GENERATION OF QUASIMONOCHROMATIC RESONANT TRANSITION RADIATION X RAYS USING A K-SHELL PHOTOABSORPTION EDGE

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Abstract

We propose a simple method to produce quasimonochromatic X rays by means of photoabsorption-edge transition radiation tuned by tilting a thin-foil stack. We have calculated energy spectra of transition radiation for two cases of radiators at an electron beam energy of 1 GeV. One is composed of an eight-foil stack of 7.5-μm thick Kapton and a titanium filter, and the other is a combined-function type radiator of a 3-μm thick titanium eight-foil stack. The following results were obtained: In the case of the separated-function type radiator, 1) the peak energy of the spectra can be easily tuned to the 4.96 keV titanium K-edge by tilting the Kapton-foil stack, and 2) the width of the resultant energy spectra is reduced to a half or less compared to that with no titanium filter, keeping the peak intensity. For the combined-function type titanium radiator, also, the easy tunability and the width of the spectra as narrow as that for the separated-function radiator were obtained. Finally, we confirmed the calculated results by comparing with the experimental data.

1 INTRODUCTION

So far, extensive studies on the transition radiation[1] as an X-ray source have been carried out by a lot of authors. In our previous experimental work [1, 2], we have confirmed that the energy spectra of transition radiation depend on material and thickness of a thin-foil stack radiator under the condition of $\gamma \gg 1$, where γ is the Lorentz factor of an electron beam. And it is shown that the brilliance of the transition radiation obtained in our experiment is comparable to that of synchrotron radiation emitted from a bending magnet in GeV-electron facilities, and then the transition radiation can be an alternative brilliant X-ray source. Garibyan have made theoretical consideration for the transition radiation emitted by an extreme relativistic particle moving into a medium at an oblique incidence. The results show that the intensity of the radiation hardly depends on the angle of incidence except for an incidence close to parallel [3]. Finman et al. proposed an X-ray source using the resonant transition radiation tuned by tilting a stack of foils to make a foil thickness variable, and verified the method experimentally [4]. Piestrup and his collaborators have done a lot of work on producing quasimonochromatic X rays using the photoabsorption-edge transition radiation [5-9]. The photoabsorption-edge transition radiation represents transition radiation that its spectrum width is reduced by absorption of photons at the absorption edge of foil-stack material. Therefore, it is necessary to carefully select the foil-stack parameters such as foil thickness, material and spacing in order to match the peak energy of the spectra to the photoabsorption-edge energy.

Then, we propose that it can be easier to produce quasimonochromatic resonant transition radiation by means of photoabsorption-edge transition radiation tuned by tilting a thin-foil stack, because it makes easy to tune the peak energy. In this paper, we report the calculated and experimental results performed for two cases of radiator. One is composed of an eight-foil stack of 7.5-μm thick Kapton and a titanium filter, and is called a separated-function type radiator. The other is called a combined-function type radiator of a 3-μm thick titanium eight-foil stack. Here, we report the performance of this new simple method.

[1] In this paper, we do not clearly distinguish between transition radiation and resonant transition radiation owing to lack of necessity.

2 THEORY

2.1 Resonant Transition Radiation

Transition radiation is an electromagnetic wave emitted when a charged particle crosses a boundary of different dielectric media. When an electron passes many periodical boundaries, that is, a thin-foil stack radiator in a vacuum, the transition radiation X rays emitted from the respective boundaries interfere with the others, and the interfered transition radiation is called resonant transition radiation. In the case that a relative velocity of an electron is β and the foil stack consists of N foils of thickness l_1 with spacing l_2, the differential intensity of emitted resonant transition radiation is given by [10]

$$\frac{d^2P}{d\omega d\Omega} = \frac{\alpha\omega \sin^2\theta}{16\pi^2 c^2}\left(Z_1 - Z_2\right)^2 F_{1foil} F_{Nfoils}, \qquad (1)$$

where P is the number of photons, θ is an emission angle, ω is an angular frequency of photon, Ω is the solid angle, and α =1/137 is the fine structure constant. Z_i ($i = 1, 2$) are the formation length of the media expressed by

$$Z_i = \frac{4\beta c}{\omega\left\{\left(\frac{1}{\gamma}\right)^2 + \left(\frac{\omega_i}{\omega}\right)^2 + \theta^2\right\}}, \quad (2)$$

where c is the velocity of light, ω_i ($i = 1, 2$) are the plasma frequencies of the respective media. The resonance factors F_{1foil} and F_{Nfoils} are expressed respectively by

$$F_{1foil} = 1 + e^{-\mu_1 l_1} - 2e^{-\mu_1 l_1/2} \cos\frac{2l_1}{Z_1}, \quad (3)$$

$$F_{Nfoils} = \frac{1 + e^{-N\sigma} - 2e^{-N\sigma/2} \cos 2NX}{1 + e^{-\sigma} - 2e^{-\sigma/2} \cos 2X}, \quad (4)$$

where $\sigma = \mu_1 l_1 + \mu_2 l_2$, $X = l_1/Z_1 + l_2/Z_2$, and $\mu_{1,2}$ are the X-ray absorption coefficients of the media.

2.2 Tunable Transition Radiation

Under the condition of $\beta \approx 1$, the shape of the energy spectra is determined mainly by the factor F_{1foil}. Neglecting absorption in the foils, Eq. (3) takes a simple form expressed by

$$F_{1foil} = 4\sin^2\left(\frac{l_1}{Z_1}\right). \quad (5)$$

Eq. (5) gives a maximum value when the following condition is satisfied:

$$\frac{l_1}{Z_1} = \frac{2n-1}{2}\pi, \quad (6)$$

where n is a positive integer. Substituting Eq. (2) into Eq. (6), one obtains:

$$\omega = \frac{\omega_1^2 l_1}{2c}\frac{1}{(2n-1)\pi}. \quad (7)$$

Eq. (7) gives an angular frequency corresponding to the peak energy of the spectra. When a thin-foil stack tilted with respect to the electron beam by θ_t, the foil thickness l_1 is replaced by the effective thickness l_{eff} to the beam view:

$$l_{eff} = \frac{l_1}{\cos\theta_t}. \quad (8)$$

Then Eq. (7) must be modified:

$$\omega = \frac{\omega_1^2}{2c(2n-1)\pi}\frac{l_1}{\cos\theta_t}. \quad (9)$$

Eq. (9) represents that the peak energy of the spectra, that is, the rough shape of spectra, can be varied only by changing the tilting angle θ_t. This means that the resonant transition radiation can be tuned by tilting a foil-stack radiator.

2.3 Calculation

The calculation was carried out based on Eq. (1), where the X-ray absorption coefficients were included in the factors F_{1foil} and F_{Nfoils}. Then the calculation involves the photoabsorption-edge transition radiation in the case of combined-function type radiator. For the case of separated-function type radiator, the extra code of absorption in titanium filter was added to the basic code.

3 EXPERIMENT

The experimental apparatus using the electron synchrotron at the KEK Tanashi branch was almost the same as that in the ref. [2]. The 1-GeV electron beam extracted from the electron synchrotron passed through the thin-foil stack radiator and was deflected by a sweeping magnet into a ionization chamber. The average beam current was monitored by the ionization chamber, and was kept between 1.3 pA and 1.8 pA during the measurement. The resonant transition radiation X rays generated from the foil stack were detected by an X-ray crystal spectrometer equipped with a LiF(200) and a Ge(111) crystal and having an energy resolution of about 3.3% at 8.1 keV of the Cu-K X ray. The background originating from Bremsstrahlung was evaluated by inserting an aluminum shutter absorbing X rays. The foil stack was mounted on a target folder in a target chamber with a given angle. The target folder was a goniometer itself and was used to set the tilting angle minutely. The titanium filters of 8-

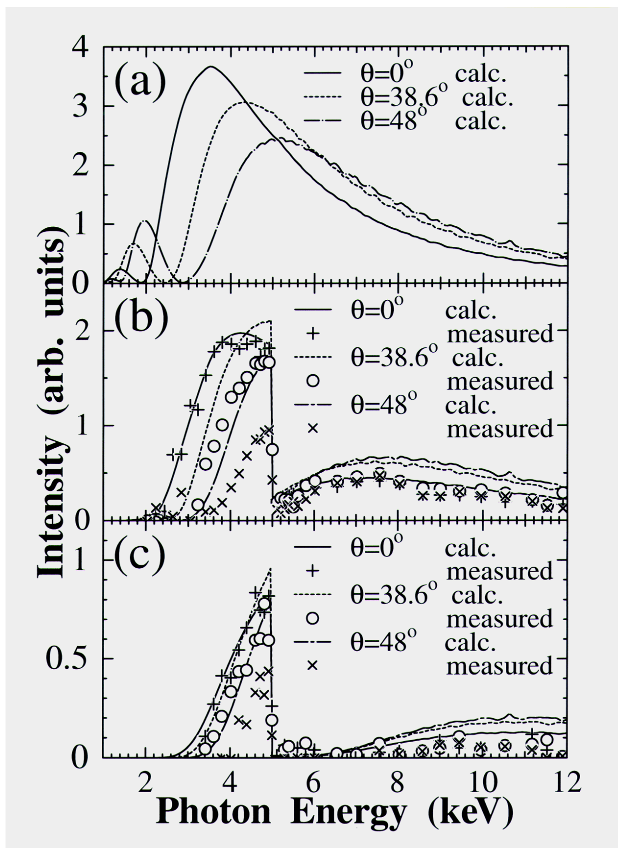

Fig. 1: The calculated and measured transition radiation spectra from the 1-GeV electron beam incident on the eight-foil stack of 7.5-μm thick Kapton tilted at θ=0°, 38.6°, 48°; (a) without the titanium filter (the calculated results only), (b) with the 8-μm titanium filter, (c) with the 28-μm titanium filter.

and 28-μm thickness as a part of separated-function type radiator were alternatively placed between the radiator and the crystal spectrometer.

4 RESULTS AND DISCUSSION

The calculated transition radiation spectra from the 1-GeV electron beam incident on the eight-foil stack of 7.5-μm thick Kapton tilted at θ=0°, 38.6°, 48° without the titanium filter are shown in Fig. 1(a). The calculated and measured results with the 8-μm and 28-μm titanium filters are shown respectively in Figs. 1(b) and 1(c). The calculated and measured transition radiation spectra from the 1-GeV electron beam incident on the 3-μm thick titanium eight-foil stack tilted at θ=0°, 31°, 45° are shown in Fig. 2. The lines and the marks respectively denote the calculated and the experimental results in Figs. 1 and 2. Fig. 1(a) shows that the peak energy shifted with tilting angle and were at tilting angles of θ=0°, 38.6°, 48° respectively, where all these peaks corresponded to the same integer $n=1$ in the Eq. (9). The tilting angles of θ=38.6° and θ=31° were optimized angles selected to give a maximum value of intensity at 4.95 keV respectively for the eight-foil stack of 7.5-μm thick Kapton and the 3-μm thick titanium eight-foil stack. Similarly the θ=48° and θ=45° were designed to give a band width half of that at θ=0°. As expected, the measured results in the Figs. 1(b)-(c), and 2 show qualitatively such features. It confirms that the new method of photoabsorption-edge transition radiation tuned by tilting a thin-foil stack has realized the reliable optimization for the photoabsorption-edge transition radiation to produce quasimonochromatic X Rays.

Figs. 1(b) and 2 showed similar profiles. This is why that the 8-μm titanium filter was selected in order that the eight-foil stack of 7.5-μm thick Kapton gives the same intensity near titaniam K-edge=4.96 keV as that of the 3-μm thick titanium eight-foil stack. So, the two type of radiators display almost the same performance if the adequate design of radiator is satisfied. One can get more narrower band width using a thicker filter as shown in Fig. 1(c), sacrificing the intensity. Furthermore, the separated-function type radiator can be used as a quasimonochromatic X Rays radiator for any photoabsorption-edge energies in the radiator spectra range. On the other hand, the benefit of the combined-function type radiator is that the photons in unnecessary energy region above an absorption edge are suppressed.

We have tested the method of photoabsorption-edge transition radiation tuned by tilting the thin-foil stacks for the two type of radiators: the separated-function type radiator composed of the eight-foil stack of 7.5-μm thick Kapton and the titanium filter, and the combined-function type radiator of the 3-μm thick titanium eight-foil stack. It is found that this method can make it easy to tune the spectra to the appreciable condition. Therefore, this method can be a useful technique to produce quasimonochromatic X Rays.

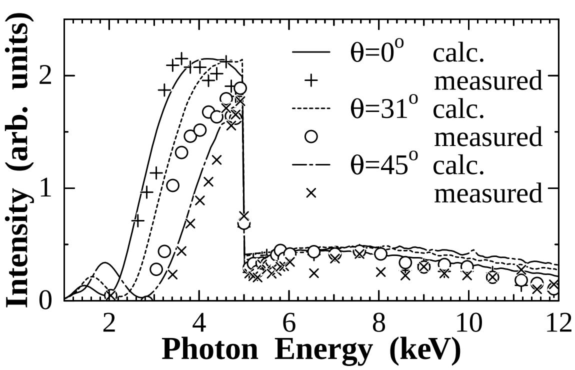

Fig. 2: Same as Fig. 1 for the 3-μm thick titanium eight-foil stack tilted at θ=0°, 31°, 45°.

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