FEL BASED PHOTON COLLIDER OF TEV ENERGY RANGE

E.L. Saldin[a], E.A. Schneidmiller[a], M.V. Yurkov[b]
[a]Automatic Systems Corporation, 443050 Samara, Russia
[b]Joint Institute for Nuclear Research, Dubna, 141980 Moscow Region, Russia

Abstract

In this paper we consider conceptual project of an FEL based photon linear collider (PLC) with the center of mass energy 0.5 – 2 TeV. Free electron laser (FEL) is considered as a source of primary photons. Proposed FEL system consists of a tunable FEL oscillator (output power $\sim 1 - 10$ MW) with subsequent amplification of the master signal in an FEL amplifier up to the power ~ 300 GW.

1 INTRODUCTION

Peculiar feature of linear colliders, namely that bunches are used only once, reveals a possibility to construct high luminosity photon linear collider (PLC) [1, 2]. High energy gamma-beams are produced in the process of Compton backscattering of laser light on electron beams of the linear collider. The requirements to the laser are as follows. It should provide peak output power of about 300 GW at diffraction limited dispersion of radiation. 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 [3]. The laser pulses should be synchronized precisely with the electron pulses with accuracy of an order of one picosecond. To provide a more reach program of physical experiments, the laser should provide a possibility to steer the polarization of the laser light. Time diagram of laser operation should follow time diagram of the main accelerator.

During last decade there were a lot of discussions on a problem which type of a laser should be chosen as a source of primary photons for photon collider. Till now there is no any reasonable conceptual study of a photon collider based on conventional quantum laser and there is no hope to develop such a project (see refs. [4]-[6] for more details). On the other hand, it was proposed from the very beginning to use free electron laser for this purpose [2]. Such an approach, totally based on accelerator technique, is the most natural way to construct photon collider. This is connected with unique potential advantages of an FEL amplifier: tunability of radiation, possibility to obtain high output power, minimal (diffraction limited) dispersion of radiation, simplicity of radiation polarization control. As FEL is based totally on the acceleration technique, the required synchronization of laser and electron pulses is provided by means of standard accelerator technique.

In this paper we present conceptual project of an FEL based photon collider of TeV energy range. When elaborating this project we have taken into account peculiar features of photon collider with respect to e^+e^- option. 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.

2 GENERAL SCHEME OF PHOTON COLLIDER

General scheme of photon collider is presented in Fig. 1. In conversion point laser beams are focused on the electron beams. Maximal energy of scattered γ-quanta are connected with energy of primary laser photons $\hbar\omega$ by relation: $\mathcal{E}_\gamma^{\max} = \mathcal{E}\chi/(1+\chi)$, where $\chi = 4\gamma\hbar\omega/m_e c^2$, m_e and $\mathcal{E}$ are the electron mass and energy, respectively, and $\gamma = \mathcal{E}/m_e c^2$ is relativistic factor. When conditions of optimal focusing of laser radiation are fulfilled, the conversion efficiency of electrons into high-energy gamma-quanta is equal to $\eta_{e\gamma} = 1 - \exp(-2W\sigma_c/\hbar c^2)$, where W is the peak laser power and σ_c is Compton cross section. Luminosity of colliding gamma-quanta is proportional to geometrical luminosity of electron beams: $L_{\gamma\gamma} = \eta_{e\gamma}^2 L_{ee}$.

3 CONCEPTUAL PROJECT OF AN FEL BASED PHOTON COLLIDER

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 produced by photoinjector and are assumed to be round.

The problem of optimal choice of the laser for the PLC

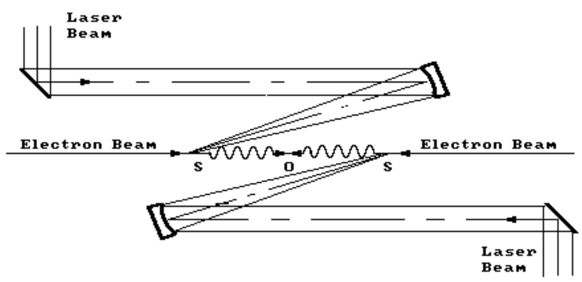

Figure 1: Photon collider scheme.

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-quanta, 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}

has been discussed in details in refs. [5, 6]. It was shown that the most optimal configuration of laser for the PLC is two-stage free electron laser (see Fig.2). The laser light wavelength is chosen to be close to the optimal value given by the relation $\chi \simeq 4.8$ which correspond to $\lambda(\mu\mathrm{m}) \simeq 4.2\mathcal{E}(\mathrm{TeV})$ [3]. The value of the laser radiation power is equal to $W = 0.3$ TW which results in the conversion efficiency $\eta_{e\gamma} \simeq 0.7$ and in the ratio $L_{\gamma\gamma}/L_{ee} \simeq 0.5$.

While the problem to construct an FEL oscillator is a routine one [7], an FEL amplifier with required parameters has not been constructed yet. Detailed analysis of the FEL amplifier parameters has been performed in ref. [5]. 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. FEL amplifier is tuned to amplify fundamental TEM$_{00}$ mode which is the most appropriate with respect to attaining of maximal field gain and reducing sensitivity to the energy spread [8]. Moreover, the transverse field distribution of this mode is optimal

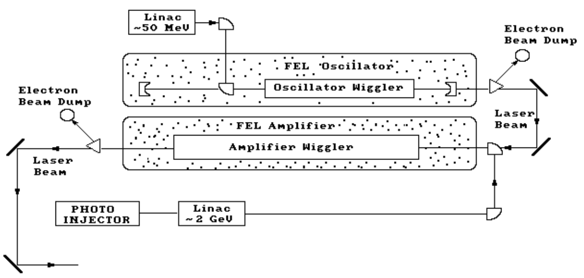

Figure 2: Two-stage FEL scheme for a photon collider.

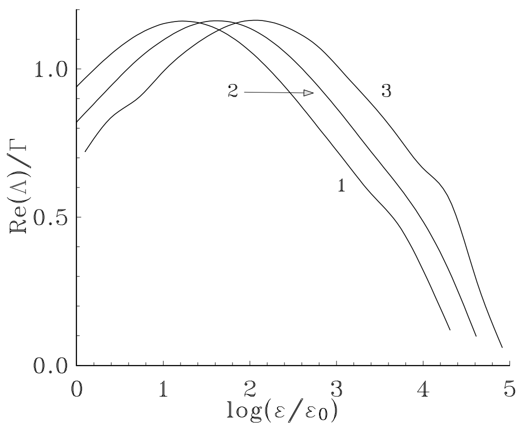

Figure 3: Dependency of the FEL amplifier field gain on emittance ($\epsilon_0 = 10^{-6}$cm$\times$rad): (1) - 2×0.25 TeV variant; (2) - 2×0.5 TeV variant; (3) - 2×1 TeV variant.

with respect to the problem of laser beam focusing on the electron beam at the conversion point. Optimal values of the emittance and the energy spread of the driving electron beam have been determined using calculations of the linear mode of the FEL amplifier operation (see Figs.3 and 4). To achieve designed value of output radiation power, undulator tapering is used [9, 10]. We have performed a set of calculations to obtain optimal conditions of the tapering. Fig.5 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 $L\sim40$ m.

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

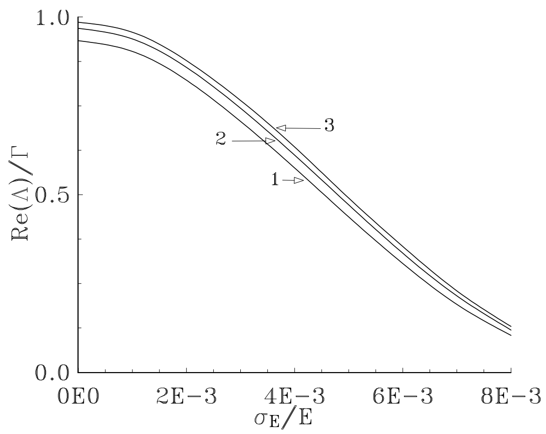

Figure 4: Dependency of the FEL amplifier field gain on energy spread: (1) - 2×0.25 TeV variant; (2) - 2×0.5 TeV variant; (3) - 2×1 TeV variant.

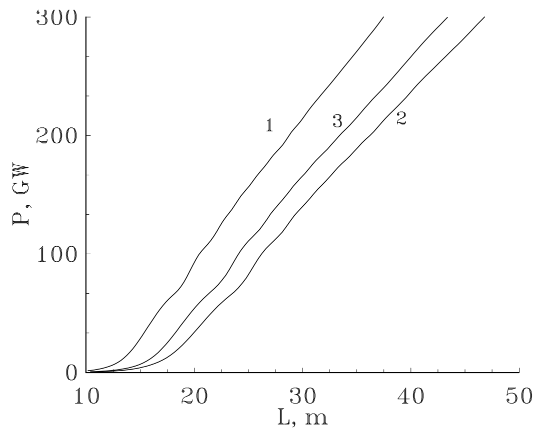

Figure 5: Output FEL amplifier power versus undulator length: (1) - 2×0.25 TeV variant; (2) - 2×0.5 TeV variant; (3) - 2×1 TeV variant.

Analysis of parameters presented in Table 2 shows that technical problems of the FEL amplifier design could be solved during R&D work on future generation linear collides, because the requirements to the driving beam of the FEL amplifier are less severe than those of the main accelerator. So, we can conclude that construction of an FEL based photon collider is technically feasible.

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