Using Mosaic Crystals for the Generation of Intense X-ray Beams

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Abstract—The parametric X-ray (PXR) yield due to 500-MeV electrons in a 2-mm-thick diamond crystal with a mosaicity angle of ~0.2 mrad has been studied. It is shown that the mosaic crystal structure leads to a significant (about fourfold) increase in the PXR yield doe to the contribution of diffracted bremsstrahlung radiation. Advantages of using mosaic crystals for the generation of intense X-ray beams are discussed.

Parametric X-ray (PXR) production by high-energy charged particles penetrating through a crystal has been extensively studied in the past two decades (see, e.g., [1, 2] and references therein). The interest in this radiation is mostly related to the search for new high-intensity, tunable X-ray sources capable of offering an alternative to storage rings. Now it is commonly accepted that the existing PXR theory in the kinematic approximation describes the experimental results for perfect crystals and electron energies in the range from several MeV to several GeV with an error not exceeding 10–15% [3]. The results of measurements performed for almost all conventional crystals with perfect structures (diamond, silicon, germanium, quartz, lithium fluoride, etc., see [1, 2, 4] and references therein) showed that, with neglect of photon absorption in the target, the PXR yield weakly depends on a particular crystal and is insufficient for practical purposes.

The X-ray reflection ability of mosaic crystals is significantly greater than that of the perfect crystals. Theoretical estimations [5, 6] showed that the mosaicity of crystals virtually did not affect the integral PXR intensity, but could increase the yield due to the contribution of diffracted photons [6]. The results of measurements performed for the best known and most widely used mosaic crystal—pyrolytic graphite (PG)—confirmed that this ensures a greater X-ray yield compared to that from perfect diamond and LiF crystals [4, 7]. The contribution of diffracted photons to the measured yield is several times the PXR yield proper [7] and well obeys the theory of X-ray diffraction in mosaic crystals [8].

The large mosaicity of PG crystals (with a typical mosaicity angle σ_m ~ 3–4 mrad) accounts for a large width of the emission spectrum [4], which is not always acceptable in practical applications. Another disadvantage of PG is large interplanar spacing, which leads to smaller Bragg angles (for a fixed photon energy) and, hence, greater bremsstrahlung background levels at the irradiated object.

The same advantages to perfect crystals must be inherent in other mosaic crystals, which can simultaneously be free of the disadvantages inherent in PG. As is known [8], the X-ray reflection ability of diamond is well described by the dynamic theory of diffraction only for the crystals of small dimensions. As the crystal size increases, deviations from theoretical predictions tend to grow, which is related to the mutual misorientation of blocks, from which large crystals of natural diamond are composed. Thus, large diamonds are close to mosaic crystals with respect to their reflection properties.

We have studied the characteristics of PXR generation in a $\langle 110 \rangle$-oriented natural diamond crystal with dimensions 6 × 8 × 2 mm and a mosaicity angle of ~0.2 mrad, bombarded with 500-MeV electrons on a Tomsk Synchrotron. The measurements were performed for a $(2\bar{2}0)$ reflection in the Laue geometry for a detector angle of $\Theta_D = 4°$ and the X-ray photon energy in the first order of reflection ω ~ 145 keV. The emission was detected by a NaI(Tl) detector with a diameter of 63 mm and a height of 63 mm placed behind a circular collimator with a collimation angle of $\vartheta_c = 1.9$ mrad. The experimental geometry, electron beam parameters, characteristics of equipment, and the procedures of crystal orientation and measurements have been described elsewhere [7].

Figure 1 shows the experimental plot of the X-ray photon yield in the first order of reflection versus misorientation angle of the $(1\bar{1}0)$ plane relative to the

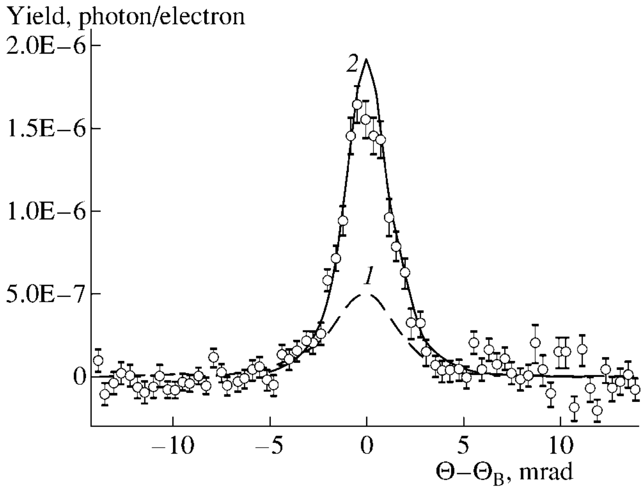

Fig. 1. Orientational dependence of the X-ray photon yield from a diamond crystal (E_0 = 500 MeV; Θ_D = 4°): (○) experimental data; (*1*) calculation using the kinematic PXR theory; (*2*) calculation for DBR + PXR in a mosaic crystal.

direction of Bragg reflection. For the convenience of comparison, we subtracted a noncoherent background (the level of which did not exceed 30% of the peak height). For comparison, Fig. 1 (curve *1*) also shows the results of calculations performed within the framework of the kinematic PXR theory [1, 7]. The emission spectrum measured at the diffraction maximum showed that the experimental PXR yields (photon/electron), Y_1^{exp} = $(1.63 \pm 0.008) \times 10^{-6}$, $Y_2^{\mathrm{exp}} = (8.2 \pm 0.09) \times 10^{-8}$, Y_3^{exp} = $(1.14 \pm 0.23) \times 10^{-8}$, in all orders of reflection significantly exceed the results of calculations according to the PXR theory: $Y_1^{\mathrm{calc}} = 5.13 \times 10^{-7}$, $Y_2^{\mathrm{calc}} = 2.6 \times 10^{-8}$, $Y_3^{\mathrm{calc}} = 3.2 \times 10^{-9}$.

The experimental data are corrected for the instrumental function and the absorption of photons on the path from the crystal to the detector. The statistical errors do not include the error in determining the number of electrons transmitted through the crystal (~10–15%).

The main factors determining the shape of the orientation dependence (OD) of the X-ray yield are the angle of radiation collimation and the multiple scattering of electrons in the crystal. For this reason, the experimental and calculated OD curves have rather similar shapes, but significantly different amplitudes. The difference between the widths (full width at half-maximum, FWHM) of the experimental and calculated OD curves ($\Delta\Theta_{\mathrm{calc}}$ = 3.97 mrad, $\Delta\Theta_{\mathrm{exp}}$ = 2.9 ± 0.2 mrad) exceeds the experimental error (OD step, ≈0.4 mrad). This is evidence for a contribution from radiation that has a narrower angular distribution compared to that of PXR. Under our experimental conditions, this can be a diffracted bremsstrahlung radiation (DBR) [1].

The results of calculations taking into account the mosaicity using a method proposed in [7], assuming a homogeneous distribution of the mosaic blocks (with dimensions below the primary extinction length) in depth of the crystal showed that the observed difference can be attributed to the crystal mosaicity. The resulting dependence for calculated PXR + DBR with allowance for the mosaicity effect on both components (curve *2*) is close to the experimental curve. The values of the X-ray yield, $Y_1^{\mathrm{calc}} = 1.94 \times 10^{-6}$, $Y_2^{\mathrm{calc}} = 1.18 \times 10^{-7}$, and $Y_3^{\mathrm{calc}} = 1.46 \times 10^{-8}$, as well as the widths of the OD curve ($\Delta\Theta_{\mathrm{calc}}$ = 2.67 mrad) satisfactorily agree with the results of measurements. The difference that still exists between the calculation and experiment is probably related to the error of normalization, the assumption about homogeneous mosaicity distribution in depth of the crystal, and the adopted estimate of σ_{m}. The X-ray yield and the OD width vary depending on the σ_{m} value and the ratio of mosaic and perfect crystal components.

The agreement between the results of measurements for mosaic diamond crystals and PG [7] and the results of model calculations allows us to compare perfect and mosaic crystals from the standpoint of their use in practical applications. In recent years, many research centers have been investigating the creation of X-ray sources (including those using PXR) for medical applications such as angiography using iodine and barium photoabsorption edge (ω ≈ 33.1 and 37.5 keV, respectively). In this context, let us compare the characteristics of radiation sources for such photon energies based on perfect and mosaic diamond crystals. In comparison to the other crystals, these provide for a narrower spectral line and a lower bremsstrahlung background at the irradiated object, which allows an increase in the crystal thickness (advantages of mosaic crystals increase with the thickness [7]). Taking into account that a small value of σ_{m} leads to a loss of the diffracted beam intensity, let us use a 1-mm-thick crystal with σ_{m} = 0.4 mrad in the Laue geometry with a Bragg angle of Θ_B = 8.37° = $\Theta_D/2$ (ω ≈ 33.6 keV) under the experimental conditions described in [9]. The emission is generated by a beam of electrons with an energy of 45 MeV and an angular divergence of ϑ_e = 1.5 mrad. A circular detector with a diameter of 5 mm is situated at a distance of 300 cm from the crystal.

Figure 2 shows the spectra calculated in the first order of reflection for perfect and mosaic diamond crystals. As can be seen, the presence of mosaicity led to a considerable increase in the X-ray yield as compared to that for the perfect crystal: $Y_{\mathrm{m}}^{\mathrm{calc}} = 1.18 \times 10^{-8}$

as opposed to $Y_p^{calc} = 2.87 \times 10^{-9}$ for the mosaic and perfect diamond respectively. As can be seen, the X-ray emission spectrum in both cases is determined by the contributions from both mechanisms. In the perfect crystal, PXR dominates and the DBR contribution does not exceed 30–40%. It should be noted that the average DBR and PXR energies differ by 0.2 keV. This fact and the importance of the DBR contribution to the X-ray emission spectrum of perfect crystals are confirmed by the experimental data obtained in [4], where the spectrum of PXR from a LiF crystal was measured upon diffraction in a different crystal at $\Theta_B = 15°$. The spectrum of diffracted radiation exhibited a shift (analogous to that in Fig. 2) relative to the PXR spectrum by 0.12 keV toward higher energies. An increase in the Bragg angle led to a decrease in this shift, which implies that DBR rather than PXR is diffracted [4].

On the contrary, the DBR component dominates for the mosaic crystal, while the PXR contribution does not exceed 20%. As can be seen from Fig. 2, the mosaicity also leads to the broadening of both DBR and PXR. However, the width of the resulting spectrum for the mosaic crystal ($\Delta\omega_m \approx 0.32$ keV) is even somewhat smaller than that for the perfect crystal ($\Delta\omega_p \approx 0.34$ keV) (cf. curves *3* and *6*), which implies that the presence of mosaicity provided for a fourfold increase in the X-ray yield without deterioration of the radiation beam characteristics.

A comparison of the mosaic crystals of diamond, silicon, and germanium with the same thickness t (in radiation length units) and mosaicity ($\sigma_m = 1$ mrad) showed that the maximum angular density of radiation is obtained for germanium ($t = 0.1$ mm): $Y_{Ge} \approx 8 \times 10^{-3}$ photon/sr. The values for silicon ($t = 0.52$ mm) and diamond ($t = 0.54$ mm) are lower: $Y_{Si} \approx 6 \times 10^{-3}$ photon/sr and $Y_d \approx 2 \times 10^{-3}$ photon/sr. These data show that a radiation flux density of 10^7 photon/mm^2 at a distance of 3 m from a germanium crystal necessary for medical purposes [10] can be obtained using a quite small average current of 1 mA.

Further increase in the crystal thickness (except for diamond) will lead to an increase in the bremsstrahlung background at the irradiated object. A smaller value of the lattice parameter in diamond allows the thickness of this crystal to be increased to $t = 1.27$ mm (for the same level of bremsstrahlung background at the irradiated object). The related increase in the DBR intensity and the reflection ability leads to the corresponding growth in the angular density of radiation up to $Y_d \approx 7.5 \times 10^{-3}$ photon/sr. With increasing electron energy and decreasing X-ray photon energy, the crystals of diamond and silicon become more acceptable, since they do not pose limitations (in contrast to germanium) on the crystal thickness in view of the photon absorption.

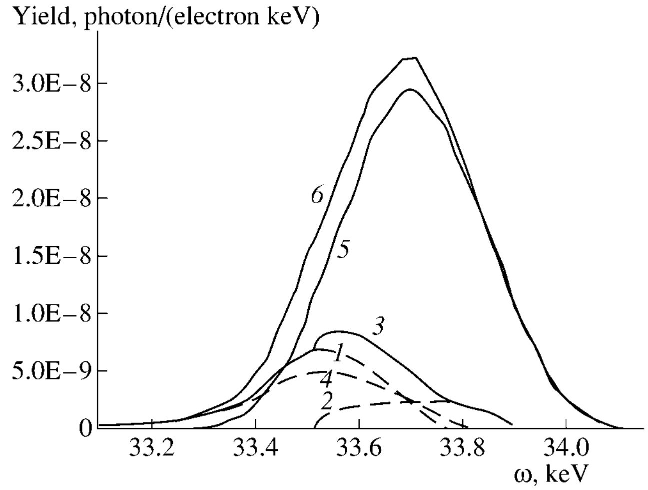

Fig. 2. X-ray emission spectra for perfect and mosaic diamond crystals ($t = 1$ mm; $\Theta_B = 8.37°$; $E_0 = 45$ MeV): (*1–3*) PXR, DBR, and PXR + DBR, respectively, in perfect crystal; (*4–6*) PXR, DBR, and PXR + DBR, respectively, in mosaic crystal.

Hayakawa et al. [11] suggested to use a system of two perfect crystals for the generation of PXR in one (thin) crystal, followed by diffraction in another (thick) crystal. A similar scheme was used by Sones et al. [4]. As was demonstrated above, the second crystal more effectively reflected DBR (rather then PRX) photons emitted from the first crystal; the main advantage of this scheme is a narrow width of the spectrum, which leads to a low radiation intensity. If the spectral width is not a critical parameter and the level of $\Delta\omega/\omega \sim 1\%$ is quite acceptable, the use of two mosaic crystals with $\sigma_m \sim 0.2$–0.4 mrad will allow the intensity to be increased by several orders of magnitude. The thickness of the first crystal (diamond or silicon) can be taken close to optimum ($t = 1$–3 mm), since the two-crystal scheme makes possible the protection from the direct radiation beam generated in the first crystal, while the bremsstrahlung radiation incident on the second crystal will be diffracted to provide a linear spectrum at the irradiated object.

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