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ON A POSSIBILITY TO CONSTRUCT HIGH-INTENSITY MONOCHROMATIC GAMMA-SOURCE AT HERA AND LEP

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1 Introduction

Despite the experimental nuclear physics is more than fifty years old, it is still staying in the frontiers of the sciences studying the structure of the matter. It is connected with the fact that nuclei is a unique form of matter. All the forces of nature are presented there: strong, electromagnetic and weak. Nowadays, with the development of QCD and the Standard Model, a precision study of processes in the nuclei and nucleons should be able to shed fresh light on our knowledge of the matter [1]. To provide precise experiments, a novel experimental equipment is developed and the CEBAF project is a bright confirmation of such a tendency [2].

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.

There are several methods to obtain monochromatic and quasi-monochromatic photon beams: radioactive γ-sources [3], electron-positron annihilation [4], Compton scattering of laser light on high energy electrons circulating in the storage rings [5] - [7] and the use of the tagged photon beams facility when the photons are obtained by bremsstrahlung of the primary beam through a very thin radiator [8]. The latter technique is the most qualitative one and provides a possibility to perform experiments in a wide energy range, from few MeV up to several GeV. Nevertheless, it possesses several significant disadvantages and the main of them is that it provides significant systematic errors due to the lack of precise knowledge of the photon flux, very broad energetic spectrum and significant problems in producing the polarized photon beams [9]. As a result, it requires to use the large acceptance and universal detectors.

It is realized nowadays that polarization observables have a promise to open the fundamental properties of the internal structure of the nucleons and nuclei. To study these phenomena, experimental facility should be supplemented with polarized photon beams and polarized targets. A new generation of polarized proton and deuteron targets made of ammonia with high polarization, short polarization time and high resistance to the radiation damage as well as recoil polarimeters are now being built [10]. A new technique is now being used to make a target of ^{3}He as a polarized quasi-neutron target [11]. On the other hand, the progress in the development of the polarized photon sources is rather limited [9]. Nowadays polarized photons are obtained by several different ways [12]:

- angular selection of γ-rays emitted in a capture reaction like $^3H(p,\gamma)^4He$;
- angular selection of bremsstrahlung from very thin targets;
- bremsstrahlung in crystals;
- Compton backscattering of laser photons by high energy electrons [5] - [7].

The latter method possesses several significant advantages. First, the Compton spectrum has a sharp maximum and the most fraction of photons is in high energy region. Second, there is definite energy-angle correlation of scattered photons and the process of Compton scattering is well described by analytical formulae. Third, there is a possibility to steer the polarization of high energy photon beam by the laser beam polarization change. Intensity of γ-sources of this type is of the order of $10^6 - 10^7$ photons per second at the energy resolution about of 0.1 – 1 % and is limited by the beam lifetime due to the losses of electrons after Compton scattering.

In the presented paper we propose a novel kind of experimental facility for monochromatic polarized photon production. We propose to build such a γ-source at the storage rings HERA and LEP. 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. The proposed source operates in a "parasitic" mode not interfering with the main mode of the collider operation. At an appropriate choice of the laser beam parameters, such a source can provide extremely high average intensity of γ-quantums at a high value of duty factor.

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 up to $10^{14}\mathrm{s}^{-1}$ with tunable γ-quantum energy up to 150 MeV, 250 MeV and 500 MeV for the HERA, LEP and LEP 2, respectively. In addition to providing a high intensity, the proposed γ-source reveals an unique possibility to steer the polarization of γ-quantums due to the simplicity of steering the polarization of the FEL radiation. So, such a γ-quantum source, operating in a CW mode, will reveal unique possibilities for precision investigations in nuclear physics.

2 Basic relations

2.1 Compton backscattering

High energy γ - quantums are produced by means of Compton backscattering of the laser photons by the high energy electrons. The frequencies of the incident and scattered photons, ω and ω_γ, are connected by the relation (in the small-angle approximation):

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

where θ is the scattering angle, $\chi = 4\gamma\hbar\omega/m_e c^2$, m_e and $\mathcal{E}$ are the electron mass and energy, respectively, and $\gamma = \mathcal{E}/m_e c^2$ is relativistic factor. We consider the case when the energy of the backscattered γ-quantum is rather small with respect to the electron energy:

$$(\hbar\omega_\gamma)_{\max} < \Delta\mathcal{E}_{\max}, \tag{2}$$

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

$$(\hbar\omega_\gamma)_{\max} \simeq 4\gamma^2\hbar\omega. \tag{3}$$

2.2 Focusing of laser beam

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. It may be performed, for instance, by means of a metal focusing mirror (see Fig.1).

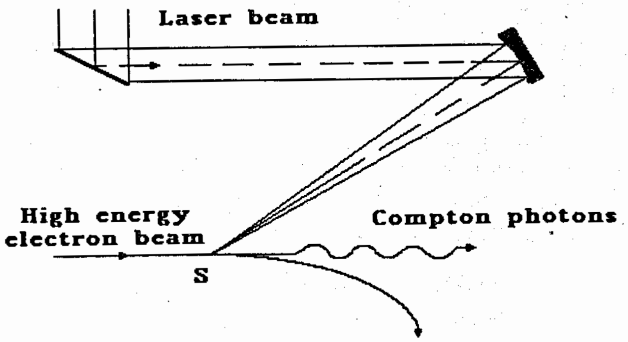

Figure 1: Scheme of Compton γ-source

Electrons move along the z axis and pass through the mirror focus S. To calculate the conversion coefficient, it is necessary to find the distribution of the optical field intensity in the focal spot.

The conditions of optimal focusing are as follows [13]:

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

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. The first condition (4) assumes the transverse size of electron beam at the conversion point to be much less than laser beam size, so, when calculating the probability of Compton scattering, only axial change of the electrical field strength along the z axis should be taken into account. The second condition (4) means the characteristic axial size of the region with strong optical field to be much less than electron and laser beam lengths.

2.3 Yield of γ-quantums

Total number of γ-quantums, produced at a single passage of electron beam through the mirror focus, is given with the following relation:

$$N_\gamma = N_e \frac{\sigma_T}{2\pi\hbar\omega} \int |E|^2 \, dz, \tag{5}$$

where N_e is the number of electrons in the bunch and E is the amplitude of optical field. It is assumed here that the optical field is circularly polarized.

Taking into account the fact that the optical field reduces quickly with the removal from the focus (it is almost vanished at $|z| > 4\pi c F^2/a_o^2\omega$), the integral in the right-hand side of eq. (5) can be calculated in the limits $-\infty < z < \infty$. Using Huygens-Fresnel integral, we may write:

$$\int_{-\infty}^{\infty} |E|^2 \, dz = \frac{4\pi W\omega}{c^2}, \tag{6}$$

where W is the peak power of the optical beam. Substituting (6) into (5) we finally obtain:

$$N_\gamma = N_e \frac{2W\sigma_T}{\hbar c^2}. \tag{7}$$

An important feature of the obtained result is that the number of produced γ-quantums does not depend on the details of the optical field distribution on the mirror surface and is defined with the total laser beam power only.

At approximately equal laser and electron beam lengths, the rate of γ-quantum production is given with the following formula:

$$\frac{dN_\gamma}{dt}\,[\mathrm{s}^{-1}] = 2 \times 10^{-11} N_b N_e W f, \tag{8}$$

where f [Hz] is the repetition rate of electron bunch collisions with the laser bunch, N_b and N_e are number of bunches and number of electrons in the bunch, respectively and laser peak power W is in watts. Formula (8) is valid for an arbitrary laser beam polarization.

2.4 Excitation of energy oscillations

The proposed γ-source operates in a "parasitic" mode and does 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:

$$< \frac{d(\delta\mathcal{E}/\mathcal{E})^2}{dt} >= \frac{f}{2\pi\hbar\omega} \int_{-\infty}^{\infty} |E|^2 \, dz \int \left[\frac{\hbar\omega_\gamma}{\mathcal{E}}\right]^2 d\sigma_T,$$

where $\hbar\omega_\gamma = 4\gamma^2\hbar\omega/(1+\gamma^2\theta^2)$. is the energy of γ-quantums scattered under the angle θ and

$$\frac{d\sigma_T}{d(\gamma^2\theta^2)} = 4\pi r_e^2 \frac{1+\gamma^4\theta^4}{(1+\gamma^2\theta^2)^4}$$

is Thompson differential cross section written down in ultrarelativistic approximation $\gamma \gg 1$. Using relation (6) we get:

$$< \frac{d(\delta\mathcal{E}/\mathcal{E})^2}{dt} >= \frac{448}{15} \frac{r_e^2 \lambda_c \gamma^2 \omega^2 W f}{mc^5}, \tag{9}$$

where $\lambda_c = h/mc$. This expression may be written in the following form convenient for calculations:

$$< \frac{d(\delta\mathcal{E}/\mathcal{E})^2}{dt} > [\mathrm{s}^{-1}] \simeq 4 \times 10^{-23} \frac{\mathcal{E}^2 W f}{\lambda^2}. \tag{10}$$

where electron energy $\mathcal{E}$ is in GeV units, laser peak power W is in watts, rate of collisions f is in Hz units and laser wavelength λ is in centimeters.

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 FEL based γ-quantum source at HERA

An 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.[1] Main parameters of the electron storage ring HERA are presented in Table 1 (see also refs. [15] and [16]).

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[1] Parameters of electron beam in the TRISTAN collider are close to those of the HERA collider, so the γ-source with similar parameters may be constructed on the base of TRISTAN collider, too [14].

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}	
Electron 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 and Fig.2).

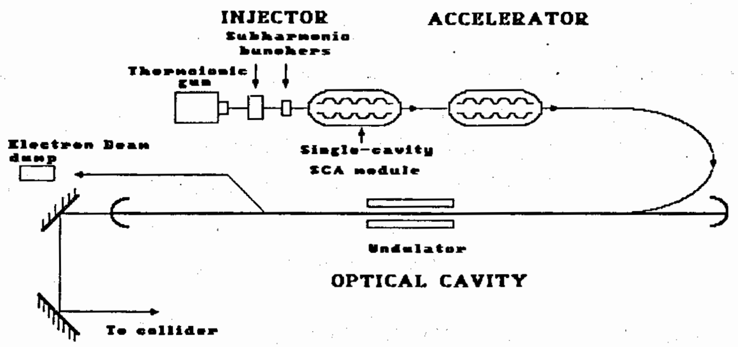

Figure 2: FEL oscillator scheme

The project of the FEL oscillator with the parameters close to those required has been developed at LBL [17]. 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.

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

Accelerator of the FEL driving beam

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 ($f = 500$ 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 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.

Undulator

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 $B_w = 2.7$ kGs at the undulator gap $g = 28$ mm.

Optical resonator

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 (8) 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 electron HERA 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 (see Fig.3).

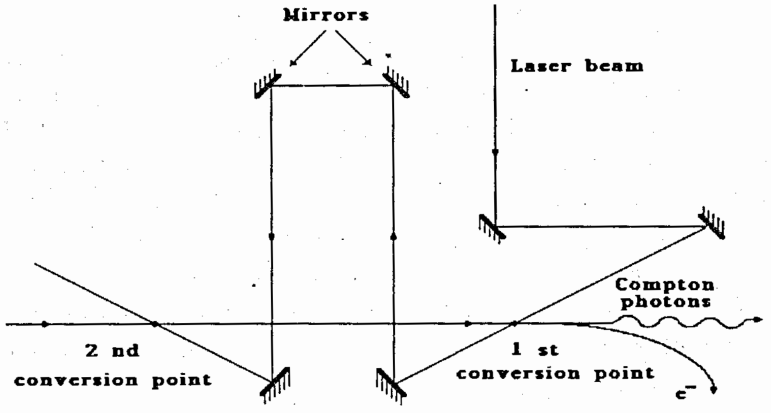

Figure 3: Scheme of optical delay providing multiple collisions of electron and optical bunches

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 $\lambda \simeq 100 \mu$m 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 synchrotron radiation [2] is equal to $< d(\delta\mathcal{E}/\mathcal{E})^2/dt >_{SR} \simeq 10^{-3}$s^{-1}. Using relation (10), we obtain that coefficient of energy diffusion due to the scattering of electron 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}. As a result, the energy spread will be increased by 1.3 times with respect to the case of operation of electron ring without laser.

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

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

4 FEL based γ-quantum source at LEP

The storage ring LEP is destined for precision study of Z^0-boson physics (LEP with the center-of-mass energy about of 100 GeV) and $W^{\pm}$-boson physics (LEP 2 with the center-of-mass energy about of 200 GeV) [18], [19]. Main parameters of LEP are presented in Table 1.

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 (see Fig.3) 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. 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 [17]. 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.

These γ-sources will reveal a possibility to study photonuclear physics in the energy range from several MeV up to 500 MeV with an accuracy unachievable with the existent facility. Preliminary analysis shows that physical program of investigations at these sources will not cede to the corresponding program at CEBAF. The proposed photon beam facility is extremely selective probe for investigations not only conventional nuclear physics, but the exotic nuclear states (similar to those occured 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 the microscopic nuclear structure with resolution $\gtrsim$ 200 MeV is unexplored field [20]. An idea is to work in 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 the nonpertur QCD effects. Investigations of this transition energy region from the perturbative to nonperturbative QCD are the most attractive and perspective direction of 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 an additional information about the hadron or the nuclear structure which is usually hidden in the spin-averaged analysis [21]. Polarization observables has a promise of opening a new field in the photoproduction of pion from nucleon and nuclear targets [22], in the processes of photodisintegration of the lightest nuclei [8, 12] and others. Many problems in the photonucleon and photonulear physics are not resolved till now due to the lack of high quality photon beams.

We believe that the experiments with the proposed photon beam facility will be able to shed fresh light on these and other unresolved problems of the nuclear physics.

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О возможности создания интенсивных источников монохроматических
гамма-квантов на накопителях HERA и LEP

Обсуждается возможность создания интенсивных, перестраиваемых по энергии, монохроматических γ-источников на накопителях HERA и LEP (LEP 2). Предлагается производить γ-кванты путем обратного комптоновского рассеяния лазерного излучения на электронах пучка накопителя. Длина волны лазерного излучения выбирается таким образом, что после рассеяния электроны не покидают сепаратрису. Так как вероятность рассеяния мала и до следующего акта рассеяния энергия рассеянного электрона релаксирует к равновесной энергии, то подобный источник фотонов практически не изменяет характеристики пучка, циркулирующего в накопителе.

Установка на накопителях HERA и LEP лазеров на свободных электронах с перестраиваемой длиной волны $\lambda \sim 100$—400 мкм, пиковой и средней мощностью порядка 10 МВт и 1 кВт, позволит создать источники монохроматичных поляризованных гамма-квантов со средней интенсивностью порядка 10^{14} сек$^{-1}$. Предлагаемые фотонные источники позволяют менять в широких пределах энергию фотонов. Максимальная энергия фотонов ограничена энергетической апертурой накопителей и составляет величину порядка 150 МэВ, 250 МэВ и 500 МэВ для накопителей HERA, LEP и LEP 2.

Отмечено, что предлагаемые фотонные источники открывают широкие перспективы проведения уникальных экспериментов в области ядерной физики.

Работа выполнена в Лаборатории сверхвысоких энергий ОИЯИ.

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Saldin E.L. et al. E9-94-236

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

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 ~10 MW and ~1 kW, respectively. It will result in the intensity of the γ-source ~10^{14} 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.

The investigation has been performed at the Particle Physics Laboratory, JINR.

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