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Study of the Dependence of the End-Point Bremsstrahlung Energy on the Residual Gas Pressure during the Pyroelectric Source Operation in Vacuum

O. O. Ivashchuk[a,c,*], A. V. Shchagin[a,b], A. S. Kubankin[a,c], I. A. Kishchin[a,c], A. N. Oleinik[a,d], Yu. V. Grigor'ev[e], M. E. Giltz[a], V. I. Alekseev[c], and A. N. Eliseev[c]

[a] *Laboratory of Radiation Physics, Belgorod National Research University, Belgorod, 308015 Russia*

[b] *Institute of Plasma Electronics and New Methods of Acceleration, Kharkov Institute of Physics and Technology, Kharkov, 61108 Ukraine*

[c] *Department of High Energy Physics, Lebedev Physical Institute, Moscow, 119991 Russia*

[d] *John Adams Institute at Royal Holloway, University of London, Egham, Surrey, TW20 0EX United Kingdom*

[e] *Shubnikov Institute of Crystallography, Federal Scientific Research Center "Crystallography and Photonics," Russian Academy of Sciences, Moscow, 119333 Russia*

* *e-mail: ooleg.ivashuk@gmail.com, ivashchuk@bsu.edu.ru*

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Abstract—Experimental results on the determination of the end-point bremsstrahlung energy during the operation of a pyroelectric source in vacuum at different residual gas pressures are presented. The range of operating residual gas pressures is determined.

Keywords: pyroelectric deflector, X-ray radiation

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The operation scheme of the pyroelectric X-ray source based on two crystals was proposed for the first time by Danon [1]. In the first test experiments, Danon detected X-ray generation with a record at that time end-point energy of ~160 keV. The X-ray penetrability directly depends on its end-point energy. Previously [2], the dependence of the maximum X-ray energy generated during pyroelectric source operation in vacuum on the preliminary change in the pyroelectric source temperature was studied. In [3], the dependence of the X-ray yield on the temperature variation rate of a single crystal source is demonstrated. The effect of the target shape in the pyroelectric source based on a single crystal on X-ray spectral characteristics was studied as well [4]. This paper is devoted to the determination of the optimum pressure at which the end-point energy of X-ray bremsstrahlung generated during the two-crystal pyroelectric source operation reaches a maximum. It should be noted that the two-crystal X-ray source being the object of the present study, in contrast to the single crystal source [2], can generate X-rays with doubled end-point energy. Figure 1 shows the schematic diagram of the experimental setup for studying the dependence of the end-point energy of X-ray bremsstrahlung on the residual gas pressure in vacuum during the pyroelectric source operation.

The study was carried out in vacuum chamber *5* 45 L in volume. The residual gas pressure in the vacuum chamber is measured using an ERSTVAK MTM9D-KF25 vacuum gauge; the pressure is changed by a vacuum shut off valve of the MDC E-GV-4000M manual drive. Two pyroelectric lithium niobate $LiNbO_3$ crystals *1* 10 × 20 × 20 mm in size are placed in the vacuum chamber *5* at a distance of 11 mm coaxially and in parallel to each other. The spontaneous polarization vectors of each pyroelectric are codirected. Crystals *1* are heated by silicon semiconductor diodes MUR 1660 *3* through heat conductors *2* made of aluminum 40 mm in diameter and 5 mm thick. The operating supply current of semiconductor silicon diodes *3* was 4.5 A. The temperature of pyroelectric crystals *1* was measured by a K-type thermocouple *4* mounted on the rear surface of heat conductors *2*. Each assembly consisting of a pyroelectric crystal *1*, heat conductor *2*, semiconductor silicon diode *3*, and K-type thermocouple *4* was fixed on opposite walls of the vacuum chamber *5*. Pyroelectric crystals *1* were cooled naturally due to heat dissipation on heat conductors *2* and vacuum chamber walls *5*. The X-ray spectrum was measured using an Amptek CdTe 123 semiconductor X-ray detector *6* with a working area of 25 mm^2 and a thickness

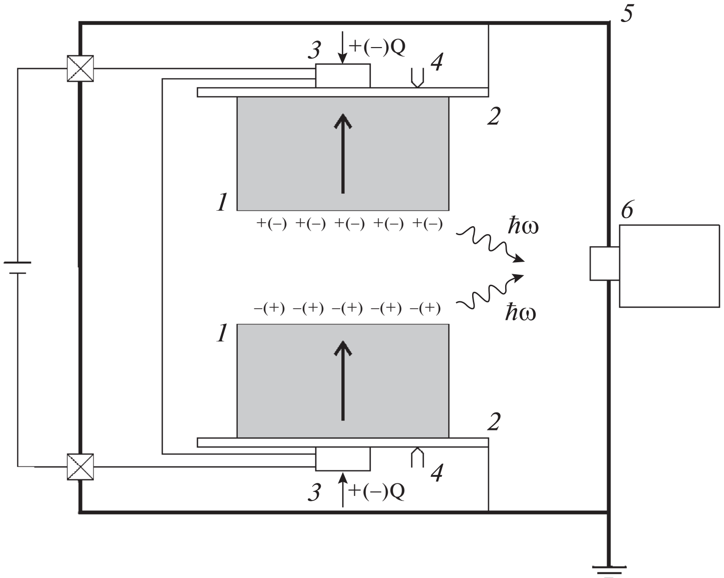

Fig. 1. Schematic of the experimental setup: (*1*) pyroelectric lithium niobate crystals, (*2*) heat conductor, (*3*) silicon semiconductor diodes, (*4*) K-type thermocouple, (*5*) vacuum chamber, and (*6*) X-ray detector.

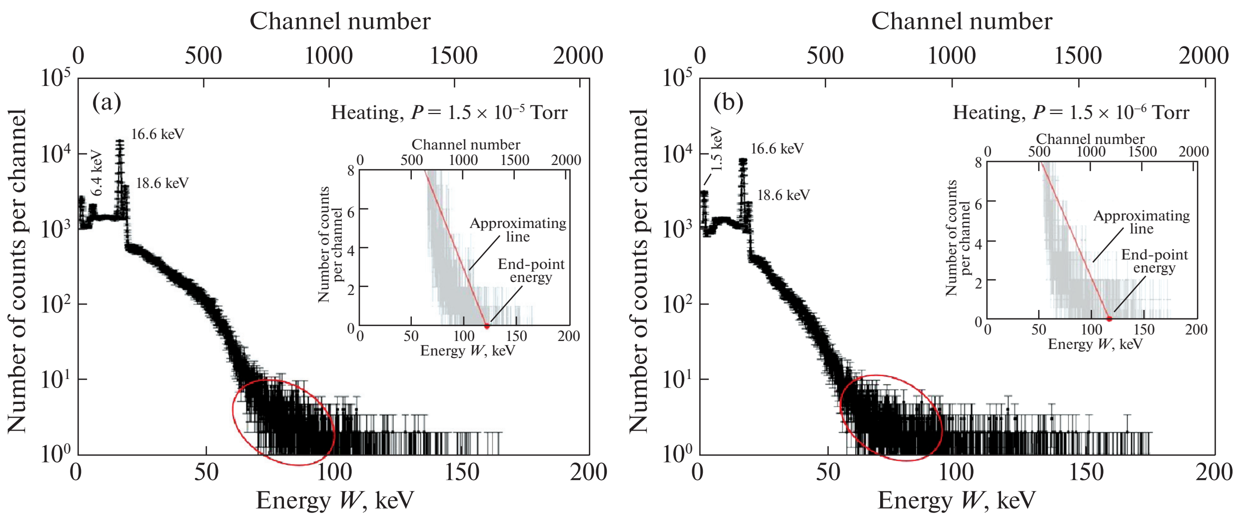

Fig. 2. X-ray spectra generated during (a) heating and (b) cooling of the pyroelectric source at a residual gas pressure of 1.5×10^{-5} Torr.

of 1 mm. The entrance window of the semiconductor detector is made of beryllium foil 100 μm thick. The detector was calibrated by spectral lines of the ^{57}Co cobalt isotope. The detector energy resolution was 530 eV in the ^{57}Co spectral peak with an energy of 14.4 keV; its peaking time was 1 μs.

A system of vacuum pumps provides a pressure of 1.3×10^{-6} Torr in the vacuum chamber *5*. Pyroelectric crystals *1* are heated from room temperature of 25°C to 71.2°C within 900 seconds. At a supply current of 4.5 A in each semiconductor diode *3*, the average temperature variation rate of crystals *1* is 3°C/min. Then, pyroelectric crystals *1* are naturally cooled due to thermal dissipation on heat conductors *2* and vacuum chamber walls *5* until the temperature of each crystal reached 30°C. The crystal natural cooling in vacuum to room temperature requires significant time-consuming (several hours); therefore, the temperature variation range of pyroelectric crystals was changed by 30—71.2°C.

The X-ray spectra were measured during heating and cooling of the pyroelectric deflector at various residual gas pressures from 1.3×10^{-6} to 1.5×10^{-2} Torr with a step depending on the manual adjustment accuracy of the vacuum shut off valve. Figure 2a shows the X-ray spectrum measured during heating of

Table 1. Results of processing of obtained experimental data

P, Torr	W, keV (heating)	W, keV (cooling)
1.3×10^{-6}	91.2	115.9
4.3×10^{-6}	101.5	109.9
7.5×10^{-6}	80.3	105.9
$1.5 \cdot \times 10^{-5}$	120.2	117.1
6.3×10^{-5}	102.6	76.3
4×10^{-4}	87.2	67
3×10^{-3}	85	83.4
8×10^{-3}	68.7	90.9
1.5×10^{-2}	65.3	89.1

the pyroelectric deflector in vacuum at a residual gas pressure of 1.5×10^{-5} Torr. The X-ray spectrum measured upon cooling of the pyroelectric source at a residual gas pressure of 1.5×10^{-5} Torr is shown in Fig. 2b. Both spectra are presented on a log scale.

Both figures contain characteristic X-ray peaks with energies of 16.6, 18.6, and 6.4 keV corresponding to K_α and K_β lines of niobium whose atoms include into the pyroelectric crystal composition, and iron K_α, i.e., a vacuum chamber material. To the left of the iron K_α line, we can see a peak with an energy of ~1.5 keV corresponding to aluminum K_α line. The presence of this peak in the measured spectra confirms the feasibility of acceleration of electrons emitted from the pyroelectric crystal surface to grounded aluminum heat conductors. Over the main X-ray spectra, the same spectra on the linear scale are shown on the right top corner. Each additional spectrum in Fig. 2 shows the approximating straight line. The end-point energy of X-ray bremsstrahlung is defined by the abscissa of the intersection point of the approximating straight line to the horizontal axis.

Fitting was performed in the high-energy spectral range [5]. Using this method, the end-point energy of X-ray bremsstrahlung was determined in all spectra measured in this experiment. The results of processing of the obtained experimental data are listed in Table 1.

Figure 3 shows the dependences of the end-point energy (W, keV) of X-ray bremsstrahlung generated upon heating and cooling of the pyroelectric source at various residual gas pressures in the range from 1.3×10^{-6} Torr to 1.5×10^{-2} Torr.

The end-point energy of X-rays registered in experiments reaches a maximum of 120.2 keV in the case of heating (Fig. 2a) and 117.1 keV in the case of cooling (Fig. 2b) of the pyroelectric source at a residual gas pressure of 1.5×10^{-5} Torr. The absence of a unified shape of curves shown in Fig. 3 is presumably

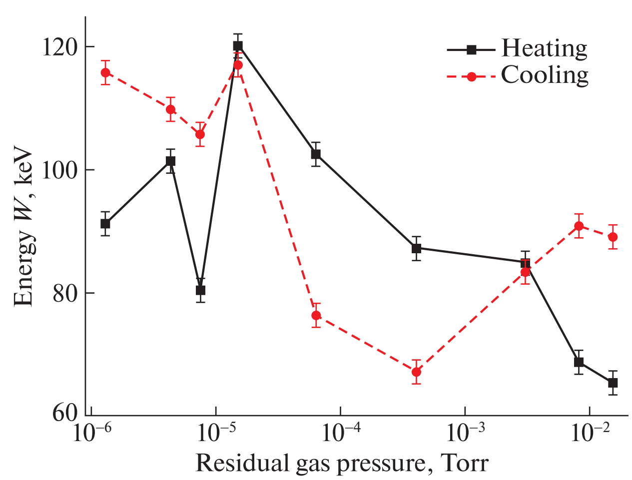

Fig. 3. Dependences of the end-point energy of bremsstrahlung X-rays on the residual gas pressure.

associated with different temperature variation rate modes [3] during heating (the average value reaches 3°C/min) and cooling (the average value reaches 0.7°C/min) of the pyroelectric source.

Photons with energies to 150—175 keV are observed in the spectra presented in Fig. 2. The energy of these photons exceeds the end-point energy. The cause of the formation of such photons requires further investigation.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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