Overview of experimental investigations of X-ray radiation generated by 500-800 MeV electrons in multicrystal and multilayer radiators carried out at Tomsk synchrotron

V V Kaplin, S I Kuznetsov, S R Uglov, V N Zabaev
National Research Tomsk Polytechnic University, P.O. Box 25, Lenin Ave. 2-a, 634050 Tomsk, Russia
E-mail: vnz@tpu.ru

Abstract. The results of studies on X-ray radiation generated by ultrarelativistic electrons in multicrystal and multilayer radiators are shortly described. The experiments with mentioned radiators have shown that these types of new radiators could generate more intensive and narrower directed beams of x-rays than that generated in single crystals.

1. Introduction
Studying of X-ray generation with fast electrons in single crystals and periodic stacks of amorphous foils performed at the Tomsk synchrotron led to the investigations of artificial radiators such as periodic multicrystal stacks and multilayer X-ray mirrors. The investigation with the multicrystal radiator has been carried out in the collaboration with University of Tokyo and Hiroshima University \[1, 2\]. The multicrystal stacks consisted of 3, 10 and 100 thin crystals were created by Toshiba Corporation. A triple-crystal radiator was used at the Tomsk synchrotron for the detailed measurement of the characteristics of X-ray radiation generated by 800 MeV electrons in each crystal. The crystals were slightly disoriented relatively each other in the radiator. In principle, it is a disadvantage of any multicrystal radiator which is composed from a set of thin single crystals. But, such disorientation of the crystals of this radiator allowed to observe the separate angular distributions of X-rays emitted from each crystal. Later, in order to exclude the mutual disorientation of the crystals, the multicrystal structure was created on the surface of crystalline plate in Tomsk \[3, 4\].

Experiments with multicrystals led to the investigations with the multilayer radiators at the Tomsk synchrotron about 15 years ago in the collaboration with Adelphi Technology Inc (USA) \[5\]. Multilayer X-ray mirrors are widely used in X-ray optics for producing the X-ray beams with required parameters under Bragg reflection of real photons. X-rays are emitted in a narrow cone in the Bragg direction due to the diffraction of pseudophotons of the fast electron field in layers of X-ray mirror.

This paper presents a short review of the results of above mentioned investigations which have shown that both types of new radiators excited by relativistic electrons can generate more intensive and narrow beams of X-rays than that generated in single crystal with equivalent thickness.

2. Experimental installation
A general scheme of installation used for the experiments with new sources of radiation is represented in figure 1. A beam of accelerated electrons of the Tomsk synchrotron with the energy of 500 or 800
MeV was directed to the internal radiator of one or another type (figure 1a). Pulse duration of the electron beam was 10 ms, pulse-repetition frequency was 5 Hz.

![Diagram](image)

**Figure 1.** a – Scheme of installation: Q – quantometer, D – detector; b - Geometry of X-rays generation in triple-crystal target (TCT); I, II, III – X-rays emission from the 1st, 2nd and 3rd crystals, respectively; c - Multicrystal radiator on crystal surface; d - Multilayer radiator (mirror).

Bremsstrahlung (Bs) generated in a target was recorded by a Gauss-quantometer (Q). Readings of the quantometer were used to normalize the measurement results. Coherent radiation emitted from the radiators at an angle $\theta_D$ came out through a 200 μm beryllium window of a synchrotron chamber and got into a detector (D).

3. **Triple-crystal radiator**

Triple-crystal radiator consisted of three Si crystals with thickness of 16 microns separated by gaps of 147 microns [6]. Crystal wafers were cut for obtaining crystallographic planes (220) oriented perpendicular to their surfaces. Outside left and right crystals were disoriented relative to the middle crystal on 4.3 and 5.7 mrad in different directions. With a narrow electron beam transmitted through such radiator at some angle to planes (220) in Laue geometry, one can obtain three well-separated reflections of X-ray radiation in Bragg directions (figure 1b). Difference in angles is a doubled angle value of mutual disorientations of the crystals.

The first reflex of radiation (I) emitted from the first crystal is formed by parametric x-ray radiation (PXR) and the diffraction of transition radiation (TR). Transition radiation is generated on the input surface of this crystal. TR contribution would be small in comparison with PXR in case of first reflex. The second reflex of radiation (II) is formed by PXR from the second crystal and diffraction of resonance transition radiation (RTR) generated by the surfaces of the first crystal. The third reflex (III), respectively, is formed by PXR from the third crystal and diffracted RTR (DRTR) generated on the surfaces of the previous two crystals. Having measured characteristics of reflexes, it is possible to judge about the formation of coherent X-ray radiation of a relativistic electron passing through a complex crystal structure.

Single Si crystal with equivalent thickness (48 micron) was used to measure “pure” PXR without the contribution of DRTR. Both radiators were fixed on a goniometric head. Moving the goniometer head vertically allows placing the radiators on the electron beam by turns.

In this experiment a 2 mm NaJ(Tl) spectrometer was used. Energy resolution was about 35% for $^{57}$Co (line 6.4 keV) and 16% for $^{241}$Am (line 59.6 keV). Detection threshold was set at 7 keV. The
input beryllium window of the detector has a diameter of 40 mm and a thickness of 200 microns. In front of the detector there was a vertical slit collimator with width of 2 mm. The distance between the target and detector was 458 cm, including 243 cm of air.

There are spectral peaks of the first and second orders in the experimental spectrum of PXR obtained on the equivalent target in Bragg orientation. The ratio of yields of PXR photons into the energy intervals (29 – 44) and (10 – 29) keV corresponding to the second and first spectral peaks is 0.13. Orientation dependencies (OD) of yields of PXR photons in these energy intervals were also measured for the equivalent target. Figure 2 represents the experimental OD (points) of the yield of (10 – 29) keV photons of PXR + DRTR emitted from a triple-crystal radiator. OD has three maxima (I, II and III) appearing with successive passing of crystals through Bragg positions of orientation. Three dashed curves show partial PXR contributions formed in each crystal for the total OD. The shape of these curves was obtained by the processing of OD of radiation, measured on the equivalent target. Figure 2 shows that the peaks of OD of DRTR from second and third crystals are considerably narrower than OD of PXR yield. Widths of these peaks are 1.25 and 4.75 mrad, respectively. Thus, DRTR is a more narrowly directed X-ray source than PXR. Besides, it follows from the figure 2 that DRTR yield in the maximum of OD increases with the increasing of crystal number, so that the angular density of DRTR from the third crystal exceeds the density of PXR by approximately 1.7 times.

![Figure 2](image1.png)

**Figure 2.** Measured OD (points) of yield of X-rays from triple-crystal radiator; dashed curves – ODs of PXR from three crystals; continuous curve – a sum of these ODs; left and right peaks with points – ODs of DRTR from second and third crystals.

![Figure 3](image2.png)

**Figure 3.** Calculated ODs of PXR from three crystals (dashed curves), ODs of DRTR from the second and third crystals (two peaks below) and ODs of PXR + DRTR (solid curve) with its interference.

Figure 3 shows the comparison of the calculated ODs of PXR and DRTR yields with the experimental one. The calculations were performed in the kinematic approximation. In the calculations the theoretical models for PXR [7] and DRTR [8] were used taking into account the experimental conditions. The dashed curves show the partial yields of PXR from three crystals, two thin continuous curves show ODs of DRTR yields from the second and third crystals. Comparing the data presented in figures 2 and 3, it can be concluded that the calculated ratio of DRTR and PXR yields does not correspond to the ratio, obtained in the experiment, and their sum does not describe a form of experimental orientation dependence. Abnormally high radiation yield in the experimental maxima II and III can be connected with interference of DRTR and PXR. Considering of interference was carried out in model approach when the square of sum of PXR and DRTR amplitudes for a whole cone was
calculated. And after that the detector geometry was considered. The dependence, shown in figure 3 by a solid curve, is in better agreement with the experiment, though the difference is still large, especially for peak III. Probably, additional study is required to understand the observed effect.

The experiment showed that the making of radiator as a number of crystals leads to an effective increase of the X-ray yield in comparison with the case of a monocrystal with a thickness which is equivalent of the total thickness of the assembly. At the same time the angular distribution of radiation is much narrower than distribution of PXR from a monocrystal due to DRTR.

4. Multicrystal radiator on crystal surface

Further, at the Tomsk synchrotron a multicrystal radiator has been investigated. This radiator has no disadvantages which are inherent to radiators assembled from thin crystals [3, 4]. It was created on the surface of GaAs wafer by the method of microlithography with plasma chemical etching, and represents a flat, periodic, multistrip structure. The scheme of the radiator cross-section is shown in figure 1c. The 10 μm crystalline elements of the radiator are accurately oriented with respect to each other. This radiator is more compact than multicrystal stack and is easier to manufacture. Electrons cross the system of crystalline strips at an angle $\theta_s$ to its atomic planes, and PXR is emitted at the Bragg angle to them. X-ray photons of RTR generated on the surfaces of strips are emitted near the direction of electron beam and then diffract in the Bragg direction. Such radiator is equivalent to a compound multicrystal radiator with a number of crystals $N = H / L \cot \theta_s$, where $H$ is height of a strip, $L$ is period of structure, $\theta_s$ is the angle between surface of GaAs wafer and electron beam. The asymmetric geometry of X-ray generation was used in order to reach a larger value of $N$. The angle between the crystallographic planes (100) and surface of GaAs wafer was $\theta_a = 2.7^\circ$. The angle $\theta_s$ was equal to $\theta_s/2 - \theta_a = 6.8^\circ$ when the angle of radiation detection was $\theta_D = 19^\circ$. Accordingly, the effective number of crystals $N = 20$ with the parameters of the radiator created for this experiment $H = 100 \, \mu m$, $L = 43 \, \mu m$. Multicrystal radiator was fixed to a goniometer head and was able to move vertically. It was possible to change the position of the electron beam on the radiator and to obtain radiation from a multistrip structure or from a smooth part of the crystal. The photons emitted from multicrystal radiator were detected by a CdTe detector positioned at an angle $\theta_D = 19^\circ$ to the beam of 500 MeV electrons and at a distance of 245 cm from the radiator. A radiation spectrum from a continuous part of a crystal wafer and a radiation spectrum from a structure were measured at a symmetric orientation of radiator $\theta_0 = \theta_s/2 = 9.5^\circ$. These spectra have bright peaks on the photon energy 27 keV and weak peaks of characteristic radiation. The yield of 27 keV photons from a multicrystal structure is much higher than that from a continuous crystal. The increase of radiation yield is created by diffracted RTR (DRTR). RTR is generated on the side surfaces of crystalline strips and then it is diffracted on the crystallographic planes (100) of a set of next strips of multicrystal structure of the radiator.

![Figure 4](image_url)

**Figure 4.** Curve 1 (points) – the measured orientation dependence of radiation yield from multicrystal periodic structure of a radiator; Curve 2 (circles) – contribution of PXR; Curve 3 – contribution of DRTR.
Figure 4 shows the results of measurements of OD of the yield of radiation generated by 500 MeV electrons in the multicrystal radiator. Energy range of detected photons was (25 – 28) keV. Curve 1 represents the measured orientation dependence of the radiation yield generated in a periodic structure. The radiator was oriented at certain angles to the beam of electrons to obtain this dependence and the photons yield was determined in this photon energy range. Curve 2 shows OD of PXR generated in a periodic multicrystal structure. It was obtained from OD of PXR measured from continuous part of radiator, reduced by coefficient \( k = 2.38 \). Coefficient \( k \) is a relation of a path length in a continuous part of radiator to a path length in a substance of periodic structure. Orientation dependence of radiation from a multicrystal structure is approximately 6 times higher and 3 times narrower than the orientation dependence of the "pure" PXR. This means that the cone of radiation from multicrystal periodic structure is also 3 times narrower than that of PXR from a monocrystal part of the radiator. Curve 3 was obtained by subtracting the data for PXR from the data for radiation from the structure. It represents the orientation dependence of DRTR and the possible contribution of the interference of PXR and DRTR. It can be seen that for a given multicrystal structure and conditions the mechanism of DRTR is about 5 times more effective than that of PXR.

5. X-ray mirror as a radiator of X-ray radiation

Another type of new source of coherent X-ray radiation has been studied at the Tomsk synchrotron [5] using the multilayer interference structures, known as X-ray mirrors. The generation of both PXR and DRTR is also possible when relativistic electrons are passing through such a radiator. Two X-ray mirrors (product of OSMIC Inc.) consisted of 300 W/B4C bilayers with the repetition period \( d = 1.236 \) and 1.8 nm were used as multilayer radiators. For example, in the case of the first X-ray mirror, vertical and horizontal dimensions of the multilayer radiator were about 10 and 29 mm, respectively. Thickness of its Si substrate was about 100 microns. The CdTe detector was placed at an angle \( \theta_D = 66.3 \) mrad to the direction of 500 MeV electron beam and at a distance of 443 cm from the radiator.

In figure 5 the measured OD of radiation yield in the ranges of photons energy of (9.24 – 20.17) and (92 – 268) keV. One can see in figure 5 the effect of coherent radiation generation in the X-ray mirror and possible PXR from its Si substrate. Both dependences demonstrate the bright peaks at the radiator orientation angles of 33.2 and –39 mrad. The first orientation angle corresponds to...
symmetrical position of multilayer structure of X-ray mirror relative to the direction of electron beam and the direction from the X-ray mirror to a detector. The second orientation angle corresponds to the symmetrical position of (113) Si substrate.

Radiation spectra measured at the X-ray mirror with d = 1.236 nm and at its orientation angle of 31.1; 33.2 and 36.1 mrad are depicted in figure 6. The spectral peak changes its position and amplitude when tilting radiator and it is maximal at the symmetric orientation. The dependence of PXR spectrum on the orientation of atomic planes of Si substrate was also measured. PXR spectral peak from the substrate also changed its position and amplitude when tilting radiator and reached its maximum at photons energy of 142 keV. It must be taken into account, that the (113) crystallographic planes of Si substrate, which are responsible for generation of this radiation, are disoriented relative to the layers of X-ray mirror at an angle of 71.3 mrad. Taking into account that electrons path in multilayer structure is approximately 300 times smaller than that in its substrate, it can be concluded that the efficiency of multilayer radiator is considerably higher, than the efficiency of crystalline radiator.

6. Conclusion
The experiments carried out at the Tomsk synchrotron have shown that new radiators based on multicrystal and multilayer structures can be effective X-rays generators when they are excited by 500–800 MeV electrons. Later, when the operation of the Tomsk synchrotron had been discontinued, the study of multicrystal radiators didn’t get continuation, while the experiments with the X-ray mirrors were continued using betatron B–35 [9]. The experiments were carried out to investigate characteristics of radiation generated by the 15–33 MeV electrons in the X-ray multilayer mirrors which were installed inside the betatron chamber. The generation of X-rays by fast electrons in more complex multilayer structure as a triple-layer X-ray waveguide [10] was recently investigated at the betatron [11]. This structure consists of two multilayer substructures separated by waveguide channel. Currently, in the X-ray optics such structures are referred to as non-uniform X-photonic crystals or as Bragg waveguides. The use of these structures as new narrow-focus X-ray source provides the combination of the two effects: parametric X-ray radiation in the channel walls (multilayer structures) and the waveguide effect for X-rays generated in the wall structures and then penetrating the radiator in the waveguide modes similar to the Borrmann effect with low absorption. Recently, the investigation of extreme ultraviolet radiation generated by 5.7 MeV electrons in multilayer radiators was also begun at the Tomsk microtron M–5 [12].

References
[1] Andreyashkin M Yu, Zabaev V N, Yoshida K et al 1995 Russian Pisma v JETP 62 770
[2] Andreyashkin M Yu, Kaplin V V, Potylitsin A P et al 1996 Nucl. Instr. Meth. B 119 108
[3] Kaplin V V, Uglov S R, Zabaev V N et al 2000 Nucl. Instrum. Meth. A 448 66
[4] Kaplin V V, Kuznetsov S I, Timchenko N A et al 2001 Nucl. Instrum. Meth. B 173 238
[5] Kaplin V V, Uglov S R, Zabaev V N et al 2000 Appl. Phys. Lett. 76 3647
[6] Andreyashkin M Yu, Zabaev V N, Kaplin V V et al 1997 Russian Pisma v JETP 65 594
[7] Feranchuk I D and Ivashin A V 1985 J. Physique 46 1981
[8] Garibiyun G M, Yan-Shi X-Ray Transition Radiation 1983 (Yerevan: Publishing House of Academy of Science of Armenia)
[9] Kaplin V V, Sohoreva V V, Uglov S R et al 2009 Nucl. Instr. Meth. Phys. Res. B 267 777
[10] Kaplin V V, Sohoreva V V, Uglov S R et al 2011 Nucl. Instr. Meth. Phys. Res. B 269 1518
[11] Kaplin V V, Uglov S R 2012 Proceedings of the 7th International Forum on Strategic Technology (IFOST2012) IEEE cat. # CRP12786-PRT, 2 422
[12] Uglov S R, Zabaev V N, Kaplin V V et al 2012 Journal of Physics: Conf. Series 357 012012