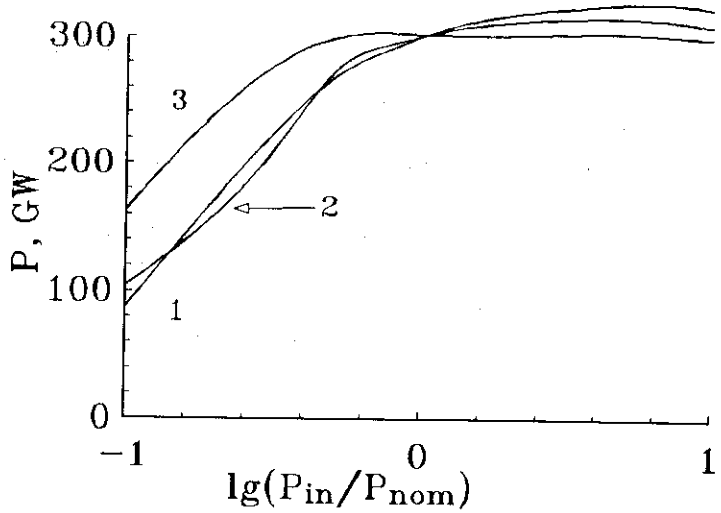

Figure 10: Output FEL amplifier power versus input power: (1) - 2 × 0.25 TeV variant; (2) - 2 × 0.5 TeV variant; (3) - 2 × 1 TeV variant

Experience obtained at the existing FEL oscillators has shown that there takes place a problem of amplitude stability of the output power [18]. So, when using the FEL oscillator as the master oscillator for the FEL amplifier, one should analyze the problem of the sensitivity of the FEL amplifier output power to the fluctuations of the input signal power. Fig.10 presents such dependencies. It is seen from the plots that the FEL amplifier output power is rather stable with respect to the fluctuations of the input signal amplitude.

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 the electron pulse length should be larger than the required laser pulse duration by the value $\lambda L/\lambda_w$.

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 examples presented this effect is negligibly small and should not be taken into account.

5 Summary

Let us summarize some problems of technical realization of the FEL based photon linear collider of TeV energy range.

There is no significant interdependence of the parameters of the key PLC systems: main linear accelerator, optical system, conversion region and interaction region. Nevertheless, when designing the PLC on the base of e^+e^- linear collider, some peculiarities of the PLC should be taken into account. First, there is no need in positrons for the PLC operation, so injection system may be simplified and optimized for the PLC mode of operation. We suppose that the injection system based on a photoinjector technique will be the most appropriate. Second, there is no need to produce flat electron beams and round beams may be more preferable. Third, a single bunch mode of operation (as accepted in the VLEPP project [6]) is more preferable to reduce requirements on the optical system parameters.

The key element of the PLC project is the optical system providing the required parameters of the laser beam: radiation wavelength $\lambda \sim 1 - 4\mu$m, peak output power $W \sim 3 \times 10^{11}$ W at minimal (i.e. diffraction limited) dispersion, pulse length of the order of several picoseconds, repetition rate about several hundred cycles per second. It is desirable that the laser for the PLC applications should produce polarized radiation.

The most optimal configuration of laser for the PLC is two-stage free electron laser (see Fig.3). The first stage of laser is tunable FEL oscillator with moderate peak output power and the second stage is an FEL amplifier with tapered undulator. Such an FEL configuration meets all the requirements for the PLC laser. It 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 radiation of the FEL amplifier is totally polarized and always has minimal, i.e. diffraction dispersion.

The problem of the FEL master oscillator seems to be rather routine one: the FEL oscillators of infrared wavelength range providing the output power $W \sim 1 - 10$ MW, are operating successfully nowadays at many locations [18, 19, 20].

A central problem to construct optical system is the problem of the FEL amplifier. The driving electron beam for the FEL amplifier should provide ($\mathcal{E} \sim 1 - 2$ GeV, $I \sim 1 - 2$ kA, $\epsilon_n \sim 3 \times 10^{-2}$ cm×rad. Undulator of the FEL amplifier should have period $\lambda_w \sim 10 - 20$ cm and peak magnetic field $H_w \sim 10 - 15$ kG.

Acknowledgments

The authors should like to thank Yu.N. Ulyanov, for many useful discussions and recommendations. We express our deep gratitude to V.E. Balakin for a kind invitation to perform this investigation and for support during our work. We are extremely grateful also to V.A. Aleksandrov, E.A. Kushnirenko, A.A. Sery, N.A. Solyak and other members of the VLEPP staff for collaboration and useful discussions. We thank G.V. Dolbilov, A.M. Kondratenko, I.A. Savin and V.I. Telnov for a kind interest in our work.

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Received by Publishing Department
on March 9, 1994.