Compton back scattering of X-photons from 8 GeV electrons at SPring-8

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Abstract

The experimental feasibility of using an intensive photon beam at the SPring-8 for producing a high energy $\gamma-$ ray beam is examined. Compton back scattering of the soft X-photons emitted by an undulator and reflected back by a multi-layer mirror from the electron beam can produce a quasi-monochromatic $\gamma-$ray beam up to an energy very close to 8 GeV. The intensity of the $\gamma-$ray beam in the energy range of 6.6 $\sim$ 7.8 GeV has been estimated. The energy shape and the scattered angle of γ-rays produced in Compton back scattering of the soft X-photons from an 8 GeV electron beam are calculated.

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1 Introduction

The new facility for nuclear and particle-physics experiments with a polarized photon beam in the energy range of 1.5 $\sim$ 3.5 GeV is under construction at the SPring-8 [1]. The photon beam is produced by Compton backward scattering (CBS) of laser photons with energies of 3.54 eV ($\lambda = 350\ nm$) and 6.2 eV ($\lambda = 200\ nm$). The laser power used is about $20 \sim 25\ W$. On the other hand, at the SPring-8 there are high power sources for soft and hard X-radiation with a total power exceeding several kW [2].

For example, the Soft X-ray Twin Helical Undulator (H120) [3] has a total power of $P_{total} \simeq 2\ kW$ and the Soft X-ray Undulator (UF100) has $P_{total} \simeq 10\ kW$. It is very attractive to use these sources for Compton backscattering from an 8 GeV electron beam and to produce a quasi-monochromatic γ-ray beam with an energy close to the kinematic limit. The energy of CBS γ-rays scattered at the angle $\theta = 0^o$ is determined as follows:

$$E_\gamma(\theta = 0^o) = \frac{E_0}{1 + \frac{m_e^2}{4E_{ph}}\frac{1}{E_0}}, \tag{1}$$

where E_0 is electron energy, E_{ph} is the energy of incoming photons and m_e is the electron mass. The γ-rays energy which is close to the electron energy via CBS can be achieved by increasing the energy of incident photons.

The idea to use Compton scattering of the soft X-rays from a high energy electron beam was discussing about thirty years ago by Arutyunian and Tumanian [4]. The progress in the accelerator construction [5] and recent development in X-ray optical elements enables us to produce intensive high energy $\gamma-$ray beam by using the X-ray beam emitted by the undulator.

Recently a nearly monochromatic γ-ray beam was obtained with 100% linearly polarization via CBS of the $3.0 \sim 3.6\ eV$ photons from the electron beam inside a free electron laser optical cavity at Duke University [7]. This work has demonstrated that the radiation emitted by the electron beam can be used again for the next scattering on the same beam. The polarization and energy of the γ-ray beam can be tuned to desirable magnitudes by adjusting the undulator and mirror parameters.

The luminosity of CBS depends on the beam density and the collision path length. A multi-bunch mode of the electron beam in the storage rings provides synchronization of collisions. The SPring-8 facility has conditions to make the first experiment to obtain the $\gamma-$ray beam using CBS of soft X-photons at one of existing undulators. We suggest to use for beginning a helical undulator which radiates an axial symmetrical photon beam with a high degree of circular polarization. For this purpose, we examined the twin helical undulator BL25 [3] which has 24 periods with a length of 12 cm with a maximum field of $B \sim 0.58\,\mathrm{T}$. The electron and photon beams have the following parameters:

− current of 100 mA;

− horizontal size of 0.38 mm with an angular divergence of 15.7 μrad;

− vertical size of 0.033 mm with a divergence of 3.6 μrad;

− tunable energy range for photons is of 0.12∼4.5 keV;

− total power of radiation is of 3.8 kW.

We present a possible scheme of experiments and estimate the γ-rays intensity expected.

2 Synchrotron radiation from a helical undulator

In this section, we write basic formulas used in our calculations. As starting point we may neglect effects of the size and angular divergence of the electron beam on the X-ray beam radiated by the undulator. The angular divergence will smear out an angular distributon of photons emitted from the undulator and will be transferred to the final γ-ray beam.

Relativistic electrons emit syncrotron radiation with a wide energy spectrum in an angle cone with averaged opening of $\sim 1/\gamma$ where $\gamma = E/mc^2$, m is the electron mass, and c is the speed of light. The magnetic field $\mathbf{B}$ inside helical undulator has a constant magnitude with the direction rotated in the plane perpendicular to the electron trajectory. The length of rotating period, the value of magnetic field, and the number of periods determine the intensity and spectrum of radiation for a given energy and current of the electron beam. Electron moves along a helical trajectory as it propagates through this rotating field with the radius r dependent on the magnetic field B. The pitch angle of the helical trajectory determines the opening angle of emitted radiation [9]:

$$\Theta_{undulator} \equiv \Theta_{pitch} \approx 2\pi r/\lambda_0 = \lambda_0/2\pi\rho, \tag{2}$$

where ρ is the cyclotron radius and λ_0 is the magnet period length given by

$$\rho = \gamma\beta mc^2/eB, \tag{3}$$

where β is the electron speed in the units of c. For relativistic electrons, $\beta \approx 1$, and $\Theta_{undulator}$ is given by

$$\Theta_{undulator} = \lambda_0 eB/2\pi\gamma mc^2 \equiv K/\gamma. \tag{4}$$

The deflection parameter K defines the angle of the radiation cone (in the units of $1/\gamma$) in which radiation is concentrated. The velocity of electron along the axis the z is defined as

$$\beta^* = \beta \cdot \cos\Theta_{pitch} = \beta\left[1 - \left(\frac{\lambda_0}{2\pi\rho}\right)^2\right]^{1/2}. \tag{5}$$

The radiation intensity per unit of the frequency and solid angle as a function of frequency radiated by electron along a curve trajectory is given [10] by the following equation

$$\frac{d^2 I(f)}{df\,d\Omega} = \frac{2\pi f^2 e^2}{c^3} \left| \int\limits_{-\infty}^{\infty} [\mathbf{n} \times (\mathbf{n} \times \dot{\mathbf{r}}(t))] e^{2\pi i f[t-(\mathbf{n}\cdot\mathbf{r}/c)]} dt \right|^2, \tag{6}$$

where $\mathbf{n}$ is a unit vector directed from the origin to the observer and $\mathbf{r}(t)$ is the vector describing the trajectory of the electron (Fig. 1). The motion of electrons is given by:

$$\mathbf{r}(t) = \beta^* ct\mathbf{k} + b\,\sin(\omega_0 t)\mathbf{j} + b\,\cos(\omega_0 t)\mathbf{i}, \tag{7}$$

$$\dot{\mathbf{r}}(t) = \beta^* c\mathbf{k} + b\omega_0 \cos(\omega_0 t)\mathbf{j} - b\omega_0 \sin(\omega_0 t)\mathbf{i}, \tag{8}$$

$$\omega_0 = 2\pi\beta^* c/\lambda_0, \tag{9}$$

where $\mathbf{i}, \mathbf{j}, \mathbf{k}$ are the unit vectors directed along the x, y and z coordinates, respectively, and the radius of helical orbit is given by $b \approx \lambda_0^2/4\pi^2\rho$ [9]

The equation (6) for the numerical calculations can be rewritten[11] in the formula describing the motion of electrons in the periodic undulator magnetic field:

$$\frac{d^2 I(f)}{df\,d\Omega} = \frac{2\pi f^2 e^2}{c^3} \left[\frac{\sin\left[N\pi f\left(1-\beta^* n_z\right)T\right]}{\sin\left[\pi f\left(1-\beta^* n_z\right)T\right]} \right]^2 \left| \int\limits_{0}^{T} [\mathbf{n} \times (\mathbf{n} \times \dot{\mathbf{r}}(t))] e^{2\pi i f[t-(\mathbf{n}\cdot\mathbf{r}/c)]} dt \right|^2 \tag{10}$$

where $T = \lambda_0/\beta^* c$, and N is the number of periods.

The intensity of radiation polarized along the vector $\mathbf{u}$ can be obtained by taking the scalar product[10] of the vector $\mathbf{u}$ and the vector integral before calculating the squared value:

$$\frac{d^2 I(f)}{df\,d\Omega}(\mathbf{u}) = \frac{2\pi f^2 e^2}{c^3} \left[\frac{\sin\left[N\pi f\left(1-\beta^* n_z\right)T\right]}{\sin\left[\pi f\left(1-\beta^* n_z\right)T\right]} \right]^2 |\mathbf{A}\cdot\mathbf{u}|^2 \tag{11}$$

where $\mathbf{A}$ is the vector integral in eq.(10) and $\mathbf{u}$ defines the direction of polarization by the following way:

1. $\mathbf{u}(1,0,0)$ and $\mathbf{u}(0,1,0)$ for linear components along x- and y-axis;

2. $\mathbf{u}(1,1,0)/\sqrt{2}$ and $\mathbf{u}(1,-1,0))/\sqrt{2}$ for linear components along directions at $\pm 45^o$ with respect to the x,y-axis;

3. $\mathbf{u}(1,i,0)/\sqrt{2}$ and $\mathbf{u}(1,-i,0)/\sqrt{2}$ for left and right circularly polarized components, respectively.

The undulator BL25 has a length of period $\lambda_0 = 12\,\mathrm{cm}$ and the total number of periods, $N = 24$. These parameters are included in a computation of the energy spectrum of photons under the condition with $K = 6$ and with an electron beam current of 100 mA. The value of $K = 6$ was determined by the magnitude of the first harmonic in the energy spectrum $E_{ph} = 136\,eV$ as more suitable for reflection by a multi-layer mirror [6]. Consideration of the angle distribution in the energy range close to $E_{ph} \sim 130\ eV$ shows that the most part of radiation which can be used for reflection is concentrated in the rather narrow angle less than 0.4 mrad. Fig. 2 shows photon intensity emitted by the undulator in the angular range of $0 \sim 0.4$ mrad and in a more narrow range of $0 \sim 0.05$ mrad. There is an angle-energy correlation described by the following formula:

$$\lambda_n = \frac{\lambda_0}{2n\gamma^2}\left(1 + K^2 + \gamma^2\Theta^2\right), \tag{12}$$

where n is a harmonic number, λ_n is a wave length for the n-th harmonic and Θ is a radiation angle. For detailed analysis of this correlation, Fig. 3 shows the energy spectrum (a) and polarization (b) for the 4 ranges of the radiation angle. The energy spectrum contains the tails of the second harmonic (see eq.(12)). For the angles $\theta > 0.4\,mrad$ the sign of polarization changes and we limit the range of interest from 0 to 0.4 mrad. The angle-energy correlation has to be taken at applying the multilayer mirrors for the soft X-rays [6,8]. The reflectivity band of the mirror should be fitted with respect to the undulator photon energy determined by the accepted angular ranges. It would be helpful to tray to fabricate the mirror with fluent changing the reflectivity band with respect to the energy of reflected photons.

3 Scheme of experiment.

From the angle-energy correlation follows that we have to treat the radiation at a very small angles and use a large distance between the undulator and the mirror. At SPring-8, the distance of the order of 50 m is available. Fig. 5 shows a proposed experimental set-up for CBS of soft X-ray photons from 8 GeV electrons. At the 50 m distance from the center point of the staight section, the diameter of mirror for 4th angle range has 40 mm, and the surface of mirror are divided into rings for the different energy bands of reflection appropriate to the energy range of the photons radiated. The mirror should be spherical with the focusing point in front of the undulator. In this case the photons reflected will collide with the electron beam along the straight line section of the storage ring where the undulator is installed and where the electron beam trajectory is not distorted by magnetic field of the undulator.

Inside the undulator, the electron beam has the helical trajectory with the angle $\theta_{pitch} = K/\gamma$ (see eq.(2)and (4)), and if CBS occurs inside the undulator then the γ-ray beam has to be obtaned with a wide angular distribution of the order K/γ. The available part of straight section in front of the undulator for colliding X-photons with electrons in our case can not be over $\sim$6 m. The central part of mirror should be thin to reduce the attenuation of the final γ-beam.

The reflectivity of the multilayer mirror depends on a performance. To our knowledge the recent technology [6] shows that the reflectivity of ~20% in the ~5% band width of the photon energy is achievable. In the following calculation, this reflectivity is used as a parameter of the mirror. The focusing property of the multilayer mirror was checked [6] and can provide the size of the focus close to the size of the light source or to the size of the electron beam crossover inside of the undulator.

The density of heating power is evaluated by integrating the photons flux from 0 to $\sim$ 4000 eV for each angular bin. The result is shown in Fig. 5. The magnitudes of heating power per unit of area are presented in Fig. 6. The largest heating density will be caused by the synchrotron radiation (SR) emitted from the bending magnets of the storage ringe in front of and behind the undulator. This amount of heat is absorbed by mirror and has to be taken into account at designing the mirror.

4 Luminosity

The luminosity for the colliding beams is given by the following formula:

$$L = \rho_1 \cdot \rho_2 \cdot V_{int} \cdot (v_1 + v_2), \tag{13}$$

where

$$\rho_{1,2} = \frac{I_{1,2}}{S_{1,2} \cdot v_{1,2}}$$

are the particle densities of both the beams in the volume of interaction V_{int}, $v_{1,2}$ are the velocities of beams, $I_{1,2}$ are the beam currents and $S_{1,2}$ are the beam crossovers. For the photon - electron colliding beams equation (13) can be written

$$L = 2 \cdot L_{int} \cdot I_{ph} \cdot I_e \cdot \frac{1}{S_{int} \cdot c}, \tag{14}$$

where L_{int}, S_{int} are length and crossover of collision volume, I_{ph} and I_e are photon and electron currents.

Fig. 7 shows the geometry of the collision between the beams. The magnitude of average crossover of the electron beam is approximated by $b = \sqrt{b_x \cdot b_y}$ where b_x and b_y are the horizontal and vertical sizes of the electron beam. In our calculation b is ≈ 100 μm. It is obvious that in order to increase the luminosity, it's necessary to decrease the crossover of the electron beam and to increase the length of interactions.

5 Intensity for CBS γ-ray beam

The energy spectra and angular distribution of the γ-ray beam were calculated using the well known Compton formula. Fig. 8 shows the result obtained for each mirror ring separately and the sum of intensities from four rings.

A created γ-ray beam has a narrow angle distribution and pass through the 1-th ring of the mirror. Intensity of γ-ray beam was calculated for the initial electron beam intensity of 100 mA. Highest energy of γ-ray for used energy interval of photons is 7.5 GeV. The energy spectra are obtained for the γ-ray beam concentrated in the narrow polar angle ($\Theta < 10^{-4} rad$). To have a variable energy of γ-ray we can replace the mirror by other to reflect photons with the energy, more higher or lower than previous, and just the deflection parameter K.

The photon energy range 200$\sim$500 eV is examined in the same way and experimental results of work [12] confirm that multi-layer mirrors can be delivered for these energies. To this end we estimate an intensity and angular distribution of a γ-ray beam for four magnitudes of the deflection parameter K of the undulator.

Fig. 9 shows the energy and angular spectra from the reflection by the 1-st ring of the mirror for the different values of K. Fig. 10 shows the same spectra but for the 2-nd ring of the mirror. As a result the intensity and energy of final γ-ray beam can be varied by proper choice of mirror and deflection parameter K.

6 Conclusion

This report shows that there is a method to generate a γ-ray beam with the energy close to the electron beam energy using CBS of reflected photons radiated by the undulator. To obtain the γ-ray beam with an intensity necessary for the nuclear physics experiments, we have to optimize a system comprising the undulator and a straight section where the undulator is installed.

We have a limited length of straight section of storage ring which have to be separated into two parts, one for production of primary photons and other for collision of reflected photons with electron beam. The deflection parameter K must be rather large to produce more intensive photon flux and another important reason is the photon energy which must be not too high because we have a limit related with the multi-layer mirror. In this case the length of the undulator can not be used for CBS because the obtained γ-ray beam will have a wide angular divergence of order $\Theta \sim K/\gamma$. One more promising way can be analyzed for the undulator with larger period length and higher magnetic field strength to have a lower value of parameter K and get the total length of the straight section for CBS γ-ray beam production. Moreover it is necessary to keep in mind that the undulator is a part of the magnetic lattice of the storage ring and we have limited range for playing with magnetic property of the inserted device. The optimal solution and a limit for the CBS γ-ray intensity can be found for the discussed scheme.

Another interesting question is whether or not we can observe an interference effect between radiated photon and that reflected by the mirror. As a result, a periodical magnetic field with a period length equal to the wave length of reflected photon and an electron beam must interact. Related problems are widely discussed in the free electron laser study. The SPring-8 opens a new experimental possibility to study these questions and develop new methods of beam producing.

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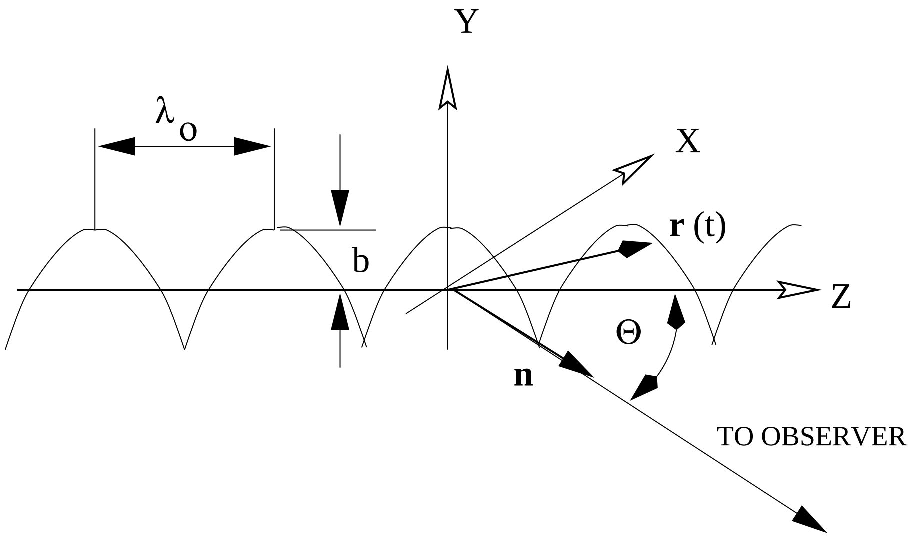

Fig. 1. The helical orbit of electron in helical magnetic field of the undulator

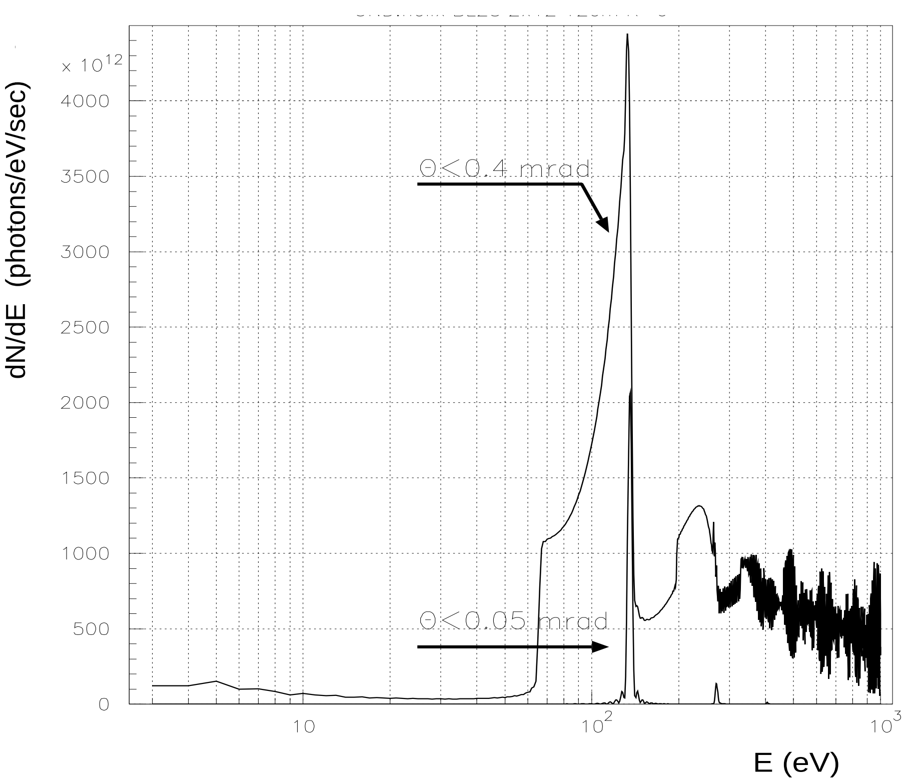

Fig. 2. The count rate of the photons emitted from the undulator for two angular ranges.

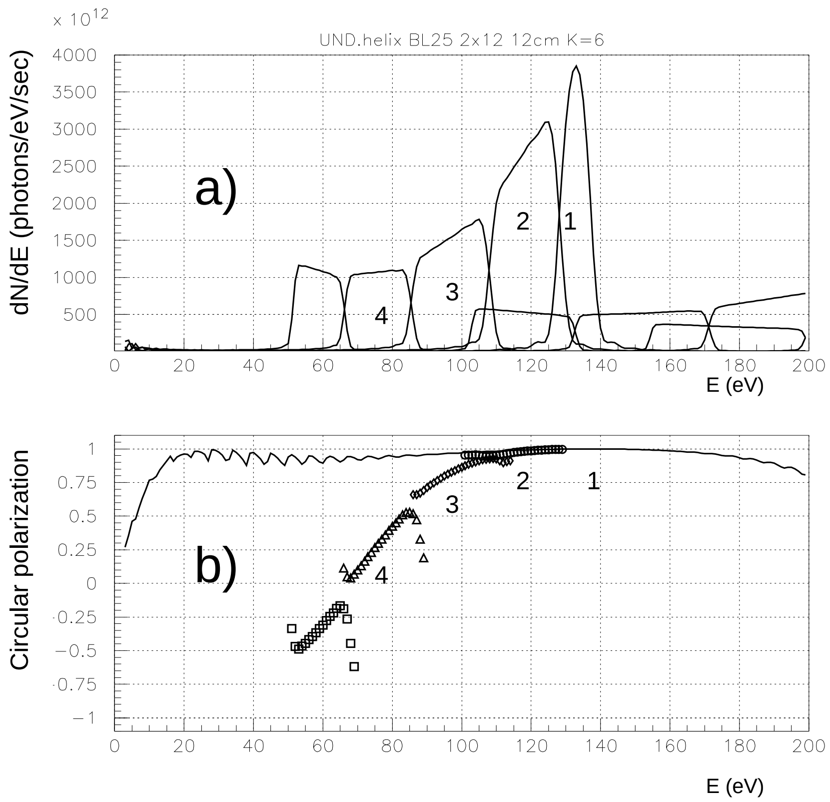

Fig. 3. The energy spectrum (a) and polarization (b) of the photons emitted from the undulator for 4 angular ranges: (1) for $\Theta = 0. \sim 0.1$mrad, (2) for $\Theta = 0.1 \sim 0.2$mrad, (3) for $\Theta = 0.2 \sim 0.3$mrad and (4) for $\Theta = 0.3 \sim 0.4$mrad

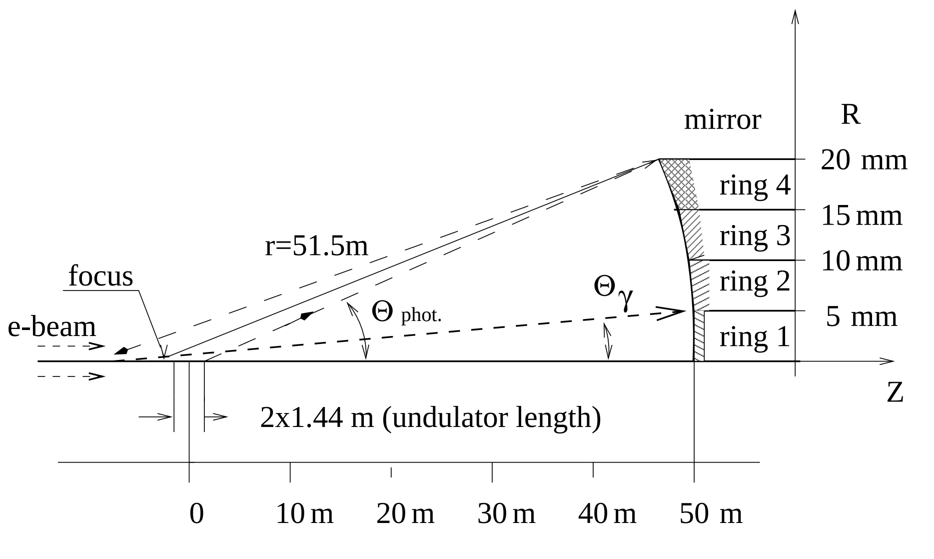

Fig. 4. The schematic explanation of the experimental set-up for CBS of soft X-rays photons from 8 GeV electrons. The total length of the H120 undulator is of 2.88 m. The total length of the straight section where the undulator installed is of 16.5 m and the length allowed for collision can not over than 6 m.

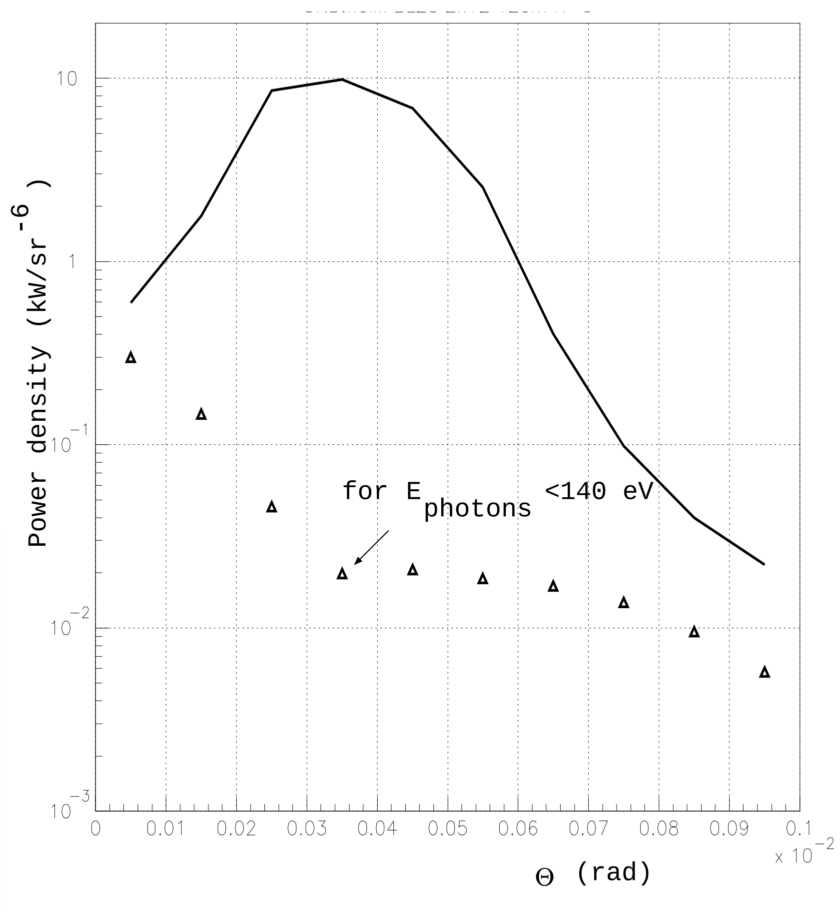

Fig. 5. The power density of radiation as a function of angle. Solid line - the total power density, triangle points - the power for the photon with the energy lower than 140 eV.

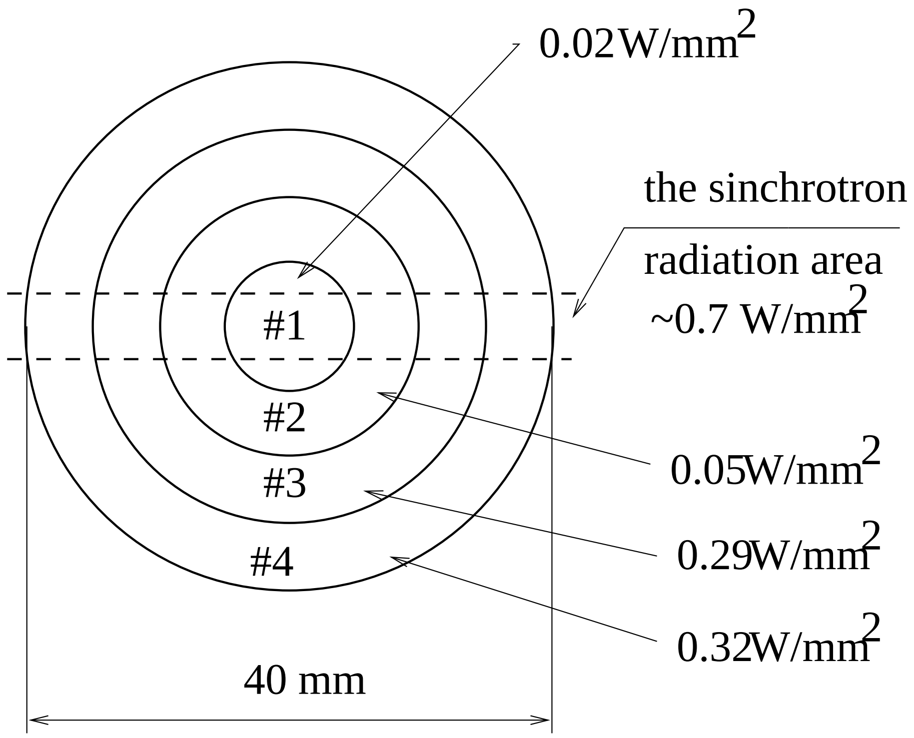

Fig. 6. The front of view of mirror surface with the averaged heating power density in each ring.

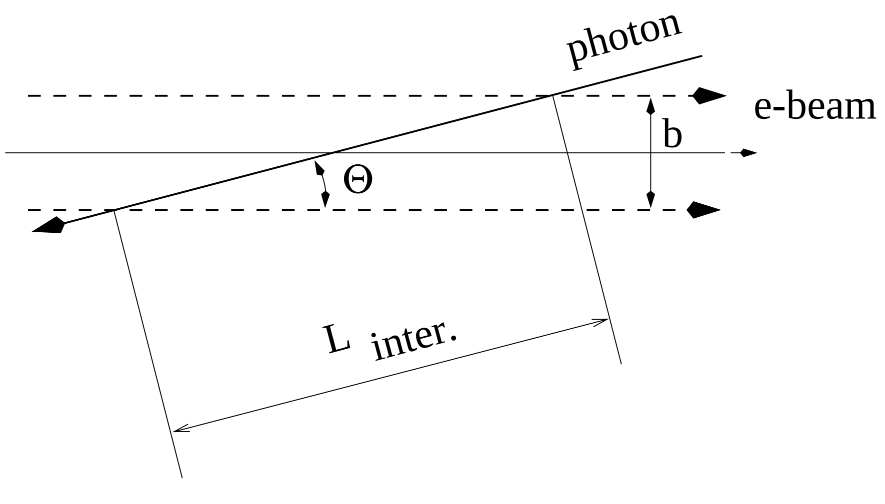

Fig. 7. The geometry of collision of photons with an electron beam. The value b is the average electron beam crossover size.

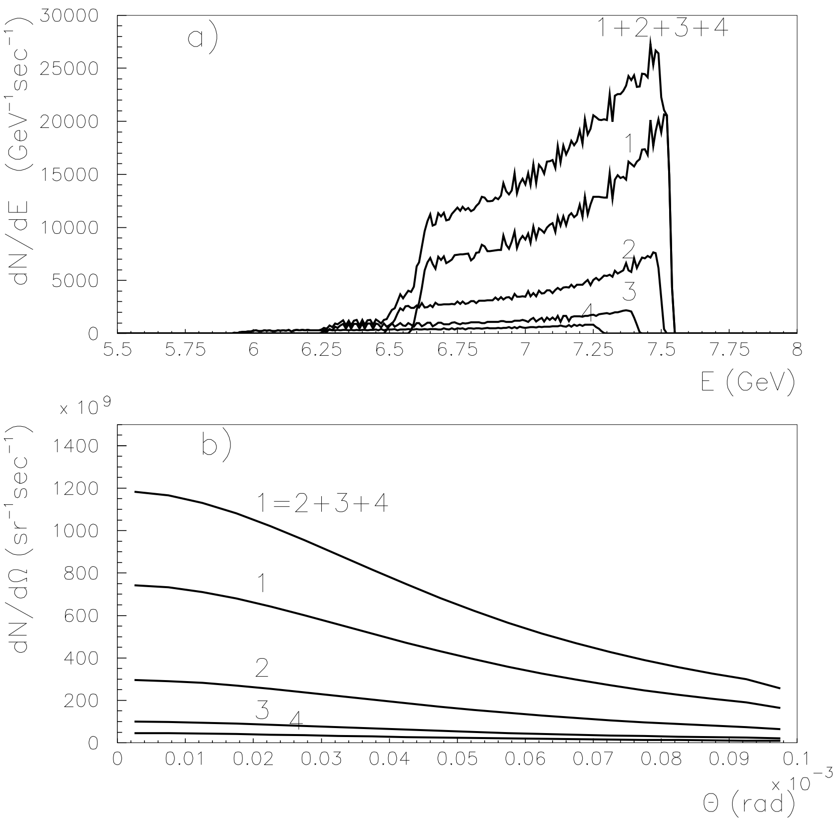

Fig. 8. The energy spectra (a) for the γ-ray beam and the angular distribution (b). The 1-,2-,3- and 4- curves are the contributions in the total γ-beam intensity (curve 1+2+3+4). The band width of the reflectivity of the multilayer mirror for the 1-ring is of $130 - 136eV$, for the 2-ring is of $120 - 126eV$, for the 3-ring is of $100 - 105eV$ and for the 4-ring is of $80 - 84eV$. Oscillations on the curves are a consequence of an inaccuracy of the calculation.

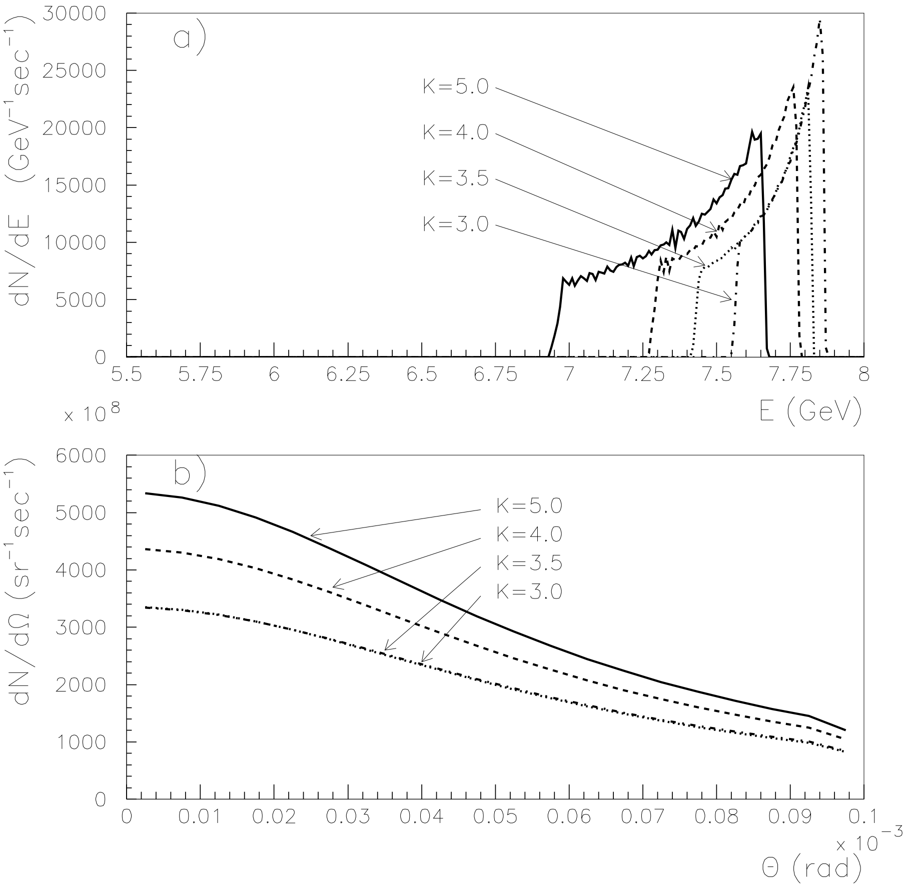

Fig. 9. The energy spectra (a) for the γ-ray beam and the angular distribution (b). The K=3 ($475 - 500$ eV), K=3.5 ($357 - 374$ eV), K=4 ($279 - 293$ eV) and K=5 ($182 - 191$ eV) curves are obtained for the undulator radiation reflecting by the 1-st ring of the mirror and values of energy in brackets are a band width of the reflectivity.

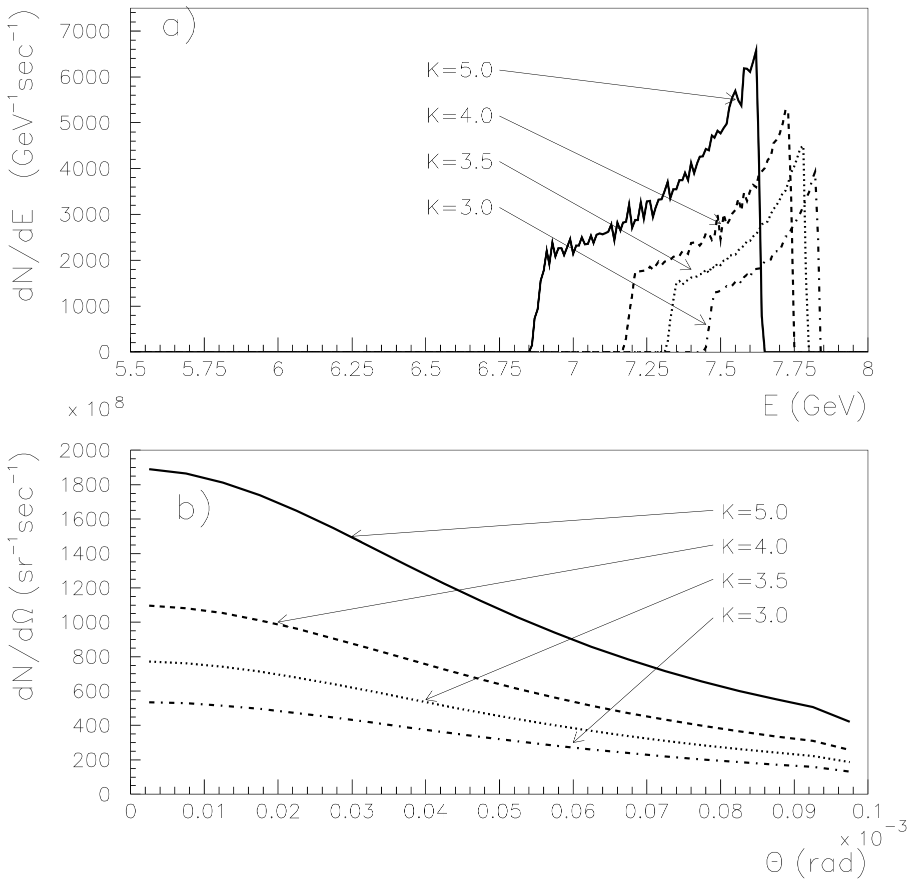

Fig. 10. The energy spectra (a) for the γ-ray beam and the angle distribution (b). The K=3 ($380 - 400$ eV), K=3.5 ($300 - 315$ eV), K=4 ($243 - 255$ eV) and K=5 ($168 - 176$ eV) curves are obtained for the undulator radiation reflecting by the 2-nd ring of the mirror and values of energy in brackets are a band width of the reflectivity.