CONCEPTUAL STUDY OF AN FEL BASED GAMMA-GAMMA COLLIDER AT TESLA-500

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Abstract

This report presents conceptual project of an FEL based 2×250 GeV gamma-gamma collider at TESLA-500. The main idea of the proposal is to use the beam of the linear collider to generate FEL radiation. At an intermediate phase of acceleration the electron beam passes the undulator of the FEL amplifier and amplifies the optical radiation of the master oscillator up to the power of 350 GW. After that the electron and optical bunches are separated. The electron bunch is accelerated up to the final energy of 250 GeV and the optical bunch is transported to the conversion point via an open optical waveguide. At the conversion point the optical beam is focused on the electron beam. The integral luminosity of the colliding γ-beams is $L_{\gamma\gamma} \simeq 1.5 \times 10^{33}$ cm^{-2}s^{-1}.

1 INTRODUCTION

Nowadays there is a tendency that $\gamma\gamma$ options are included into the projects of future generation linear colliders. It is accepted that the most suitable way to obtain high energy intensive gamma-quanta beams is to produce them in the process of Compton backscattering of laser photons on the electrons of linear collider [1, 2]. One of the main problems of the $\gamma\gamma$ collider design is that of the laser. The peak power of the laser should be of about 300 GW . The laser radiation should have minimal, i.e. diffraction dispersion, otherwise the peak power must be higher. Time structure of the laser pulses must follow the time structure of the electron bunches of the linear collider. The laser should have the capability of precise synchronization with the electron bunches (with the jitter of about 1 ps) and should provide a high repetition rate. To provide a wider range of physical experiments, there should be a possibility to steer the polarization of the colliding gamma quanta which assumes a possibility to steer the polarization of the laser light.

In this paper we present conceptual design of $\gamma\gamma$ collider at TESLA-500. FEL amplifier with diaphragm focusing line is considered as a source of primary photons. Our investigation has shown that the project parameters of TESLA-500 allow one to use the electron beam of the main accelerator at an intermediate stage of acceleration (10 GeV) as the driving beam for the FEL amplifier with a diaphragm line. Such an FEL amplifier is capable to produce the photon beam characteristics which meet the requirements for application as a laser for gamma-gamma collider.

2 $\gamma\gamma$ OPTION FOR TESLA-500

The main problem of the design of the gamma-gamma collider at TESLA is a special time diagram of the TESLA operation [3]. The laser must generate series of the macropulses at the repetition rate of 10 Hz and produce 800 laser pulses of $\gtrsim 6$ ps duration and separated by 1 μs within each macropulse. It should be noticed that such a complicated time diagram of operation completely excludes a possibility to use conventional quantum lasers and only free electron laser could be considered [4, 5].

In this paper we present a conceptual project of an FEL based 2×250 GeV gamma-gamma collider at TESLA-500 [4, 5]. A scheme of this collider is presented in Figs.1 and 2 and its parameters are summarized in Table 1. The main idea of the proposal is to use the beam of the linear collider to generate radiation. At the intermediate phase of acceleration ($\mathcal{E} = 10$ GeV) the electron beam passes the undulator of the FEL amplifier and amplifies the optical radiation from the master oscillator ($\lambda = 1.053$ μ m, peak power

Table 1: $\gamma\gamma$ option for TESLA-500

Main linear accelerator	
Electron beam energy, GeV	250
Number of electrons per bunch	5.14×10^{10}
Number of bunches per pulse	800
Bunch separation, μs	1
Repetition frequency, Hz	10
Electron bunch length σ_z, cm	0.1
Normalized emittance, cm$\times$rad	$\pi \times 10^{-3}$
Beta function at IP, cm	0.1
Diaphragm line	
Diaphragm separation, cm	100
Hole radius, cm	5
Power losses per one diaphragm	2×10^{-6}
Length, km	10
Optical system	
Laser power at CP, GW	300
Laser light wavelength, μm	1.06
Laser beam size at the mirror, cm	5
Focus distance of the mirror, cm	75
Conversion & Interaction regions	
Max. energy of γ-quanta, GeV	206
Conversion efficiency $\eta_{e\gamma}$	0.7
Distance between CP and IP, cm	3
Luminosity $L_{\gamma\gamma}$, cm^{-2}s^{-1}	1.5×10^{33}

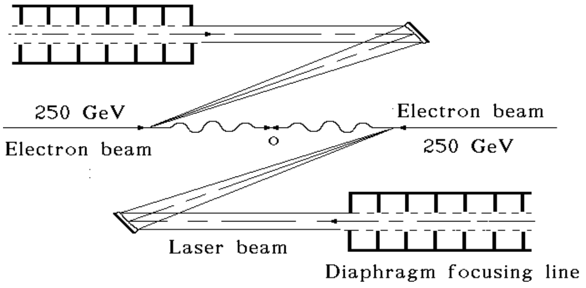

Figure 1: Conceptual scheme of the photon linear collider at TESLA-500.

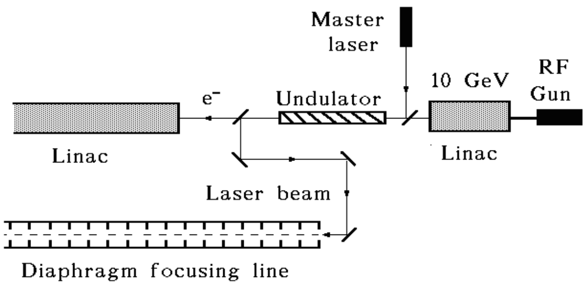

Figure 2: Conceptual scheme of an FEL amplifier for the photon linear collider at TESLA-500.

100 MW). An output radiation of 350 GW peak power is produced at the amplifier exit. Then the electron and optical bunches are separated. The electron bunch is accelerated up to the final energy of 250 GeV and the optical bunch is transported to the conversion point. After the conversion point the gamma quanta follow the initial electron trajectories and meet in the interaction point with the other gamma-beam produced by the opposite part of the collider. The integral luminosity of the colliding γ-beams is $L_{\gamma\gamma} \simeq 1.5 \times 10^{33}$ cm^{-2}s^{-1}.

Such an approach naturally provides the synchronization of the optical and laser bunches and the generation of the laser beam with the required pulse duration and repetition rate. In addition, use of free electron laser reveals wide possibilities to control polarization of colliding gamma-beams, because FEL polarization is always totally polarized.

2.1 *Injection system*

Since there is no need for positrons for the gamma-gamma collider operation, the injection system could be simplified significantly. The electron beams of the main accelerator are produced by photoinjector and are assumed to be round. To provide the required parameters of the electron beam, it is sufficient to use the laser driven rf-gun with normalized brightness $B_{\rm n} \simeq 5 \times 10^7$ A cm^{-2}rad^{-2}.

2.2 *FEL amplifier*

The source of the primary photons is the FEL amplifier designed by the MOPA (master oscillator – power amplifier) scheme. The radiation of the master oscillator (Nd:YLF laser, $\lambda = 1.053\ \mu$m, peak power $W \simeq 100$ MW and average power $\sim$ 10 W) is amplified in the FEL amplifier up to the power 350 GW. The main parameters of the FEL amplifier are presented in Table 2. The electron beam of the main accelerator ($\mathcal{E} = 10$ GeV, $I_{\rm peak} = 500$ A) is used as a driving beam. An initial section of the undulator of 73 m length is untapered and provides exponential amplification of the radiation field of the master oscillator. The final section of the undulator of 257 m length should be tapered to provide the required level of output radiation power (see Fig. 3).

Due to the relatively low value of the peak current, there is no possibility to use the conventional FEL amplifier scheme in which radiation is confined due to the "optical guiding" effect [6]. To overcome this problem, we use the scheme of the FEL amplifier with diaphragm focusing line [4, 7].

Table 2: FEL amplifier for TESLA-500

Electron beam	
Electron energy, GeV	10
Beam current, A	500
Energy spread, keV	500
Normalized emittance, cm×rad	$\pi \times 10^{-3}$
Undulator	
Undulator period, cm	40
Undulator field, kGs (enter./exit)	12 / 10.8
Length of untapered section, m	73
Total undulator length, m	330
Diaphragm line	
Diaphragm separation, cm	1
Hole radius, cm	0.3
Power losses per one diaphragm	1.1×10^{-5}
Radiation	
Radiation wavelength, μm	1.06
Input power, MW	100
Output power, GW	350
Efficiency, %	7

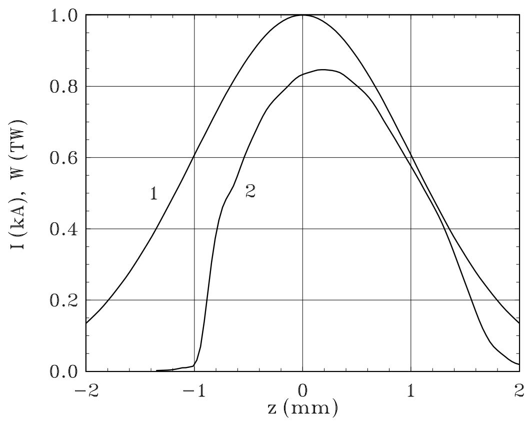

Figure 3: Axial distribution of the beam current in the electron beam (curve 1) and axial distribution of the output power in the optical beam (curve 2).

2.3 Transporting channel for radiation

Having passed the FEL undulator, the electron beam is accelerated up to the final energy 250 GeV and the optical beam is transported to the conversion point via diaphragm focusing line which has the form of periodically spaced screens with round holes (see Fig.2). The total radiation power losses along the transport channel are equal to 2%.

2.4 Conversion and interaction region

After passing their ways along the accelerator, electron and optical bunches should meet at the conversion point (see Fig.1). To provide optimal focusing conditions at the conversion point, the optical bunch should advance the electron bunch by several tens of centimeters, so we use an optical delay line which provides the delay time equal to the time interval between bunches. In this case the radiation generated by one bunch is focused on the following one. The total radiation power losses in the diaphragm and the optical delay line are equal to 15 %. Finally, 300 GW of peak radiation power are transported to the conversion point. At optimal conditions of laser beam focusing on the electron beam (see Table 2), the conversion efficiency is about 0.7. Then high energy γ-quanta follow the initial electron trajectories and meet at the interaction point with the other γ-quantum beam produced by the opposite part of the collider. The integral luminosity of the colliding γ-beams is $L_{\gamma\gamma} \simeq 1.5 \times 10^{33}$ cm^{-2}s^{-1}.

3 DISCUSSION

The scheme of the gamma-gamma collider for TESLA-500, presented in this paper, is based on a novel kind of FEL amplifier with diaphragm focusing line. So, the possibility to construct such an FEL device requires experimental verification. To perform such a verification, there is no need to build a full-scale facility, it could be done with scaled model operating at the wavelength of 10 μm (see Table 3) [4, 5]. The parameters of the driving electron beam of this scaled model correspond to those of the electron beam from the accelerator which will be constructed at the TESLA Test Facility at DESY [3].

In conclusion we should notice that proposed scheme does not exhaust all the possibilities for construction of an FEL based gamma-gamma collider at TESLA-500. For instance, special linear accelerator could be constructed to produce the driving electron beam for the FEL amplifier. The corresponding technical requirements to the systems of gamma-gamma collider could be obtained from refs. [8, 9].

4 ACKNOWLEDGEMENTS

We thank R. Brinkmann, M. Leenen, H. Mais, J. Rossbach R. Settles, D. Trines for many useful discussions. We wish to thank Prof. B.H. Wiik and Prof. A. Wagner for their interest in our work.

Table 3: Scaled model of FEL amplifier at TTF

Electron beam	
Electron energy, GeV	0.5
Beam current, A	500
Energy spread, keV	500
Normalized emittance, cm×rad	$\pi \times 10^{-3}$
Undulator	
Undulator period, cm	20
Undulator field, kGs (enter./exit)	5.4 / 4.8
Length of untapered section, m	9
Total undulator length, m	20
Diaphragm line	
Diaphragm separation, cm	1
Hole radius, cm	0.3
Power losses per one diaphragm	3.4×10^{-4}
Radiation	
Radiation wavelength, μm	10.6
Input power, MW	10
Output power, GW	17.5
Efficiency, %	7

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