Free Electron Laser for Gamma-Gamma Collider at TESLA

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Abstract

The present paper contains the results of optimization of the free electron laser for the gamma-gamma collider at TESLA. A superconducting linear accelerator, similar to the TTF (TESLA Test Facility) accelerator, produces a driving electron beam for the FEL. The MOPA FEL scheme is studied when the radiation from a master oscillator is amplified in the FEL amplifier with tapered undulator. The FEL produces the radiation of TW level with the wavelength of 1 μm. Optimization of the FEL amplifier is performed with three-dimensional, time-dependent simulation code FAST.

1. Introduction

A second interaction region is under discussion in the TESLA linear collider project which is intended for gamma-e and gamma-gamma collisions [1]. The idea of the gamma-gamma collider takes its origin in the early 80's when it has been shown that a high luminosity colliding gamma-gamma beams can be produced by means of the Compton backscattering of powerful FEL radiation on the electrons of the main accelerator [2,3]. The conceptual scheme for organization of gamma-gamma collisions (see Fig. 1) can be explained as follows. Two electron (or electron and positron) bunches are focused into the interaction point. Prior the collision each electron bunch is irradiated by a powerful laser pulse. High energy gamma-quanta are produced in the process of Compton backscattering and, following the electron trajectories, collide at the interaction region. The time structure of the laser pulses should be identical to the time structure of the electron bunches. It means, that the laser should have a capability of precise synchronization (with an accuracy of about 1 ps) with the electron bunches and should provide a high repetition rate. In the case of the TESLA collider a sub-terawatt level peak power laser is required with the repetition rate of about 1 MHz. The average power should be of the order of 10 kW. The laser radiation should be circularly polarized and

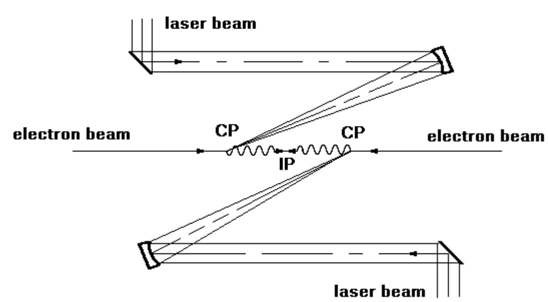

Fig. 1. Conceptual scheme of a gamma-gamma collider.

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transversely coherent. A reliable technical solution for a conventional laser system with required parameters seems to be a problem. Indeed, even optimistic estimation of the scale of the conventional laser facility shows that the laser equipment should occupy an area of about 50 000 m^2. The cost of the equipment is estimated as 200 M$ [4].

On the other hand, the FEL technique provides a possibility to construct the laser system which meets all the requirements for the PLC [3,5–7]. 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. With a sufficient quality of the driving electron beam, the FEL peak output power is defined by the peak power of this driving beam. At an electron beam energy of $\mathcal{E} \sim 1$ GeV and a peak beam current of $I \sim 1$ kA, this power reaches the TW level. The problem of synchronization can be solved naturally as it is based totally on the accelerator technology. The FEL output radiation is totally polarized: circularly or linearly for the case of helical or planar undulator, respectively. This feature of the FEL radiation reveals wide possibilities to steer the helicity and energy spectrum of colliding gamma quanta [6]. An option of a free electron laser for the gamma-gamma collider is considered now in the TESLA project [1,7].

2. FEL system for gamma-gamma collider

FEL system is built as a MOPA scheme where the low-power radiation from Nd glass laser ($\lambda = 1$ μm) is amplified in a long tapered undulator by an electron beam. The driving accelerator has the same time diagram as the main TESLA linac.

2.1. Accelerator

Driving electron beam for the FEL is produced by the accelerator based on TESLA technology and similar to the TTF (TESLA Test Facility) accelerator [8]. Parameters of the accelerator are presented in Table 1. The beam with the charge of 12 nC and normalized emittance of 30π mm mrad is generated in photoinjector, accelerated in superconducting modules with the gradient 20 - 25 MV/m and compressed down to 2 ps duration in the bunch compressors. Note that the emittance is not a critical parameter for considered FEL.

2.2. Master laser

The peak power of the master laser with the wavelength of 1 μm is assumed to be 1 MW with pulse duration of several picoseconds, so that the average power will be below 0.1 W. It means that only small fraction of power can be taken out of 2 W of infrared radiation generated in the laser system of photoinjector. Then this radiation can be transported to the undulator entrance. The problem of synchronization of electron and optical bunches is, therefore, solved naturally.

2.3. FEL amplifier

To obtain reasonable luminosity of the gamma-gamma collider at TESLA, the energy in radiation pulse at the FEL amplifier exit should be above 2 J and peak power should reach sub-terawatt level. For chosen parameters of electron beam it means that the FEL efficiency must exceed 10 %. In FEL amplifier with uniform undulator the efficiency is limited by saturation effects and is below 1 % in the considered case. Saturation of the radiation power in the FEL amplifier occurs due to the energy losses by the particles which fall out of the resonance with the electromagnetic wave. Nevertheless, effective amplification of the radiation is possible in the nonlinear regime by means of using a tapered undulator [9]. In this case large fraction of particles is trapped in the effective potential of interaction with electromagnetic wave and is decelerated.

Table 1
Parameters of the accelerator

Energy	1.5 GeV
Charge per bunch	12 nC
Peak current	2.4 kA
Bunch length (RMS)	0.6 mm
Normalized emittance	30π mm mrad
Energy spread (RMS)	1 MeV
Repetition rate	5 pps
Macropulse duration	800 μs
# of bunches per macropulse	1130
Bunch spacing	708 ns
Average beam power	102 kW

Table 2
Parameters of the FEL amplifier

Undulator	
Type	Helical
Period	10 cm
Magnetic field (entr./exit)	1.4 T / 1.08 T
Total length	60 m
Length of untapered section	10.7 m
Beam size in the und. (RMS)	230 μm
Radiation	
Wavelength	1 μm
Dispersion	Dif. limit
Pulse energy	2.2 J
Pulse duration (HWHM)	4 ps
Repetition rate	5 pps
Macropulse duration	800 μs
# of pulses per macropulse	1130
Peak output power	0.7 TW
Average power	12.5 kW
Efficiency	12.2 %

Parameters of the FEL amplifier with the tapered undulator are presented in Table 2. The undulator is helical to provide polarized radiation and is superconducting what seams to be natural solution in the context of TESLA. The resonance is maintained by decrease of the magnetic field at fixed period of the undulator.

We begin our study with analysis of physical effects influencing the operation of the FEL amplifier. Within the scope of the three-dimensional theory of the FEL amplifier we obtain that all the important physical effects are connected with the corresponding dimensionless parameters defining the power of the effect. These parameters are the diffraction parameter B, the space charge parameter $\hat{\Lambda}_{\mathrm{p}}^2$, the parameter of the longitudinal velocity spread $\hat{\Lambda}_{\mathrm{T}}^2$ and the efficiency parameter ρ [12]:

$$
\begin{aligned}
B &= 2\Gamma\sigma_{\mathrm{r}}^2\omega/c \\
\hat{\Lambda}_{\mathrm{p}}^2 &= \Lambda_{\mathrm{p}}^2/\Gamma^2 = 4c^2(\theta_{\mathrm{s}}\sigma_{\mathrm{r}}\omega)^{-2} \ , \\
\hat{\Lambda}_{\mathrm{T}}^2 &= \Lambda_{\mathrm{T}}^2/\Gamma^2 = (\sigma_{\mathrm{E}}^2/\mathcal{E}_0^2 + \gamma_{\mathrm{z}}^4\sigma_\theta^4/4)/\rho^2 \ , \\
\rho &= c\gamma_{\mathrm{z}}^2\Gamma/\omega .
\end{aligned}
$$

The gain parameter Γ defines the scale of the field gain and is defined as

$$\Gamma = \left[I\omega^2\theta_{\mathrm{s}}^2/(I_{\mathrm{A}}c^2\gamma_{\mathrm{z}}^2\gamma)\right]^{1/2} \quad ,$$

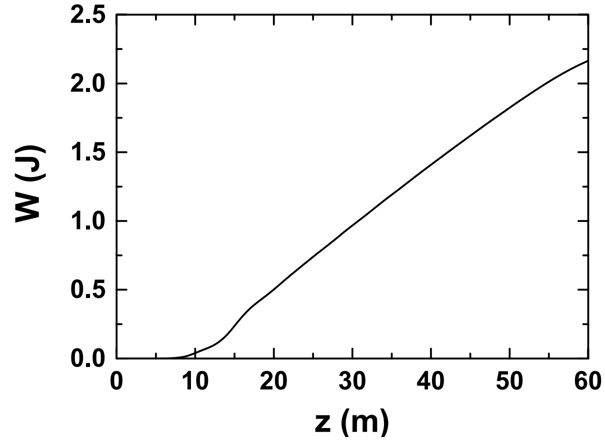

Fig. 2. Energy in the radiation pulse versus the undulator length.

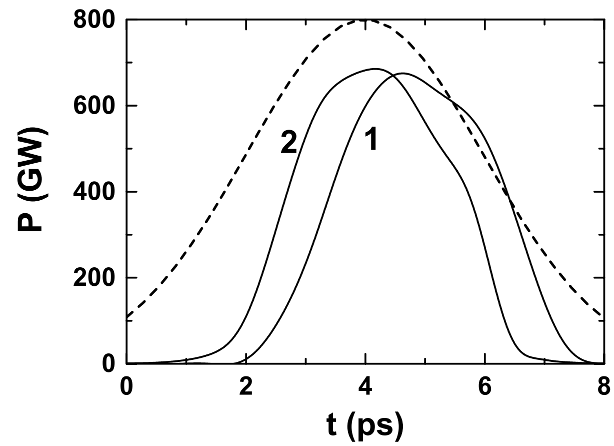

Fig. 3. Time structure of the radiation pulse at the exit of the FEL amplifier (curve 1) and of the power loss in the electron bunch (curve 2). Dashed line is the longitudinal profile of the electron bunch (maximal value of the beam current is equal to 2.4 kA).

where $\omega = 2\pi c/\lambda$ is the frequency of the radiation field and $I_{\mathrm{A}} = m_{\mathrm{e}}c^3/e$. To be specific, we have written all the formulae for the case of the gaussian distribution of the electrons in the transverse phase space with the RMS radius and the RMS angle spread given by $\sigma_{\mathrm{r}} = \sqrt{\epsilon_{\mathrm{n}}\beta/\gamma}$ and $\sigma_\theta = \sqrt{\epsilon_{\mathrm{n}}/\beta\gamma}$, where ϵ_{n} is rms normalized emittance, β is focusing beta function and $\gamma = \mathcal{E}_0/m_{\mathrm{e}}c^2$ is relativistic factor. Energy spread in the electron beam is assumed to be gaussian with the rms deviation σ_{E}. Undulator is assumed to be a helical one with amplitude of the magnetic field H_{w} and period λ_{w}. The undulator parameter K, the electron rotation angle θ_{s} and the longitudinal relativistic factor γ_{z}: $K = eH_{\mathrm{w}}\lambda_{\mathrm{w}}/2\pi m_{\mathrm{e}}c^2$, $\theta_{\mathrm{s}} = K/\gamma$

and $\gamma_z^2 = \gamma^2/(1+K^2)$.

The main effects influencing on the operation of the FEL amplifier with tapered undulator are the diffraction effect and the slippage effect. Calculations based on the steady-state theory [10] show that at the length of the undulator of 60 m, the efficiency of the FEL amplifier is about 20 %. Axial inhomogenity of the beam current leads to visible reduction of the efficiency. Also, at such a length of the undulator one should take into account the finite length of the electron bunch. Kinematic slippage of the radiation with respect to the electron bunch is 0.6 mm which what is comparable with the bunch length. So, steady-state approach can be used only for rough estimations, and parameters of the FEL amplifier should be optimized using time-dependent approach. Here we present results of optimization performed with three-dimensional, time-dependent code FAST [11]. The efficiency 12.2 % is reached in the end of the undulator, what corresponds to 2.2 J in optical pulse (see Fig. 2). In Fig. 3 we present time structure of the radiation pulse at the undulator exit. One can see that the slippage of the radiation pulse is visibly less than the kinematic slippage of about 0.6 mm (or, 2 ps). This is explained by the fact that the group velocity of the radiation in the electron beam, $v_{\mathrm{g}}^{-1} = \mathrm{d}k/\mathrm{d}\omega$, is less than the velocity of light. Fig. 4 illustrates suppression of the slippage rate in the linear regime of the FEL amplifier operation. In the case under study the value of diffraction parameter is $B \simeq 0.5$, and the slippage effect is suppressed by a factor of 5. Suppression of the slippage effect in the tapered regime is not so strong, but is still significant as it is illustrated with Fig. 3. So, we find that the effect of suppression of the slippage effect reveals the possibility to use short electron bunches for effective amplification of the radiation in a long undulator.

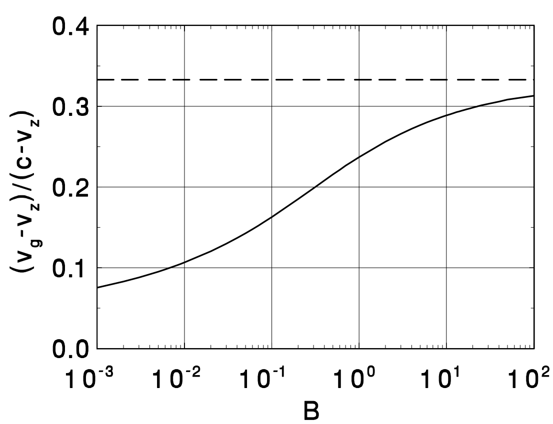

Fig. 4. Ratio of the slippage rate of the radiation wavepacket and kinematic slippage rate, $(v_{\mathrm{g}} - \bar{v}_z)/(c - \bar{v}_z)$, as function of diffraction parameter B. Dotted line represents one-dimensional asymptote.

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