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Investigation of the Yield of X-Ray Radiation from Pyroelectric Sources with Cone-Shaped Targets

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Abstract—The results of experimental studies of the spectral composition and yield of X-ray radiation from pyroelectric sources with cone-shaped targets are presented. A distinct maximum of the yield as a function of the distance between the pyroelectric crystal and the target is found for a single-crystal pyroelectric source with a truncated cone target. It is demonstrated in the experiment involving a source with two pyroelectric crystals and a cone-shaped target that the X-ray parameters are virtually independent of the direction of temperature change in the crystals.

Keywords: pyroelectric accelerator, X-rays, cone-shaped target

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INTRODUCTION

Pyroelectric crystals can create an electric field with a strength of up to 100 kV/cm or more [1] upon their heating and cooling in vacuum. In these fields, electrons and ions can be accelerated to energies of 100 keV or more. The generation of X-rays by electrons accelerated in a pyroelectric accelerator was first observed in the experiment in [2]. In studies on the generation of X-ray radiation using a pyroelectric accelerator [3, 4], a pyroelectric crystal of rectangular or cylindrical shape is usually used, which is mounted opposite a flat thin target, and an X-ray detector is placed behind the target on the source axis. By heating or cooling the crystal, accelerated electrons excite X-ray emission in the target or in the crystal. X-rays, passing through the thin target, hit the detector. Soft X-ray radiation is absorbed in the target and does not reach the detector; a thin target is required for such a source. In addition, a two-crystal radiation source is also used [5], in which X-ray emission is excited by accelerated electrons on the crystal surface. Pyroelectric radiation sources were also proposed, which operate by means of laser illumination of the surface of a pyroelectric crystal with impurities rather than due to changes in the temperature of the crystal [6, 7]. In the present paper, we describe experiments with a thick cone-shaped target and a detector set at a right angle to the axis of the single-crystal and two-crystal sources. The use of a thick target in this geometry helps to avoid the application of a thin target and allows the observation of low-energy X-ray radiation.

SINGLE-CRYSTAL X-RAY SOURCE WITH A CONE-SHAPED TARGET

The X-ray yield was studied using a target in the shape of truncated cone, in a vacuum chamber at a residual gas pressure of approximately 1 mTorr. The experimental setup is schematically shown in Fig. 1.

We used a cylindrical pyroelectric crystal of $LiNbO_3$ 10 mm diameter and 10 mm height. The target was a truncated cone made of brass, 11 mm in diameter (the diameter of the truncated part was 5 mm) and an apex angle of 60°. The crystal was heated and cooled using a Peltier element, to which the crystal was fastened via conductive epoxy adhesive. Between the crystal and the Peltier element, a grounded aluminum foil was placed using epoxy adhesive; the foil covered the entire area of the Peltier element. A rigid duralmin arm which served as a heater was attached for the removal and supply of heat from the opposite side of the Peltier element. The distance between the crystal and the target was varied by moving the target with vacuum compatible manipulators. The temperature was monitored using a DS18B20 digital sensor, fixed to the bottom of the crystal on the Peltier element.

The X-ray spectra were measured using an Amptek CdTe XR-100T semiconductor X-ray detector with a crystal surface area of 25 mm^2 and a thickness of the beryllium input window of 100 μm. The detector was placed at 90° to the source axis, as shown in Fig. 1 by the dotted line, on the two opposite sides at the same distance from the source axis. The spectra were measured upon both heating and cooling of the pyroelec-

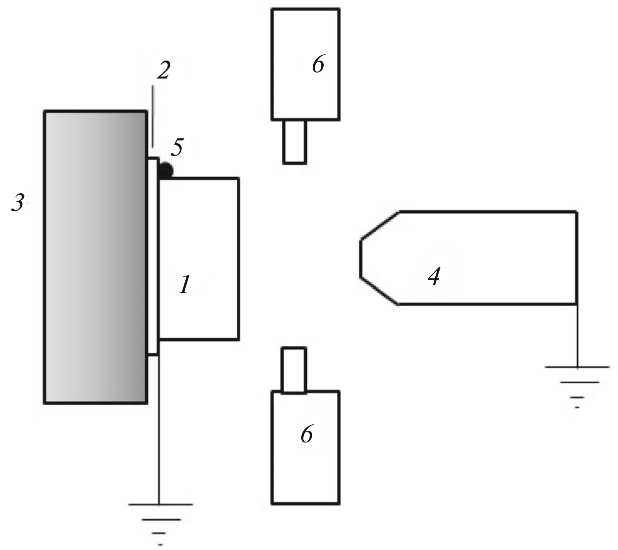

Fig. 1. Schematic diagram of the experiment with a single-crystal source: (*1*) pyroelectric crystal, (*2*) Peltier element, (*3*) cooler, (*4*) target, (*5*) digital thermometer, and (*6*) X-ray detector.

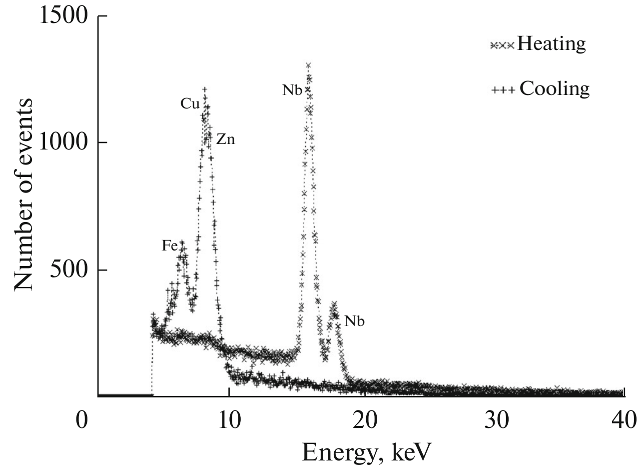

Fig. 2. X-ray spectra measured upon heating and cooling of the pyroelectric crystal; the distance between the crystal and the target is 8 mm.

tric crystal; the temperature of the crystal was varied by 25°C near room temperature. The duration of the heating–cooling cycle was approximately 300 s. Typical spectra measured upon heating and cooling of the crystal are shown in Fig. 2.

Upon heating the crystal, a positive charge is produced at its surface facing the target. Electrons are accelerated in the direction to the crystal and produce bremsstrahlung radiation and the characteristic radiation of atoms within the crystal. Peaks of the characteristic radiation of niobium atoms contained in the crystal are observed in the spectrum against a background of bremsstrahlung radiation. Upon cooling the crystal, a negative charge is produced at its surface facing the target. The electrons are accelerated in the direction from the crystal to the target and produce bremsstrahlung radiation and the characteristic radiation of atoms within the target. Peaks of the characteristic radiation of copper and zinc atoms of the target are observed in the spectrum against bremsstrahlung radiation; because of the close location of the peaks of copper (8.04 keV) and zinc (8.64 keV), the corresponding lines merged into a single peak.

The dependence of the X-ray yield on the distance between the crystal and the target was measured with the target moved by means of a vacuum actuator. The results of measurements of the total number of photons recorded by the spectrometer for the heating–cooling cycle is shown in Fig. 3.

A pronounced maximum at a distance between the target and crystal of 8 mm is observed in the obtained dependences. We can assume that this maximum is related to the phenomenon of self-focusing of the beam of electrons emitted by the crystal, which is described in [3]. In this study, such self-focusing may occur upon heating of the crystal, when electrons are accelerated from the crystal to the target. To reveal the possibility of this process, we recorded the emission spectra upon separate heating and cooling of the crystal. The results of measurements of the total number of photons in the peaks of the characteristic radiation are presented in the form of diagrams (Fig. 4).

It is found that the maximum yield at a distance of 8 mm is observed when the electrons are accelerated both toward the target and toward the crystal. With increasing distance, emission from the target prevails, and as the distance decreases, emission from the crystal becomes predominant. Perhaps this behavior of the

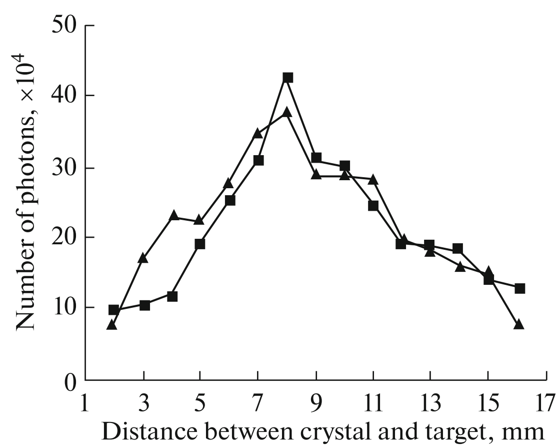

Fig. 3. Dependence of the total number of photons recorded by the spectrometer for one heating–cooling cycle on the distance between the crystal and the target. The measurements were carried out for two symmetrical positions of the X-ray detector.

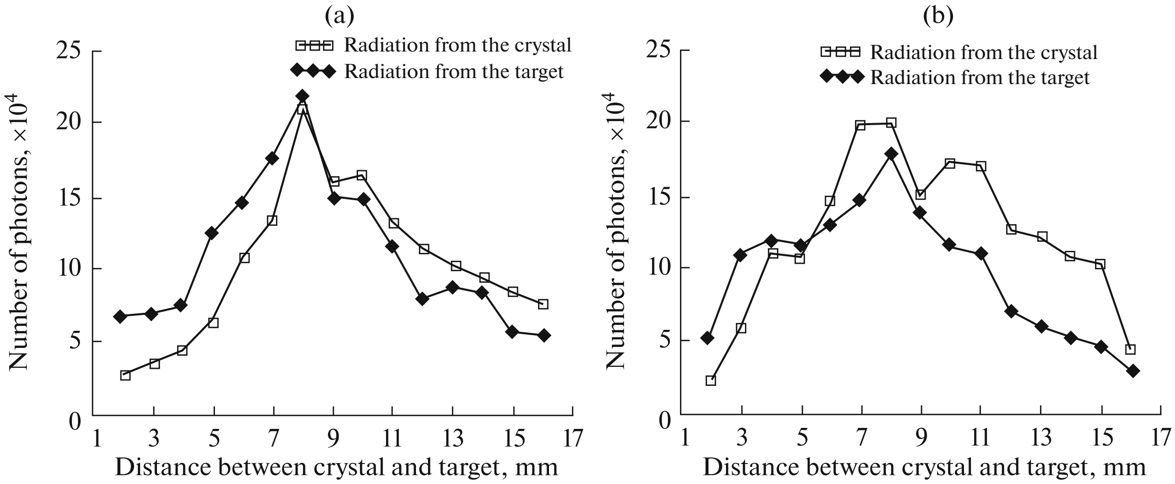

Fig. 4. Dependence of the yield of characteristic X-ray radiation upon heating and cooling of the crystal on the distance between the crystal and the target. (a, b) Demonstrate the results of measurements in two symmetrical positions of the X-ray detector.

X-ray yield is due to the dependence of the number of accelerated electrons on the distance between the crystal and the target.

TWO-CRYSTAL X-RAY SOURCE WITH A CONE-SHAPED TARGET

A two-crystal pattern of a pyroelectric accelerator was proposed in [5]. In such an accelerator, two pyroelectric crystals are mounted opposite one another so that the temperature variations produce charges of opposite sign on their surfaces. Therefore, the potential difference between the crystals is doubled as compared with the single-crystal version, and electrons are accelerated between the crystals up to twofold energy values. X-ray radiation is caused by the movement of electrons in the crystals.

In order to ascertain the possibility of applying a two-crystal pattern for obtaining the characteristic X-ray radiation from a removable thick target, we measured the X-ray spectra in a two-crystal system with a cone-shaped target mounted between the crystals. The experiment was carried out in a vacuum chamber with a residual gas pressure in the range from 1 to 5 mTorr. The experimental setup is schematically shown in Fig. 5. Pyroelectric LiNbO3 crystals with a diameter of 11 mm and a height of 10 mm were fixed at a distance of 22 mm from each other so that their polarization vectors were collinear. A cone-shaped brass target with a diameter of 12 mm and an apex angle of 60° was set between the crystals.

The X-ray spectra were measured using an Amptek CdTe XR-100T detector upon a variation in temperature of the crystals by 15°C near room temperature. Crystal heating and cooling was carried out for 200 s (100 s for each of the processes). The resulting X-ray spectra are shown in Fig. 6. It is seen that the spectrum for crystal heating is only slightly different from the spectrum obtained upon cooling. The characteristic radiation of niobium occurs when accelerated electrons interact with a lithium-niobate crystal, and the characteristic radiation of copper is due to the movement of electrons in the brass target. The presence of iron and chromium lines is due to the vacuum-chamber walls. The presence of a spectral peak of characteristic radiation of the target shows that a target set between crystals can be applied in the elemental analysis of samples.

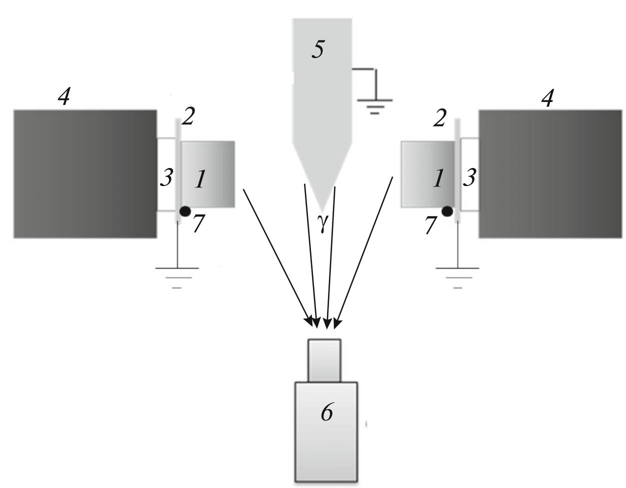

Fig. 5. Schematic diagram of the experimental setup: (*1*) pyroelectric crystals, (*2*) grounded conductive pad, (*3*) Peltier element, (*4*) heater, (*5*) target, (*6*) X-ray detector, and (*7*) digital thermometer.

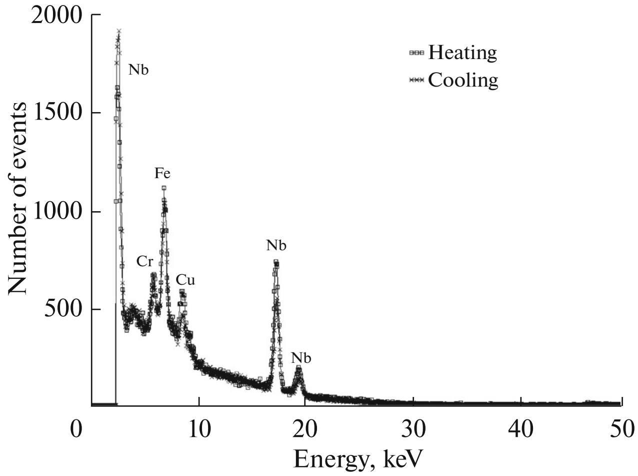

Fig. 6. X-ray spectra of the two-crystal source with a conical brass target, measured upon heating and cooling of the crystals.

CONCLUSIONS

The paper presents the results of measurements of the X-ray spectra of single-crystal and two-crystal pyroelectric X-ray sources with cone-shaped targets. A maximum is observed in the dependence of the yield of the single-crystal X-ray source on the distance between the crystal and the target. It demonstrated experimentally the possibility of observing X-ray radiation from the side of the target that is irradiated with electrons accelerated in the pyroelectric accelerator is demonstrated experimentally. In the future, it will give the opportunity to observe X-ray radiation from thin surface layers of a substance on a cone-shaped target.

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