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Optimization of periodic temperature variation of a lithium tantalate single crystal in a pyroelectric accelerator for stable X-ray generation

© A.N. Oleinik[1], M.E. Giltz[1], P.N. Zhukova[2], V.S. Sotnikova[1,3], Yu.S. Shablov[1], P.G. Shapovalov[1,4]

[1] Laboratory of Radiation Physics, Belgorod State National Research University, Belgorod, Russia
[2] Saint-Petersburg University of State Fire Service of EMERCOM of Russia, St. Petersburg, Russia
[3] Shukhov State Technological University, Belgorod, Russia
[4] National Research Nuclear University „MEPhI“, Moscow, Russia
E-mail: oleynik_a@bsu.edu.ru

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Analysis of the X-ray spectra and curves of periodic temperature variation of a lithium tantalate single crystal shows that the shift in temperature oscillations is a negative factor that leads to unstable operation of the pyroelectric accelerator. However, there is a range of permissible displacements at which the generation of particles remains stable. Thus, it is necessary to monitor the implementation of the law of temperature change for the effective operation of the pyroelectric accelerator. The influence of the residual gas pressure and the amplitude of temperature oscillations on the discussed effect is also analyzed.

Keywords: pyroelectric effect, X-ray generators, pyroelectric accelerator, lithium tantalate.

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The possibility of emission and acceleration of electrons induced by the pyroelectric effect in single crystals of the type of lithium niobate and tantalate makes these materials applicable as drivers of production of various particles: X-ray photons, ions, and neutrons [1–4]. The concept of a pyroelectric accelerator is fairly appealing, since it offers an opportunity to fabricate promises compact, cheap, and easy-to-use ionizing radiation sources. The first commercially available sources [5] had several substantial defects, which have thus far impeded the application of pyroelectric accelerators. The following two defects are the most significant: a nonzero „dead“ time with no particle production and an unstable nature of operation, which may be perturbed by electric breakdowns or even without any visible cause.

The ways to stabilize the flux of produced particles in a pyroelectric accelerator are being studied in the Radiation Physics Laboratory of the Belgorod State University. The basic strategy consists in finding a suitable temperature variation law that provides a smooth transition from one accelerator polarity to the other. Periodic sinusoidal variations (oscillations) of temperature [6,7] allow one to stabilize the particle flux substantially, predict an impending electric breakdown [8], and establish the mechanism of stabilization of the electric potential in a pyroelectric accelerator [9]. The periodic temperature variation law itself may be written as

$$T(t) = T_0 + T_1 \sin 2\pi\nu t, \tag{1}$$

where T_0 is the initial temperature of a pyroelectric sample and T_1 and ν are the amplitude and the frequency of periodic temperature variations.

Although the performance of a pyroelectric accelerator in experiments were clearly improved, perturbations of particle production and deterioration of the produced radiation flux were still observed (although less often). This fact motivated the search for the probable causes of these effects. In the present study, the results of analysis of a large set of X-ray radiation spectra and the corresponding curves of temperature variation of a lithium tantalate single crystal are reported. The obtained data suggest the presence of an additional factor contributing to the instability of the produced particle flux.

This factor is the temperature oscillation shift due to additional heating of the pyroelectric material as a result of insufficient heat exchange with the environment and ohmic heating of the Peltier element and under the influence of external climatic parameters. With the oscillation shift taken

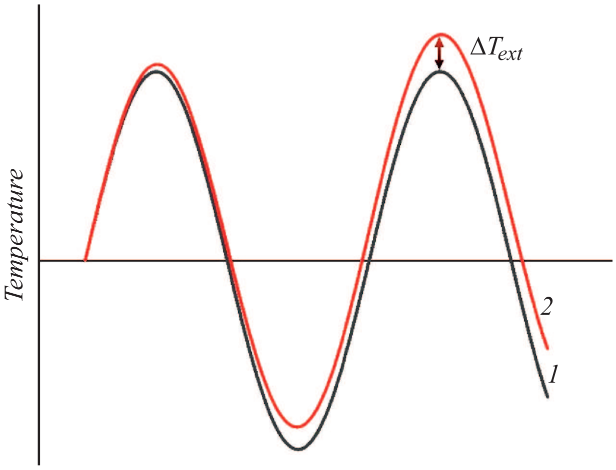

Figure 1. Examples of periodic temperature variation curves with oscillation shift rate $\alpha = 0$ (*1*) and 0.05°C/min (*2*).

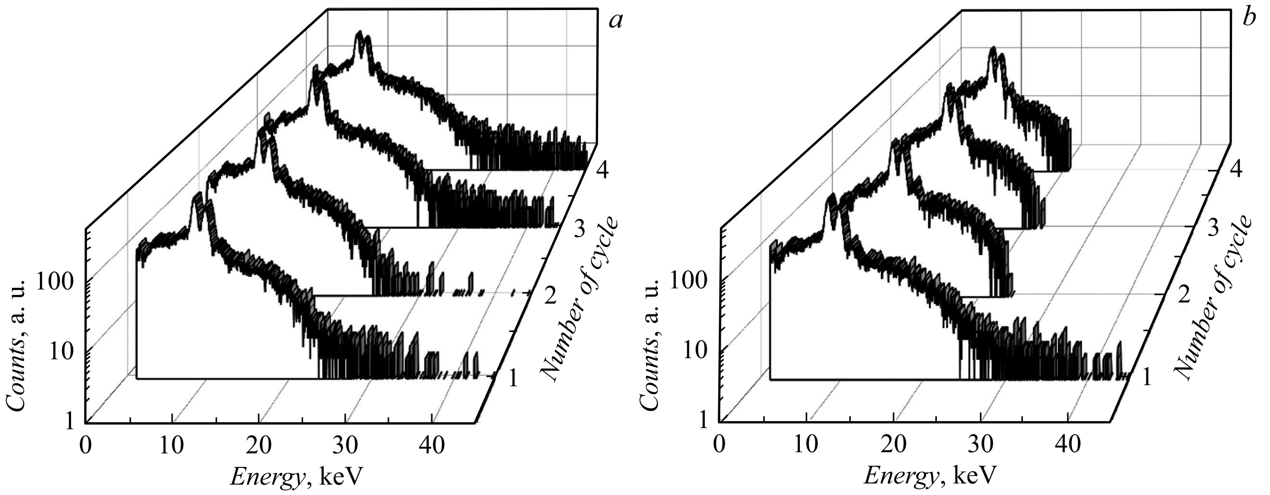

Figure 2. Evolution of the X-ray radiation spectrum within four thermal cycles at a temperature oscillation shift rate of 0.006 (*a*) and 0.024°C/min (*b*). The temperature variation frequency is 0.5 mHz, the variation amplitude is 20°C, and the residual gas pressure is 2.5–5 mTorr.

into account, the actual temperature variation law takes the form

$$T(t) = T_0 + T_1 \sin 2\pi\nu t + \alpha t, \qquad (2)$$

where α is the quantity characterizing the temperature oscillation shift rate. Figure 1 illustrates the influence of the temperature oscillation shift.

A zero oscillation shift implies that the pyroelectric material temperature varies with no shift of extrema and, crucially for the pyroelectric accelerator operation, the heating and cooling phases are identical. This condition ensures that equal overall amounts of charge are produced at positive and negative polarities. If an oscillation shift is present, extrema shift in one direction (ΔT_{ext}), providing an amplitude and duration advantage to one of the thermal phases (in the illustrated case, to heating) and disrupting the charge balance in thermal cycling.

An assembly of a heatsink, a Peltier element, a lithium tantalate ($LiTaO_3$) single crystal, and a target was the key component of the tested pyroelectric accelerator model. A signal with a given frequency and amplitude from a generator was fed to the Peltier element and induced sinusoidal temperature variations. The heatsink was cooled by an internal water jacket with a preset water flow rate, providing an opportunity to control the heat transfer between the Peltier element and the environment and thus adjust the temperature oscillation shift rate. The experimental range of temperature shift rates was 0.004–0.118°C/min. The temperature was measured remotely with a FLIR-E8XT infrared camera. The X-ray radiation spectrum was recorded by an Amptek Cd–Te X-123 spectrometer that was positioned at approximately equal distances from the single crystal and the target in order to estimate correctly the contribution of negative- and positive-polarity phases to the overall X-ray photon flux. The experimental setup for investigation of particle production in a pyroelectric accelerator was characterized in more detail in [8,9].

Figure 2 presents the evolution of the X-ray radiation spectrum within four complete thermal cycles at two different temperature oscillation shift rates. At a temperature oscillation shift rate of 0.006°C/min (Fig. 2, *a*), the spectrum is almost unchanged, and the levels of intensity and endpoint energy remain approximately the same. When the temperature shift rate increases by a factor of 4 (Fig. 2, *b*), the X-ray radiation spectrum deteriorates: the tail of bremsstrahlung emission with a relatively high energy vanishes, and the spectrum intensity decreases by 10–20% with each cycle.

Thus, certain magnitudes of the temperature oscillation shift are permissible and preserve the stability and reproducibility of X-ray radiation production. It follows from the results of data analysis that the measure of photon flux stability and the temperature oscillation shift rate are correlated linearly. Figure 3 presents this linear correlation for various oscillation amplitudes and residual gas pressures. The percentage ratio of the mean-square deviation of the X-ray radiation yield to the yield averaged over a series of four cycles was used as the mentioned measure of photon flux stability.

A firm conclusion may be drawn that the production of X-ray radiation becomes more and more unstable as the temperature oscillation shift rate increases. Notably, the slope of the linear dependence is explicitly dependent on the residual gas pressure and the amplitude of temperature oscillations. The higher these parameters are, the more unstable the production of X-ray photons becomes at one and the same oscillation shift rate. However, the ratio of the mean-square deviation of the radiation yield to the average yield in the region below 0.010–0.015°C/min remains lower than 10%, which is sufficient for stable and efficient

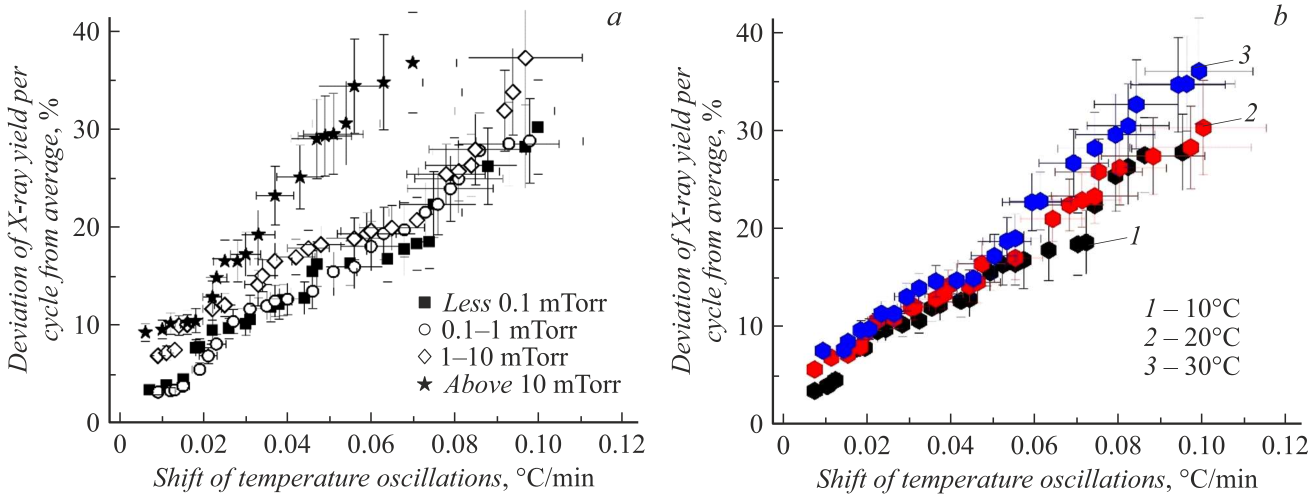

Figure 3. Dependence of the temperature oscillation shift rate on the ratio of the mean-square deviation of the X-ray radiation yield to the yield averaged over four cycles. *a* — At various residual gas pressures, an oscillation amplitude of 10°C, and an oscillation frequency of 0.5 mHz; *b* — at various oscillation amplitudes, a residual gas pressure below 0.1 mTorr, and an oscillation frequency of 0.5 mHz.

operation of a pyroelectric accelerator, at different parameter levels.

Therefore, the temperature oscillation shift is another factor that affects adversely the stability of particle production in a pyroelectric accelerator. The residual gas pressure and the temperature oscillation amplitude are parameters altering the degree of influence of the discussed factor. The presence of a region of permissible shifts preserving the stability of particle production bodes well for further development of pyroelectric accelerators, but requirements as to implementation of the temperature variation law, the heat removal system, and external climatic parameters should be made stricter.

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Conflict of interest

The authors declare that they have no conflict of interest.

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