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PRODUCTION OF QUASI-MONOCHROMATIC GeV PHOTONS BY COMPTON SCATTERING USING UNDULATOR X-RAY RADIATION AT SPring-8

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Abstract

Backward Compton scattering (BCS) of X-ray photons emitted by undulator and reflected back by a single crystal from the electron beam can produce a quasi-monochromatic gamma-ray beam up to an energy very close to the electron beam energy. The SPring-8 beam diagnostics beamline (BL05SS) is used to inject a reflected undulator X-ray radiation against 8 GeV stored electron beam and to extract a quasi-monochromatic 8 GeV gamma-ray produced by BCS. BL05SS has conditions to do a pilot experiment to obtain the gamma-ray beam using BCS of X-ray photons from existing undulator. Experimental setup including a Bragg mirror system is now under construction. Preliminary reflectivity measurement of a silicon Bragg mirror using around 10 keV photons has been done. Status of the experimental preparation and the future outlook is presented.

INTRODUCTION

Beamlines for hadron and nuclear physics experiments with a polarized gamma-ray beam in the energy range of 1.5 − 2.9 GeV are running at SPring-8. The gamma-ray beams are produced by Backward Compton scattering (BCS) of laser photons with wavelength of 355 nm (E_L = 3.49 eV) and 266 nm (E_L = 4.66 eV). In the case of collision between 8 GeV electrons and 355 nm laser light, the maximum energy of the gamma-ray reaches at 2.4 GeV.

Although the gamma-ray production by using the lasers has been established with the successful results, further improvements concerning the maximum energy are desired to advance hadron and nuclear physics. The extension of the maximum photon energy of gamma-ray opens new fields of the photo production experiments. For example, it becomes feasible to study the photo production of heavy particles.

Also, a monochromatic high energy gamma-ray is very important. Normally, in the nuclear physics experiment using BCS gamma-ray, the photon intensity and energy are measured by a tagging system, which counts number of recoil electrons in the BCS and analyses momenta of them event by event. The tagging system is installed at the downstream of BCS interaction region, which are formed by 10 fingers of trigger scintillators and scintillation fibers. If a monochromatic gamma-ray with a moderate bandwidth could be used, the tagging system would be unnecessary.

In the third generation synchrotron radiation facility, there are many high power X-ray photon source such as X-ray undulators. It is very attractive to use these photon sources as incident photon source for BCS, so that we could produce a quasi-monochromatic gamma-ray beam with photon energy close to the kinematic limit.

The idea to use BCS of the soft X-rays from a high-energy electron beam was discussed by Arutyunian and Tumanian in 1963 [1]. V. Nelyubin et al. discussed a possibility to use the spherical multi-layer mirror with a reflectivity of ~20% in the ~5% band width of the photon energy of range 200 − 500eV which is produced by soft X-ray undulator [2].

Recently, K.-J. Kim et al. discussed the possibility of X-FELO using the single crystal with high-reflectivity at normal-incidence [3]. The progress in accelerator technology and recent development in X-ray optical elements enable us to produce a high energy gamma-ray beam by using the X-ray radiation emitted from the undulator.

We plan to use a single crystal at a normal-incidence for reflecting X-ray undulator radiation and to go back to BCS interaction region in the straight section of the storage ring. The following part of this paper describes the recent activity of the LEPS and LEPS2 beamlines. In the next section, theory of BCS process by an incident photon with a higher photon energy. Preliminary experimental results for the reflectivity of single crystal Bragg mirror and a future outlook for our experimental plan of the production of a quasi-monochromatic gamma-ray beam with a photon energy close to the kinematic limit.

LEPS AND LEPS2 ACTIVITY

At SPring-8, two beamlines for nuclear and particle physics experiments using high energy GeV photons by BCS are under operation, which are called BL33LEP (LEPS) and BL31LEP (LEPS2). In experimental collaborators of these beamlines, a laser BCS gamma-ray beam is referred as a Laser-Electron Photons (LEP) beam.

At the LEPS experiments at BL33LEP, which started from 1999, the ultraviolet (UV) laser light with the wavelength of 355 nm (E_L = 3.49 eV) has been injected into the 8 GeV electron storage ring in order to produce BCS photon beam [4]. The beam intensity has exceeded the order of 10^6 Hz in the tagged photon energy range of 1.5–2.4 GeV.

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The construction of the LEPS2 beamline at SPring-8 was approved in 2010, aiming one order of magnitude higher intensity and larger acceptance coverage compared with the LEPS experiments. We have successfully obtained the first photon beam at the LEPS2 beamline, resulting in the beam size of σ ~6 mm and the intensity of ~7 MHz for the gamma-ray energy range of 0 to 2.4 GeV. A large BGO ($Bi_4Ge_3O_{12}$) crystal was used for the measurement of the photon energy spectrum of produced BCS gamma-ray [5, 6].

The LEPS2 beamline utilizes a 30-m long straight section (LSS), the number of which is limited to only 4 of total 62 beamlines at SPring-8. The horizontal divergence of the electron beam at LSS is reduced to 14 μrad in σ, while the usual 7.8-m straight section including the LEPS beamline provides the divergence of 58 μrad. The BCS photon beam spread at the LEPS2 beamline is determined not largely by the electron beam divergence but mostly by the Compton scattering angle, which is calculated by the kinematics depending on the photon energy. This achieves a well collimated photon beam with the radius below 10 mm even at the 135 m downstream from the Compton scattering point, enabling us to construct a large experimental site outside of the experimental hall, whose size is 12 m × 18m in area with the height of 10 m. The constructed experimental building has the volume 15 times larger than the experimental hutch of the LEPS experiments.

We also aim to increase the tagged photon beam intensity nearly up to 10^7 Hz for the photon energy range below 2.4 GeV by using the UV lasers with the wavelength of 355 nm (E_L = 3.49 eV). We plan the simultaneous injection of four lasers, whose output power have increased from 8 W to 16 W or 24 W. In addition to the BCS GeV photons with the UV lasers, we plan to improve the intensity of a high energy photon beam using the deep UV lasers with the wavelength of 266 nm (E_L = 4.66 eV).

THEORY

A schematic drawing of the BCS is shown in Fig. 1. The scattered photon energy k_2 is written as

$$k_2 = k_1 \frac{1+\beta\cos\theta_1}{1+\beta\cos\theta_2+\dfrac{k_1}{E_e}(1-\cos\chi)} \qquad (1)$$

where k_1 is the photon energy of the incident photon, β is the velocity of the electron normalized by speed of light, E_e is the electron energy, $\pi-\theta_1$ and $\pi-\theta_2$ are the angles between the direction of the electron beam and the directions of the photon before and after scattering, respectively, and χ is the scattering angle of the photons.

In the case of head-on collision, the maximum energy of the scattered photon, $k_{2\max}$, is obtained as

$$k_{2\max} = \frac{k_1(1+\beta)}{1+\beta+\dfrac{2k_1}{E_e}} \approx \frac{4k_1E_e^2}{(m_ec^2)^2+4k_1E_e} \qquad (2)$$

where we used the relation

$$1-\beta^2 = \frac{1}{\gamma^2} = \left(\frac{m_ec^2}{E_e}\right)^2 \qquad (3)$$

and $\beta \approx 1$. According to Eq. (2), when k_1 is very high (e.g. 10 keV), the maximum BCS gamma-ray photon energy $k_{2\max}$ is nearly equal to 8 GeV for the electron beam of E_e = 8 GeV.

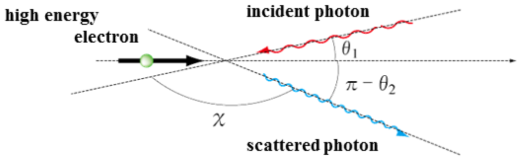

Figure 1: Schematic drawing of backward Compton scattering.

The spectral shape has been derived by Milburn [7] as

$$\frac{1}{\sigma_0}\frac{d\sigma}{d(k_2/E_e)} = \frac{3}{16\lambda}\left[\frac{\lambda^2(1-x)^2}{1+\lambda(1-x)} + 2(1+x^2)\right] \qquad (4)$$

where σ_0 is the Thomson scattering cross-section, σ_0 = 665 mb, $\lambda = 2\gamma k_1/m_ec^2$ and $x = \cos\theta_0$, where θ_0 is the photon scattering angle in the electron rest frame.

In case of low energy incident photon energy k_1 such as laser light, the second term of Eq. (4) becomes dominant and gamma-ray spectrum is the parabolic shape with wide photon energy range. On the other hand, when incident photon energy is high such as undulator radiation, the first term of Eq. (4) becomes dominant and gamma-ray spectrum damps in the low energy region.

Furthermore, when incident photon energy is very high such as hard X-ray, higher-order term $(1-x)^2$ $(n > 2)$ of Eq. (4) becomes important and gamma-ray spectrum uprises steeply near the maximum BCS gamma-ray of $k_{2\max}$.

Figure 2 shows the calculated spectrum of BCS gamma-ray with incident photon energy as a parameter.

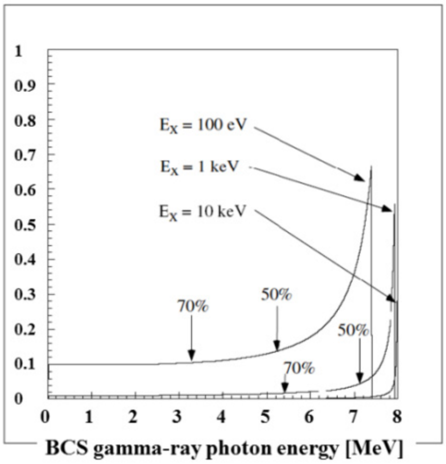

Figure 2: The calculated spectrum of BCS gamma-ray with incident photon energy as a parameter [8].

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MEASUREMENT OF REFLECTIVITY OF SILICON SINGLE CRYSTAL AT NORMAL-INCIDENCE

We measured reflectivity of silicon (Si) single crystals. Figure 3 shows the experimental setup of reflectivity measurement of Si single crystal. Two ion chambers are tandemly arranged. Absorber of aluminium foil is put between two ion chambers. A Si single crystal is mounted on the goniometer and the crystalline axis of Si can be adjusted for the optical axis of incident X-ray.

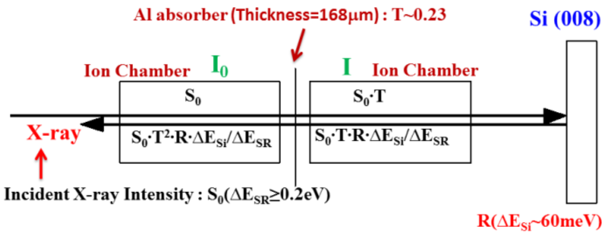

Figure 3: Experimental setup of reflectivity measurement of Si single crystal.

S_0 is the intensity of incident X-ray from the double crystal monochromator, T is transmissivity of aluminium foil absorber, and R is the reflectivity of a Si single crystal.

Figure 4 shows the preliminary measurement result of reflectivity of Si single crystal as a function of the photon energy at normal-incidence to the (0 0 8) planes.

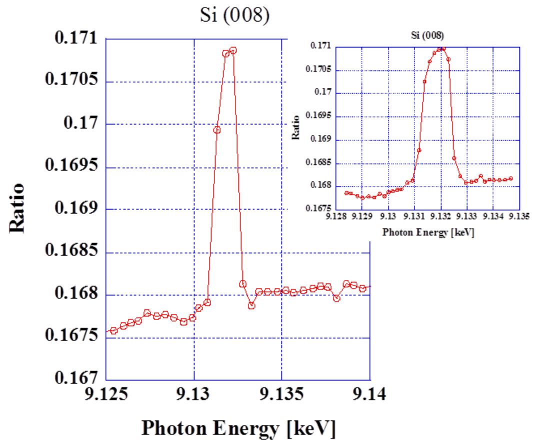

Figure 4: Preliminary results of reflectivity of Si (0 0 8) planes.

The reflectivity of Si (0 0 8) planes at the photon energy of 9.132 keV is ~6 % for total incident X-ray intensity from a double crystal monochoromator. We also measured reflectivity of Si (5 5 5) planes at 9.886 keV and Si (3 3 3) planes at 5.932 keV, which were ~5 % and ~11 %, respectively. The full spectral width of a Si single crystal was about 100 meV.

FUTURE OUTLOOK

We are now fabricating the mirror system for experiment of GeV photon production by BCS using undulator radiation and a single crystal reflection at normal-incidence. It will be installed at BL05SS for the beam diagnostics beamline at SPring-8 [9]. We plan to use a diamond single crystal for Bragg mirror. A reflectivity measurement of (4 4 4) planes of a diamond single crystal will be done at an early date using a similar experimental setup as Fig. 3.

Figure 5 shows the schematic drawing of quasi-monochromatic gamma-ray production system by using an undulator, Bragg mirror of a normal-incidence single crystal, and BGO gamma-ray detector with the diameter of 8 cm and the length of 30 cm. The undulator of BL05SS is a planer out-vacuum undulator with magnet array of 51 periods of 76mm long.

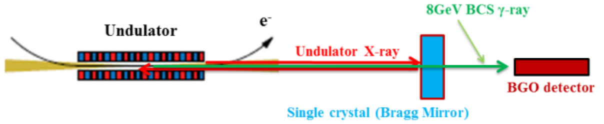

Figure 5: Schematic drawing of quasi-monochromatic gamma-ray production system.

Furthermore, when the focusing of undulator radiation will be necessary, we plan to use parabolic compound refractive lenses.

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