On a Possibility to Construct High-Intensity Monochromatic Gamma-Source at HERA and LEP

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Abstract

A possibility to construct high-intensity tunable monochromatic γ-source at HERA and LEP (LEP 2) is discussed. It is proposed to produce γ-quantums by means of Compton backscattering of laser photons on electrons of the collider. The laser light wavelength is chosen in such a way that after the scattering, the electron does not leave the separatrix. So as the probability of the scattering is rather small, energy oscillations are damped prior the next scattering. As a result, the proposed source can operate in "parasitic" mode not interfering with the main mode of the collider operation.

It is proposed to install at the colliders HERA and LEP tunable free-electron lasers operating at 100 – 400 μm wavelength band with the peak and average output power $\sim$ 10 MW and $\sim$ 1 kW, respectively. It will result in the intensity of the γ-source $\sim 10^{14}\mathrm{s}^{-1}$ with tunable γ-quantum energy up to 150 MeV, 250 MeV and 500 MeV for the HERA, LEP and LEP 2, respectively. Such a γ-quantum source will reveal unique possibilities for precision investigations in nuclear physics.

1 INTRODUCTION

Investigations of photonuclear processes provide a valuable information about a structure of nuclei, nucleons and nucleon resonances. To study this physics, several experimental methods to obtain intensive photon beams have been developed [1] – [5]. To perform a more deep investigations, there exists an urgent need in the development of high-intensity monochromatic polarized photon beam sources. In the presented paper we propose to build such γ-sources at the storage rings HERA and LEP. Gamma quantums are produced by means of Compton backscattering of infrared FEL radiation on electrons of the collider. Proposed sources operate in "parasitic" mode not interfering with the main mode of the collider operation. They possess the following unique features:

- high intensity of γ-quantums;
- γ-quantum spectrum is rather sharp and the most fraction of photons is in high energy region;
- there is definite energy-angle correlation of scattered photons and the process of Compton scattering is well described by analytical formulae;
- possibility to steer the polarization of high energy photon beam by change of the polarization of FEL radiation.

2 BASIC RELATIONS

High energy γ - quantums are produced by means of Compton backscattering of the laser photons by the high energy electrons. We consider the case when the energy of the backscattered γ-quantum is rather small, $(\hbar\omega_\gamma)_{\max} < \Delta\mathcal{E}_{\max}$, where $\Delta\mathcal{E}_{\max}$ is maximal admissible energy losses of electron given with the energetic aperture of the storage ring. As a rule, the value of $\Delta\mathcal{E}_{\max}/\mathcal{E}$ does not exceed 1 %. It means that the Compton scattering process meets the condition of quasi-classical approximation, $\hbar\omega_\gamma \ll \mathcal{E}$. As a result, Compton cross section is given with Thompson cross section $\sigma_T = 8\pi r_e^2/3$ $(r_e = e^2/mc^2)$ and energy of backscattered γ-quantum is given with

$$(\hbar\omega_\gamma)_{\max} \simeq 4\gamma^2\hbar\omega, \qquad (1)$$

where ω and ω_γ are the frequencies of incident and scattered photons, respectively and $\gamma = \mathcal{E}/mc^2$.

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. The conditions of optimal focusing are as follows [6]:

$$\sigma_o^2 \ll \lambda^2 F^2/4a_o^2, \qquad F^2 \ll a_o^2 l_{ph}/2\lambda, \qquad l_b \simeq l_{ph}, \qquad (2)$$

where F is the focus distance of the mirror, a_o is the size of the laser beam spot on the mirror, σ_o is transverse size of the electron beam at conversion point, $\lambda = 2\pi c/\omega$ and l_b and l_{ph} are the lengths of electron and laser beam, respectively. In this case total number of γ-quantums, produced at a single passage of electron beam through the mirror focus, is given with the following relation [6]:

$$N_\gamma = N_e \frac{2W\sigma_T}{\hbar c^2}, \qquad (3)$$

where W is the peak laser power and N_e is number of electrons in the bunch.

The proposed γ-source operates in a "parasitic" mode and should not change significantly parameters of circulating electron beams. The laser light wavelength is chosen in such a way that after the scattering, the electron does not leave the separatrix. During energy oscillation damping time the electron energy is relaxed to the nominal value. Nevertheless, at a sufficiently large power W of laser beam and a high repetition rate of the collisions f, the process of multiple scattering leads to increase of energy spread of electrons in the beam. The coefficient of energy diffusion is given with the formula [7]:

$$< \frac{d(\delta\mathcal{E}/\mathcal{E})^2}{dt} >= \frac{448}{15}\frac{r_e^2\lambda_c\gamma^2\omega^2 W f}{mc^5}, \qquad (4)$$

where $\lambda_c = h/mc$.

The growth of the rate of the energy oscillation excitation leads to the growth of the energy spread of electrons in the beam. For instance, the growth of the energy diffusion by a factor of Q with respect to energy diffusion defined by quantum fluctuations of synchrotron radiation, results in the growth of energy spread by a factor of $(1+Q)^{1/2}$.

3 GAMMA-SOURCE AT HERA

FEL based γ-quantum source at HERA will allow one to produce about of 10^{14} γ-quantums per second with the energy up to 150 MeV. Main parameters of the electron storage ring HERA are presented in Table 1 (see also ref. [8]).

Table 1: Parameters of the HERA and LEP storage rings

	HERA	LEP / LEP 2
Electron energy $\mathcal{E}$, GeV	30	55 / 90
Circumference, m	6335.8	26658.9
Number of bunches N_b	210	4 / 8
Bunch spacing, μs	0.096	22.2 / 11.1
Number of electrons in the bunch N_e	3.7×10^{10}	4.2×10^{11}
Bunch length σ_z, cm	0.8	1.6 / 1.8
RF frequency f_{RF}, MHz	499.667	352.21
Energy loss/turn, MeV	118	260 / 1855
RF voltage, MV	260	400 / 2400
Polarization time, min	24	135 / 11.5

3.1 Free electron laser

To achieve such parameters of γ- source, a free electron laser ($\lambda \sim 100$ μm) should be installed (see Table 2). The project of the FEL oscillator with the parameters close to those required has been developed at LBL [9]. Designers of this project assume to use superconducting accelerating four-cell structure manufactured for the HERA project at DESY. This project of the FEL oscillator may be considered as a prototype of the FEL for γ-source at HERA.

To match the FEL operation with the electron storage ring operation, the accelerator of FEL driving beam should be designed on the base of accelerating SC cavities of the electron storage ring ($f_{RF} = 500$ MHz).

The electron bunches (pulse duration 1.5 ns, peak current 1.5 A, average current 12 mA, pulse repetition rate 5.2 MHz) are produced by a gridded electron gun. Then the electron bunches are fed into a subharmonic buncher consisting of two coaxial resonators operating at 6-th and 3-rd subharmonic frequency, respectively. Then they are fed into the buncher operating at 500 MHz frequency. This buncher has a form of four-cell SC accelerating structure. At the exit of the buncher the beam has the energy 5 MeV. Then the bunches are passed through the energy slit and

Table 2: Free electron laser parameters

Electron beam	
RF frequency	500 MHz
Energy, $\mathcal{E}_0$	10 MeV
Peak current, I	50 A
Energy spread	150 keV
Normalized emittance, ϵ_n	10 mm·mrad
Micropulse duration	30 ps
Micropulse repetition rate	5.2 MHz
Mode of operation	CW
Average beam current	8 mA
Average beam power	80 kW
Undulator	
Undulator period, λ_w	5cm
Undulator field, H_w	2.7 kG
Number of undulator periods, N_w	40
Optical resonator	
Radiation wavelength, λ	100 μm
Resonator length	28.8 m
Curvature radius of mirrors	14.47 m
Radiation power losses	10 %
Efficiency	0.8 %
Peak radiation power	4 MW
Average radiation power	0.65 kW

are accelerated up to 10 MeV energy in the single-cavity SC accelerator module.

RF power supply of such an accelerator may be constructed on the base of two TH2133 klystrons with output power 75 kW.

The undulator is a steel-$SmCo_5$ hybrid one with the following parameters: period $\lambda_w = 5$ cm, number of undulator periods $N = 40$, field amplitude $B_w = 2.7$ kG at the undulator gap $g = 28$ mm.

Optical resonator is formed by two spherical copper mirrors (radius of mirror curvature is equal to 14.47 m and aperture – 30 cm). The resonator base is equal to 28.8 m and Raleigh length is equal to $L_R \simeq 1$ m. One of the mirrors has a hole for radiation output. Total resonator losses are equal to 10 %. Peculiarity of such a resonator consists in a rather large resonator base which is connected with the low micropulse repetition rate – 5.2 MHz.

At chosen values of undulator length $l_w = 2$ m and undulator gap $g = 28$ mm, diffraction losses of radiation due to the aperture restrictions are negligibly small with respect to the losses in the mirrors.

At optimal choice of the resonator losses (i.e. at optimal choice of the size oh the output hole), the FEL efficiency at saturation is equal to $\eta \simeq 0.3/N \simeq 0.8\%$. Peak and average output radiation power are equal to 4 MW and 0.65 kW, respectively.

3.2 Yield of γ-quantums

Taking into account the HERA parameters (see Table 1) and the FEL parameters (see Table 2), from relation (3) we obtain the yield of γ-quantums production to be equal to $dN_\gamma/dt \simeq 1.5 \times 10^{13}$ s^{-1}. We assume here that optical bunches meet only with the half number of bunches, $N = 105$, circulating in the HERA electron ring. The yield of γ-quantums may be increased by two different ways. First, using tapered undulator, the efficiency of the FEL oscillator may be increased up to the value about of $\eta \simeq 2.5$ %. Second, the number of conversion points may be increased. In this case, after the crossing the first conversion point, the optical beam is directed to the optical labyrinth which plays a role of delay line. Then it is focused at the next electron beam, etc. Remembering that the losses in copper mirrors of radiation with the wavelength $\lambda \simeq 100$ μm are about of 0.5 %, we may conclude, that each optical bunch can effectively interact with many electron bunches. As a result, the yield of γ-quantums $dN_\gamma/dt \simeq 10^{14}$ s^{-1} may be achieved.

3.3 Increase of energy spread

For the HERA electron ring operating at 30 GeV, coefficient of energy diffusion due to the quantum fluctuations of synchrotron radiation[1] is equal to $< d(\delta\mathcal{E}/\mathcal{E})^2/dt >_{SR} \simeq 10^{-3}$s^{-1}. Using relation (4), we obtain that coefficient of energy diffusion due to the scattering of electrons by laser beam, is of the order of $< d(\delta\mathcal{E}/\mathcal{E})^2/dt >_C \simeq 0.6 \times 10^{-3}$s^{-1} at $dN_\gamma/dt \simeq 10^{14}$ s^{-1} which results in the growth of the energy spread by 1.3 times with respect to the nominal value.

4 GAMMA-SOURCE AT LEP

Main parameters of LEP are presented in Table 1 (see also refs. [10, 11]). Installation of far-infrared FEL ($\lambda \sim 200 - 400$ μm) at LEP will allow one to obtain intensive source of γ-quantums with the energy up to 250 MeV and 500 MeV for LEP and LEP 2, respectively. The principles of its design are the same as for γ-source at HERA (see section 3). The electron driving beam for the FEL is produced by CW superconducting accelerator constructed on the base of the LEP accelerating modules (f_{RF} = 352 MHz). Output parameters of this accelerator are the same as those presented in Table 2, with the only exception that the micropulse repetition rate should be 7.04 MHz.

Assuming that each electron bunch is collided with 5 optical bunches and the FEL efficiency is about of 3 %, we can expect the yield of γ-quantums $dN_\gamma/dt \simeq 10^{14}$ s^{-1}.

5 CONCLUSION

In conclusion we should emphasize that the existence in Europe of such unique storage rings as HERA and LEP reveals a possibility to construct on their base sources of high intensity monochromatic polarized γ-quantums. These γ-sources will reveal a possibility to study photonuclear physics in the energy range from several tens MeV up to 500 MeV with an accuracy unachievable with the existent facility.

Construction of such sources is technically feasible at the present level of accelerator technique R&D. The main element of the proposed facility is far-infrared ($\lambda \sim 100 - 400$ μm) free electron laser with the peak and average output power about of 10 MW and 1 kW, respectively. Such an FEL may be constructed on the base of the project of the Infrared Free-Electron Laser for the Chemical Dynamics Research Laboratory, which has been developed at the Lawrence Berkeley Laboratory [9]. The driving accelerator for this FEL has been designed on the base of the HERA SC cavities. As for the design of conversion regions and γ-quantums output channels, these problems may be solved using experience stored during design and construction of the laser polarimeters at HERA and LEP.

[1] This value may be calculated from Table 1 remembering relation between the coefficient of energy diffusion and the time of radiative polarization τ_p:

$$< d(\delta\mathcal{E}/\mathcal{E})^2/dt >_{SR} = 11/9\tau_p.$$

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