Observation of bright monochromatic x rays generated by relativistic electrons passing through a multilayer mirror

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We have observed the emission of 15 keV x rays produced by 500 MeV electrons passing through a x-ray multilayer mirror. The mirror consisted of 300 pairs of W and B_4C layers with layer spacing of 12.36 Å and supported by a 100 μm Si substrate. The x rays were emitted at the Bragg angle $\theta_\gamma = 33.15$ mrad with respect to the mirror surface and at the angle $\theta_D = 66.3$ mrad with respect to the electron-beam direction. The spatial distribution and the spectral angular dependence of the x rays were measured and shown to be larger than the parametric x rays emitted from the Si substrate. The value of the differential photon efficiency was estimated to be about 0.22 photons/electron/str.

There is growing interest in the generation of x rays by relativistic electrons in periodic structures and crystals. A number of novel sources such as transition,[1] channeling,[2] parametric[3] radiation and combinations thereof[4,5] have been studied and considered as candidates for possible applications. However, the efficiency of these sources must be increased for them to be practical.[6]

Based on the concept of diffraction of virtual photons and the fact that multilayer mirrors are good reflectors of x rays, we suspected that multilayers would also be efficient radiators. Such mirrors, also termed multilayer nanostructures or striated media, consist of a large number of alternating nanolayers of different materials.[7] The possible generation of x rays from such structures may be complex and involve a number of photon generating processes such as transition radiation (TR), resonance transition radiation (RTR), and parametric x-ray radiation (PXR).[8,9] Theoretical analyses by others have looked into the possibility of Bragg reflected RTR from multilayers.[10–12] The radiation process should be similar to PXR, diffracted transition radiation (DTR),[5] and Bragg reflected RTR, in that the emission is Bragg scattered or reflected off the multilayer. However, our analysis of the most general case has shown that multiple and interactive combinations should be considered. For example, the interference of PXR and TR is possible[8,9] and could change the angular density of the radiation generated in the mirror. This is similar to the case of classic PXR and DTR in a multicrystal radiator.[13] For our experiment at the high energy of 500 MeV, TR reflected by the mirror is the most efficient radiation process for producing a photon flux with high angular density.[8,9] To distinguish this radiation from the other processes, we have named it ''reflected transition x-ray radiation'' (RfTR), even though other processes are probably present.

A comparison with similar processes in crystals is useful for determining the frequency spectrum. In ordinary PXR, if electrons pass through a crystal at the Bragg angle with respect to the crystal's lattice planes, then real photons are emitted due to diffraction of virtual photons of the relativistic electron's screened Coulomb field. Similarly, if electrons pass through the mirror at the Bragg angle with respect to the nanolayers, then real photons will be emitted due to the reflection of virtual photons of the relativistic electron's vacuum eigenfield by the mirror. Thus, analogously, the spectral peaks of the x rays emitted from the mirror could be described by the following expression obtained for the nth-order PXR peaks[14]

$$E_{\gamma\mathrm{PXR}} = \frac{2\pi n\hbar c \sin\theta_o}{d(1-\cos\theta_D + 1/2\gamma^2)}, \tag{1}$$

where d is the spacing of a periodic structure, θ_o is crystal orientation angle relative to the incident electron beam, θ_D is a detector disposition angle, and γ is the relativistic factor of the electrons.

The angular size, full width half maximum (FWHM), of the radiation from a multilayer reflecting virtual photons should be, according to the analogy with PXR

$$\Delta\theta_\gamma \approx 5\theta_{\mathrm{ph}}, \tag{2}$$

where $\theta_{\mathrm{ph}} = [\gamma^{-2} + (\hbar\omega_p/E_\gamma)^2]^{1/2}$ and ω_p is the plasma frequency of medium. However, if a periodic medium is very thin, the FWHM of the radiation distribution will be

$$\Delta\theta_\gamma \approx 5/\gamma. \tag{3}$$

In both cases the angular distributions have peak emission at θ_{ph} or $\approx 1/\gamma$ with respect to the radiation cone axis.

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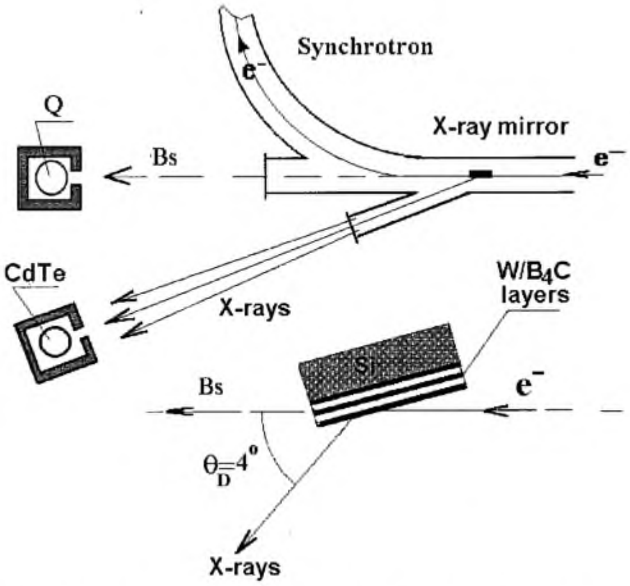

FIG. 1. The experimental apparatus: (Q) γ quantometer, (D) detector, (T) radiator mounted on the goniometer head.

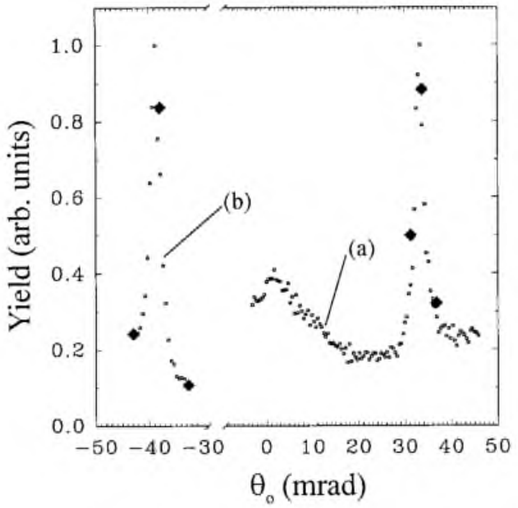

FIG. 2. The angular dependence (rocking curve) of the yield of 9.24–20.17 keV photons [curve (a)] and the 92–268 keV photons [curve (b)] generated by a 500 MeV electron beam in a 300 W/B_4C bilayers with spacing of 12.36 Å created on the surface of a flat Si crystal with thickness of 100 μm.

The scheme of the experimental setup is shown in Fig. 1. The Tomsk synchrotron has a 20 ms pulse duration with a 4 Hz repetition rate, resulting in a duty factor as high as 10%. Divergence of the electron beam was about 0.2 mrad. The radiator was mounted on a goniometer in Bragg geometry. The angle between the electron beam axis and the x-ray mirror surface was about 2° in the symmetric position.

The multilayer used for preparing the radiator was created on a 380 μm Si plate by OSMIC Inc. as a periodic structure of W and B_4C layers with spacing $d = 12.36$ Å and the $N = 300$ layer pairs. The W and B_4C layers are approximately 5 and 7 Å, respectively. The radiator prepared from this multilayer had a substrate thickness of about 100 μm and vertical and horizontal dimensions of $10 \times 29\ \mathrm{mm}^2$.

The x rays generated in the mirror or in its Si substrate were detected by a CdTe semiconductor detector, placed at an angle $\theta_D = 66.3$ mrad with respect to the electron beam direction, and at a distance of 443 cm from the radiator. The photon path in the air was about 243 cm. The detector's aperture was 4 mm^2 and its energy resolution at the ^{63}Zn line (8.1 keV) was about 10%. The bremsstrahlung γ-rays generated in the mirror were detected with a gamma-quantometer and used to determine the current through the mirror and, ultimately, its efficiency.

Both the spectra of the x-rays generated in the mirror (RfTR) and in the Si crystalline substrate (PXR) were measured for comparison. We also measured the angular dependence (rocking curves) of the photon yields in spectral peaks for both cases by means of rotating the radiator around its vertical axis. These yields were normalized using the bremsstrahlung yields measured with a gamma-quantometer. The resulting angular dependence of the normalized yield is shown in Fig. 2, curve (a). To obtain this curve, the corresponding spectra were measured for various angles of the radiator in the horizontal plane, and the photon yields in the spectral region of 9.24–20.17 keV were determined. The curve shows a bright peak at the radiator angle of 33.2 mrad that corresponds to the symmetrical position of the x-ray mirror with respect to the electron beam and detector.

The spectra of radiation generated in the multilayer structure, obtained at the mirror angles $\theta_o = 31.1$, 33.2, and 36.1 mrad [marked by diamonds on curve (a) in Fig. 2] are presented in Fig. 3. The maximum peak, curve (a) in Fig. 3, is the spectrum at the symmetrical position, $\theta_o = \theta_D/2 = 33.15$ mrad. This bright peak at 15 keV is in agreement with Eq. (1). Moreover, curves (b) and (c) in Fig. 3 show that the position of the peak moves to the harder part of the radiation spectrum also in accordance with Eq. (1).

To get an estimate of the intensity of the peak, we compared it to PXR generated in the Si substrate. Thus we measured the angular dependence of the yield of 92–268 keV x rays in order to see any effects from PXR from the Si substrate. The peak in the rocking curve was found at the angle $\theta_o = -39$ mrad, curve (b) in Fig. 2. To determine the nature

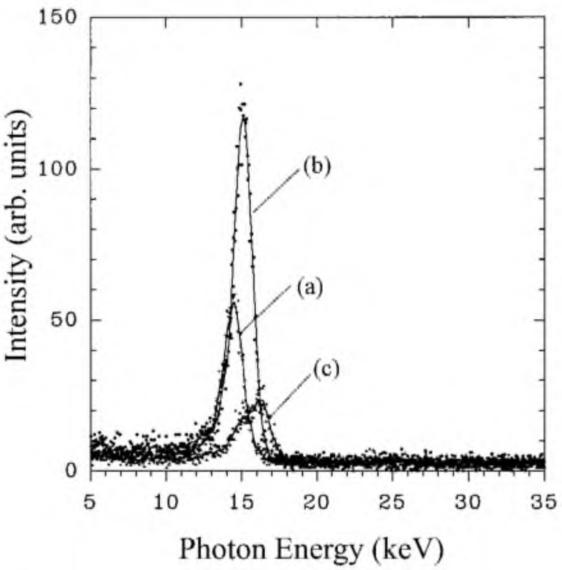

FIG. 3. The measured spectra of the x rays emitted from the multilayer mirror at angles $\theta_o = 31.1$, 33.2 and 36.1 mrad [curves (a), (b) and (c), respectively] marked by diamonds on curve (a) in Fig. 2.

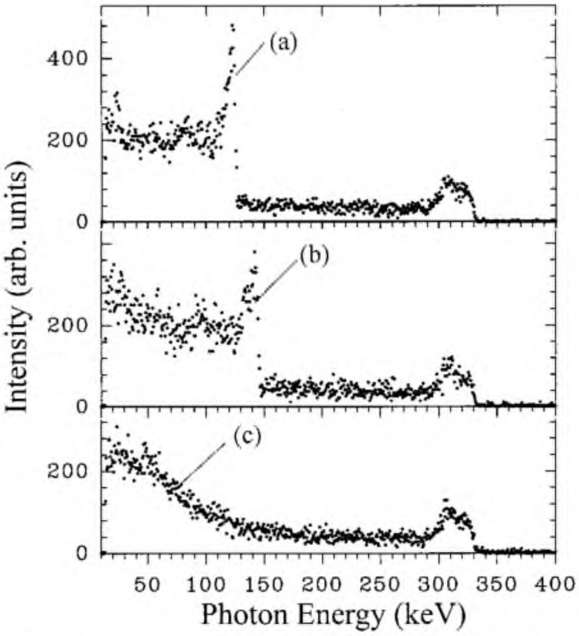

FIG. 4. The measured spectra of PXR emitted from the 100 μm Si substrate of the multilayer mirror at the radiator angles: $\theta_o = -42.7$, -38, and -32.5 mrad [curves (a), (b), (c), respectively] and marked by the diamonds on curve (b), Fig. 2.

of this effect, we measured the spectra of radiation at the peak angle. Figure 4 shows the spectra of PXR measured at the mirror angles θ_o marked by the diamonds on curve (b) in Fig. 2. The spectrum [curve (a) in Fig. 4] at the radiator angle of 42.7 mrad shows a peak at 122 keV.

Curve (b) in Fig. 4 shows that the PXR peak shifts to the hard part of spectrum in accordance with the expression, Eq. (1). At radiator angle $\theta_o = -38$ mrad, the spectrum obtained shows the peak at the photon energy of 142 keV. At the radiator angle of -32.5 mrad, the PXR peak disappears as shown in curve (c), Fig. 4. From these data it follows that the angle between the atomic planes and the substrate surface is about 71.3 mrad. Using Eq. (1) and the observed spectra, one can determine that radiation observed is generated by the (113) planes of the Si substrate.

In Fig. 5 we present a comparison of the RfTR spectra from the multilayer, curve (a), with the PXR spectra generated in the 100 μm Si substrate, curve (b). Note that the path of electrons in the multilayer is about 300 times less than that in the substrate. To get a further estimate of the mirror's x-ray efficiency, we measured the value of the electron-beam current using an inductor placed in the electron-beam path. Knowing this data, we were able to estimate the average number of electrons passing through the mirror. From this estimate, the CdTe detector's angular acceptance, and the pulse-height count rate, we were able to estimate the value of the differential photon efficiency of the mirror to be about 0.22 photons/electron/str. This rough estimate is in agreement with our calculation based on a simple model of virtual-photon reflection.

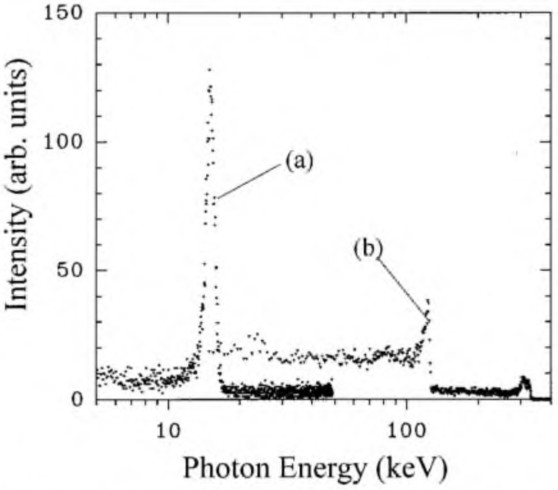

FIG. 5. Spectra of RfTR and PXR [curves (a) and (b), respectively].

A FWHM of angular distribution of radiation generated in the multilayer is two times greater than that of the rocking-curve measurement; therefore, one can see that the measured FWHM value is in agreement with the value given by Eq. (3), demonstrating that the producing medium (the mirror) is very thin. For the PXR photons emitted in the bulk of a crystal, the FWHM is given by Eq. (2), which peaks at $\theta_\gamma = \theta_{\mathrm{ph}}$. For example, if we were to generate the 15 keV photons by PXR in a Si crystal, the value of θ_{ph} would be about 2.2 times greater than the value of θ_γ for RfTR. For harder x rays these values are closer to each other, as was observed for the 120 keV PXR from the Si(113) planes.

In conclusion, the experiment has shown that, even with a multilayer of total thickness of 0.37 μm, the radiation is brighter than the PXR generated in the 100 μm Si with an efficiency of 0.22 photons/electron str at 15 keV. Using a radiator containing a larger number of layered pairs, it may be possible to make an x-ray source intense enough for medical imaging.

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