An FEL Based High Intensity Gamma-Source at the TESLA Test Facility at DESY

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Abstract

One of the possible extension of the FEL activity at DESY is connected with the installation of an additional FEL beamline providing tunable UV radiation with the peak and average power of 220 GW and 7 kW, respectively. This report presents the feasibility study of a high intensity, polarized, monochromatic gamma-source at the TESLA Test Facility. Gamma-quanta are produced in the process of Compton backscattering of the UV FEL radiation on a 1 GeV electrons of the TTF accelerator. The ultimate intensity of the gamma-source can reach the value up to 10^{12} gamma-quanta per second with the maximal energy of about 100 MeV. Energy resolution of the gamma-source can be reduced down to the value of about 0.2 %. Potential applications of the intensive gamma-source at the TESLA Test Facility are discussed, too.

1. Introduction

The Compton backscattering of laser light on high energy electrons is considered now as the most promising way to obtain high-intensity monochromatic gamma-rays [1]. Recently several investigations have been performed showing the possibility of constructing the gamma-sources with the energy of gamma-quanta of the order of tens and hundreds of MeV and the ultimate intensity $10^{10} - 10^{14} s^{-1}$ [2, 3]. These proposals suggest to use the scattering of the free-electron laser (FEL) radiation on the electron bunches in a storage ring.

In this paper we point at the possibility of constructing the high-intensity gamma-source at a high power linear accelerator. A 1 GeV superconducting linear accelerator being under construction at the TESLA Test Facility (TTF) at DESY will produce electron beam with high average and peak power, low energy spread and emittance. The main practical application of this accelerator is to use it for driving the soft X-ray free electron laser [4]. It is proposed also to construct a high power UV free electron laser at the TTF [5, 6]. The radiation from a low-power master oscillator will be amplified in the FEL amplifier with a tapered undulator providing peak and average output power up to 220 GW and 7 kW, respectively. The Compton backscattering of this radiation on the TTF electron beam allows one to reach the intensity of the gamma-quanta up to $10^{12}\mathrm{s}^{-1}$ with the maximal energy of about 100 MeV. This unique gamma-source could be used for investigations in nuclear physics as well as for testing the technical solutions of positron sources and gamma-gamma options of the future linear colliders.

2. High intensity gamma-source

Powerful UV FEL at the TTF [5, 6] can be used for construction of a high intensity, polarized, monochromatic gamma-source. The scheme of the gamma-source is presented in Fig. 1. Gamma-quanta are produced in the process of the Compton backscattering of the laser photons on incoming electrons. The process of the FEL interaction induces the energy spread in the electron bunch. If the laser radiation will be scattered on the bunches involved in the FEL process, this will result in decreasing of the energy resolution of the gamma-source. To avoid this harmful effect, master laser should operate at a half of the repetition rate of the electron bunches. So, the laser radiation amplified by an electron bunch is focused on the next, unperturbed electron bunch.

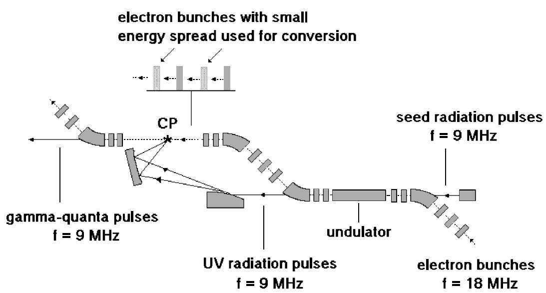

Fig. 1. Scheme of the gamma-source at the TESLA Test Facility.

The maximal energy of gamma-quanta is defined by the frequency of the primary photons ω and the energy of the electron $\mathcal{E}$: $(\hbar\omega_\gamma)_{\max} = \mathcal{E}\chi/(1+\chi)$. Here $\chi = 4\gamma\hbar\omega/m_{\mathrm{e}}c^2$, m_{e} is the electron mass and $\gamma = \mathcal{E}/m_{\mathrm{e}}c^2$ is relativistic factor. Maximal energy of gamma quanta is about 86 MeV at the wavelength of primary photon of 200 nm and the energy of electron of 1 GeV. In principle, the energy of the TTF accelerator can be upgraded up to the value of 2 GeV. In this case maximal available energy of gamma-quanta will be about 320 MeV. General parameters of the gamma-source at the TTF are presented in Table 1.

The frequencies of the incident and scattered photons, ω and ω_γ, are connected by the relation:

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

where θ is the scattering angle. It is seen from eq. (1) that there is strict correlation between the energy of the backscattered photon and the scattering angle. This allows one to use angle selection technique for selecting the gamma-quanta with the required energy. In the case of monoenergetic and laminar electron beam this technique allows, in principle, to achieve any required energy resolution of gamma-quanta. In practice electron beam has finite energy spread which imposes a limit on minimal energy resolution of the gamma-source. Influence of the angle spread in the electron beam on the energy resolution of the gamma-source can be eliminated by an appropriate choice of the beta-function at the conversion point. The value of the rms angle spread in the electron beam is $\sigma_\theta = \sqrt{\epsilon/\beta}$, where ϵ is the emittance of the electron beam and β is beta-function at the conversion point. Minimal energy resolution of the gamma-source due to the angle spread is given by the expression:

$$(\Delta\hbar\omega_\gamma)/\hbar\omega_\gamma \simeq (\gamma\sigma_\theta)^2/2 . \qquad (2)$$

Table 1. Parameters of the gamma-source at the TESLA Test Facility

General parameters	
Maximal energy of gamma-quanta	85 MeV
Yield of gamma-quanta	$10^{12}\mathrm{s}^{-1}$
Energy resolution	1 %
Angular divergence	0.5 mrad
Repetition rate	10 pps
Macropulse duration	800 μs
Number of pulses per macropulse	7200
Micropulse repetition rate	9 MHz
Micropulse duration (FWHM)	300 fs
Parameters of the electron beam	
Energy	1 GeV
Charge per bunch	1 nC
Energy spread (RMS)	1 MeV
Normalized emittance (RMS)	2 mm mrad
Beam size at the conversion point	14 μm
Bunch length (RMS)	50 μm
Parameters of the FEL	
Wavelength	208 nm
Micropulse duration	230 fs
Energy in the radiation pulse	50 mJ
Peak output power	220 GW
Average power	3.6 kW
Parameters of the focusing system	
Focuse distance of the mirror	3 m
Radiation spot size on the mirror	2.5 cm
Incident radiation flux on the mirror	350 $\mathrm{W/cm^2}$
Reflectivity of the mirror	99 %
Radiation spot size at the conversion point	8 μm
Rayleigh length	1 mm
Conversion efficiency	0.23 %

It should be also noted that there is strict correlation between the energy of the gamma quantum and its polarization, so the angular selection provides not only monochromatization, but determines also the polarization of gamma quanta.

To obtain a higher yield of gamma-quanta one should provide maximal spatial density of the primary photons and of the electron beam in the conversion region. We assume the laser beam to be close to the Gaussian one. The power flux density in the waist of Gaussian laser beam is given by the expression $dP(r)/dS \propto \exp(-2r^2/w^2)$, where w is the size of the Gaussian beam waist. The Rayleigh length of the laser beam, $Z_{\mathrm{R}} = \pi w^2/\lambda$, and the beta function of the electron beam focusing system, β, are assumed to be large with respect to the length of the laser and the electron pulse. Thus, we can neglect the change of the transverse size of the photon and electron pulses during the collision. As a result, the yield of gamma-quanta is [5]

$$\frac{dN_\gamma}{dt} = fN_e\delta \ , \qquad \delta = \frac{A\sigma_c}{2\pi\hbar\omega(\epsilon\beta + w^2/4)} \ , \qquad (3)$$

where A is the energy in the radiation pulse, f is the repetition rate of collisions, N_e is the number of electrons per bunch, δ is the conversion efficiency (number of gamma-quanta produced by one electron) and

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

is the total Compton cross section on unpolarized electrons, where $r_e = e^2/m_e c^2$ is the classical radius of electron.

The ultimate energy resolution of the gamma-source presented in Fig. 1 is limited by the energy spread in the electron beam induced by the SASE FEL process. Even in the case when there is no seed signal at the entrance of the FEL amplifier, the process of the amplification of the radiation is triggered by the shot noise in the electron beam. Simulation of this process shows that the induced energy spread due to the SASE FEL process is about 5 MeV at the exit of the undulator [5] which imposes a limit on ultimate energy resolution of the gamma-source of 1 %. Taking into account the angular spread in the electron beam, beta function of the electron beam at the conversion point should be about 20 cm in order to provide this energy resolution. The radiation spot size at the conversion point has been set to $w \simeq 8$ μm (which corresponds to the Rayleigh length of 1 mm). In this case there are no fluctuations of the gamma-source intensity due to the time jitter of the electron pulse of about 1 ps. According to (3), at chosen parameters of the colliding photon and electron bunches conversion efficiency is about $\delta \simeq 0.23$ %. At the pulse repetition rate of the accelerator equal to 18 MHz the yield of gamma-quanta is about of 10^{12}s^{-1}.

There exists another option for organization of the conversion region prior the entrance of the electron beam into the undulator. It provides the possibility to double the yield of gamma-quanta, because each electron bunch can be used for producing gamma-quanta. Due to a small value of the conversion efficiency this will not destroy the electron beam and it can be used for the amplification of the radiation in the undulator. Besides, an ultimate energy resolution of the gamma-source of about 0.2 % can be achieved. This limit is defined by the energy spread in the electron beam of 1 MeV. The value of the beta function at the conversion point should be increased up to 1 m. The yield of the gamma-source with ultimate energy resolution of 0.2 % will be about of $2 \times 10^{11}\text{s}^{-1}$.

3. Possible applications for nuclear physics

The gamma-source at the TESLA Test Facility is a unique one providing an extremely high flux of polarized, monochromatic gamma-quanta. The proposed gamma facility is an extremely selective probe for investigations of not only conventional nuclear physics, but of exotic nuclear states (similar to those which occur inside the core of neutron stars or the quark-gluon plasma) and reaction mechanisms. Up to 200 MeV we are dealing with the internucleon distance about 1 fm (which is of the order of the size of nucleon). Nowadays the investigation of microscopic nuclear structure with resolution $\gtrsim$ 200 MeV is an unexplored field [7]. The idea is to work in the kinematical region where the processes on free nucleons are forbidden (the cumulative particle production or the underthreshold particle production). This intermediate energy region is covered by nonperturbative QCD effects. Investigations of this transition energy region, from the perturbative to non-perturbative QCD, are the most attractive direction for relativistic nuclear physics to understand the role of the nonnucleonic (pion, Δ, etc, and few-nucleon configurations) and quark-gluon degrees of freedom.

Another interesting topic of these investigations is a possibility to extract additional information about the hadron or the nuclear structure which is usually hidden in the spin-averaged analysis [8]. Polarization observables has a promise of opening a new field in the photoproduction of pion from nucleon and nuclear targets [9], in the processes of photodisintegration of the lightest nuclei [10, 11] and others. Many problems in photonucleon and photonulear physics are not resolved till now due to the lack of high quality photon beams.

4. Test facility for the positron source

The projects of the next generation linear colliders assume to produce positrons by gamma-quanta in a thin target [12, 13]. Gamma-quanta are produced by the spent electron beam in a long wiggler or undulator. For instance, in the TESLA project the 250 GeV electron beam passes a wiggler of 35 m length producing powerful gamma-beam [12]. The mean energy of gamma-quanta is about 25 MeV. Positrons produced in a thin target have large energy and angle spread. After the target they should be captured and accelerated. Such a complicated system requires experimental verification prior construction of the full-scale facility. The test facility can be constructed on the base of a high intensity gamma-source described above. Energy spectrum of the gamma-source is similar to that to be used in a full scale facility. Intensity of the gamma-source described above has been limited by the requirement of the energy resolution. For the positron source test facility the value of the beta function at the conversion point can be reduced down to the value of about 1 cm (the angle divergence in the beam is about $1/\gamma$ in this case). As a result, the yield of gamma-quanta reaches the value of 10^{13}s^{-1}. Remembering that the conversion efficiency of gamma-quanta into electron-positron pair is about of 0.5 at the thickness of the target about one radiation length, we estimate the yield of the positrons to be about $5 \times 10^{12}\text{s}^{-1}$. Such a positron yield is sufficient for operation of the test facility. Taking into account that TTF accelerator has the same time diagram of operation as TESLA accelerator, this facility will allow to verify experimentally all the systems of the positron source (optimization of the target, capture efficiency, etc).

The test facility for the positron source could reveal unique opportunity for experimental investigation of the polarized positron source proposed in ref. [14]. In this case FEL amplifier should be equipped with a helical undulator.

5. Test facility for the gamma-gamma collider

An option of a gamma-gamma collider is included in several projects of the future generation linear colliders [12, 13]. The scheme for organization of gamma-gamma collisions can be explained as follows. Two electron 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 the electron bunches and should provide a high repetition rate. The last parameter is extremely severe for the TESLA collider requiring a sub-terawatt level peak power laser with the repetition rate of about 1 MHz. In this case there is no reliable technical solution for a conventional laser system with required parameters, and free electron laser system is considered now as a candidate for the laser [12, 15]. Parameters of the high power UV FEL at the TTF and of the optical system of the gamma-source are very close to those used in the project of the gamma-gamma collider. Indeed, peak and average laser power of 220 GW and 7 kW, respectively, are close to those required for the gamma-collider. Time diagram of the laser pulses is similar to the time diagram of the TESLA collider. The problems connected with alignment of the mirrors, possible radiation damage of the mirrors, time jitters and the problems of focusing the laser beam in a tiny spot are similar to those to be met at a full-scale facility. So, successful realization of this project will serve as an experimental verification of a technical feasibility of the gamma-gamma option at TESLA.

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