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Measurement of Distribution Anisotropy of X-Ray Yield from a Pyroelectric Crystal Surface

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Abstract—A technique for measuring the spatial distribution of X-rays generated by a pyroelectric source is developed and tested. Anisotropy in the spatial distribution of X-rays from the surface perpendicular to the pyroelectric axis of the lithium niobate crystal depending on the piezoelectric crystal axis orientation was detected. The result obtained shows the necessity of considering the effect of piezoelectric properties of pyroelectric crystals on X-ray generation processes.

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Introduction. The pyroelectric effect in crystals under vacuum conditions results in a high electrostatic potential generation, which can reach 350 kV [1]. This effect can be used to generate ionizing radiations, i.e., beams of accelerated electrons, ions [2], fast neutrons [3], and X-rays [4], including those for developing commercial X-ray sources [5].

Among materials exhibiting the pyroelectric effect are pyroelectric ceramics [6], lithium niobate ($LiNbO_3$) and lithium tantalate ($LiTaO_3$) crystals featuring the maximum efficiency. In addition to pyroelectric properties, these crystals have piezoelectric properties; therewith, spatial anisotropy of properties of these crystals is controlled by three axes, i.e., the piezoelectric X-axis, the mechanical Y-axis also having piezoelectric properties, and the optical Z-axis which is simultaneously a pyroelectric axis.

The polarity of the charge induced on the Z-surface (perpendicular to the Z-axis) is dictated by the Z-axis direction and the sign of the temperature gradient along the Z-axis. Some aspects of physical effects accompanying ionizing radiation generation due to the pyroelectric effect are rather actively discussed [7–10], including the study of the charge distribution on the pyroelectric crystal Z-surface [7]. The main approach to the study of the charge distribution is measurement of optical radiation caused by the interaction of electrons accelerated due to pyroelectric effect with luminophore coating a screen placed near the crystal [8] or the crystal Z-surface itself [9].

In this paper, we present a new approach to the study of properties of pyroelectric sources, which, unlike [7–9], allows the measurement of the charge formation dynamics and dynamics of changes in the maximum surface potential.

Experimental. The schematic of the experimental setup is shown in Fig. 1. The pyroelectric crystal of lithium niobate (2) shaped as a parallelepiped with edges parallel to X-, Y-, and Z-axes (edge lengths are 8, 10.5, and 10 mm, respectively), was fixed by a conductive epoxy glue on a duralumin radiator (1). The pyroelectric Z-axis is perpendicular to the radiator surface plane with an accuracy of 0.5°. The Peltier element (8) was used to change the crystal temperature by heating or cooling the radiator; the crystal temperature was maintained with an accuracy of 0.1 °C. In what follows, the pyroelectric

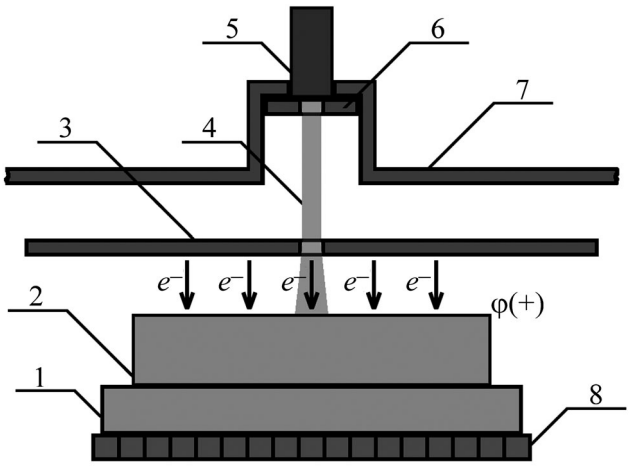

Fig. 1. Experimental scheme (see text for details).

crystal, radiator, and Peltier element are considered as a single assembly, i.e., the pyroelectric high-voltage generator (PHVG). The PHVG was placed into a vacuum chamber with a residual pressure maintained at a level of 0.75–1.5 mTorr. The PHVG position in the vacuum chamber was controlled by manipulators in two orthogonal directions along piezoelectric X- and Y-axes with an accuracy of ± 0.5 mm. As a target collimator (3), a 50×50-mm lead plate 1 mm thick with a 1.5-mm-diameter aperture at the center was used. The plate was grounded and installed at a distance of 9 mm from the crystal Z-surface. The X-ray spectrum (4) was measured using a drift semiconductor XR-100 SDD detector-spectrometer (5) fixed on a vacuum chamber flange (7). An additional lead collimator (6) with an aperture of 2.5 mm, placed at a distance of 60 mm from the target-collimator (3), provides a surveyed surface area of ~ 2 mm^2.

Thus, the setup allows measurement of the X-ray spectrum resulting from the interaction of accelerated electrons with a positively charged crystal Z-surface in the mode of Z-surface scanning by the collimated detector by moving the PHVG along X- and Y-axes.

The X-ray spectra were measured at various PHVG positions with respect to the target-collimator center from the initial position corresponding to the surface area closest to the crystal edge, observed by the detector. All spectra were measured at the same crystal heating rate in the temperature range of 21–46 ± 1 °C (the heating duration is 180 s). For each PHVG position, the crystal was heated three times, and the X-ray spectrum was measured separately during each heating process. After each heating cycle, air was let into the setup, and the crystal temperature return to the initial one was waited to avoid errors associated with the residual charge existing on the crystal surface between cycles. Then the PHVG was moved along the scanned axis and the entire measurement procedure was repeated. X-ray spectra were scanned along the X- and Y-axes with a step of 0.75 mm.

Results and discussion. The results of measurements of the number of photons with energies above 1 keV during scanning along the X- and Y-axes and the typical measured spectra are shown in Fig. 2. In these spectra, noteworthy are intense L and K lines of characteristic X-rays (CXR) of niobium (2.16 and 16.62 keV) on the smooth bremsstrahlung background, which does not exceed 5% of the CXR peak amplitude. This feature allows discrimination of radiation generated only on the crystal surface.

The results demonstrate different shapes of the spatial distribution of the X-ray yield for various axes with a pronounced distribution maximum near the Z-surface center. In this case, the width of the spatial distribution for the X-axis is significantly larger in comparison with the distribution for the Y-axis. When using the crystal asymmetric in X- and Y-axes, it might be expected that the distribution width along the crystal long side will be larger. However, we can see in Fig. 2 that the width of the distribution of the yield along the short face (X-axis) is ~ 3.5 mm which is significantly wider than the distribution along the long face, ~ 1.5 mm. This unexpected result indicates the sharply asymmetric, probably elliptical distribution of the yield on the crystal surface. In this case, the ellipse major axis is directed along the crystal short side.

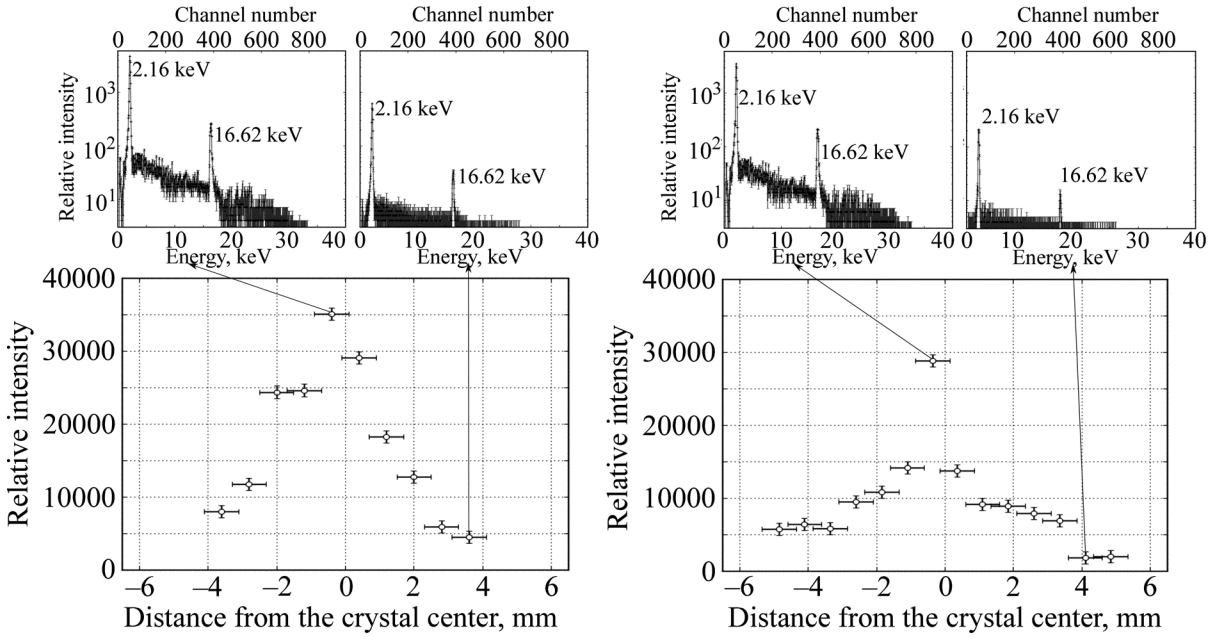

Fig. 2. Spatial distribution of the X-ray yield from the $LiNbO_3$ pyroelectric crystal surface charged positively along the X-axis (left) and Y-axis (right). Top panels show the spectra measured for the space regions indicated by arrows.

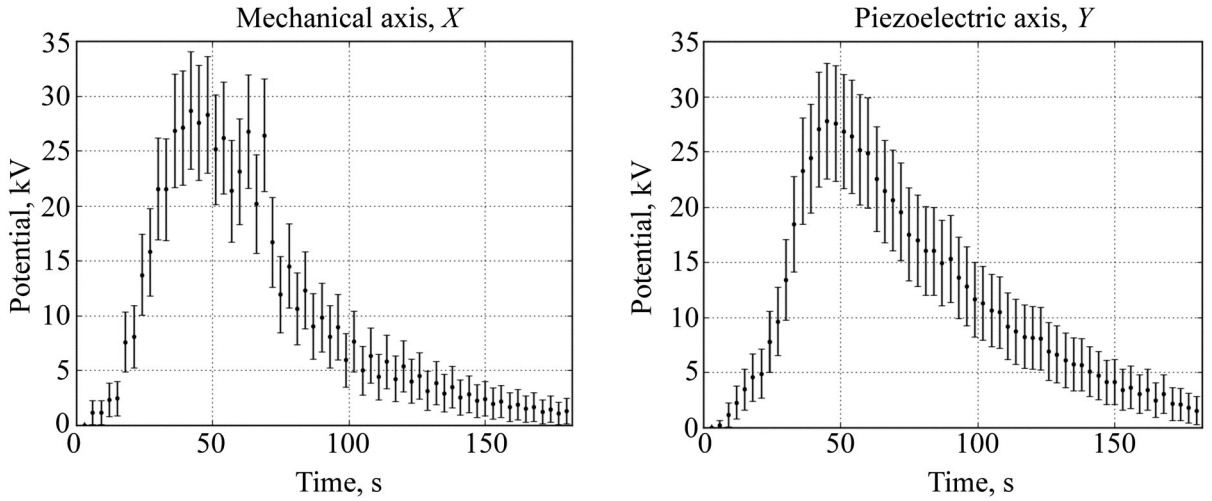

Fig. 3. Dependences of the maximum formed potential on the measurement time, averaged along the X- and Y-axes.

The used method makes it possible to measure the maximum potential of scanned areas of the Z-surface by the maximum photon energy. An additional feature of the method is the possibility of observing the dynamics of changes in the potential at the scanned region in time, which is achieved by sequential measurements of spectra within the thermal cycle. Figure 3 shows the dependences of the averaged maximum potentials formed on the Z-surface along the X- and Y-axes on the measurement time. Measurements of the maximum potential during scanning the Z-surface along the X- and Y-axes showed deviations of these values within 10%.

Thus, the results obtained show the maximum X-ray yield near the crystal Z-surface center; the maximum potential on the Z-surface varies only slightly, and the time dependences of the potential formation are similar for various surface areas. The most interesting result of the study is the detected anisotropy of the distribution of radiation yields along the X- and Y-axes (Fig. 2). Since the crystal Z-surface is axisymmetric with respect to the pyroelectric Z-axis, the observed anisotropy is probably

explained by the piezoelectric effect manifestation, since the crystal piezoelectric properties along the Z-plane are anisotropic.

Based on the currently available experimental results on the study of the charge distribution on the positively charged Z-surface of pyroelectric crystals, noteworthy is the study [9] in which it was shown that the charge distribution density maximum is at the Z-surface center, and the distribution shape is close to round. This result is in partial agreement with the results of this study, shown in Fig. 2 (in [9], the formed potential anisotropy was not observed). It should also be noted that the possible effect of X- and Y-axes on the radiation yield was not discussed in [9], and the arrangement was not indicated.

The results of the study show the anomalous anisotropic distribution of the X-ray yield when the pyroelectric effect is manifested. The detected phenomenon is associated with the possible influence of the piezoelectric effect on the process of the pyroelectric potential generation, which can manifest itself during pyroelectric crystal heating or cooling due to thermal deformation of the crystal.

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