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ENGINEERING DESIGN OF EQUIPMENT FOR NUCLEAR PHYSICS

Pyroelectric Technologies, Their Applications, and Prospects for Development

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

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

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

[c] *Institute of Plasma Electronics and New Methods of Acceleration, Kharkiv Institute of Physics and Technology, Kharkiv, 61000 Ukraine*

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

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

**e-mail: ooleg.ivashuk@gmail.com*

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Abstract—Description of modern pyroelectric technologies is presented in this article. Various schemes for generating X-ray radiation are presented. The possibility of controlling charged particle beams by means of a pyroelectric deflector is demonstrated. The prospects for the development of pyroelectric technologies and their application are discussed.

Keywords: X-ray radiation, pyroelectric source, pyroelectric deflector

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1. THE CIRCUIT DIAGRAM OF THE PYROELECTRIC X-RAY SOURCE

For the first time, the possibility of generating X-rays due to the pyroelectric effect in a vacuum was discovered by J. Brownridge in [1]. On the basis of numerous experimental results [2–5], Amptek produced commercial pyroelectric X-rays source [6]. The circuit diagram of a pyroelectric X-ray source is presented in Fig. 1. The pyroelectric crystal is located in a miniature vacuum chamber on an isolated substrate that can be heated and cooled. A copper foil target is installed opposite to the crystal surface. During heating of the substrate, a high negative potential about 30 kV appears on the free crystal surface, which leads to electron emission. Free electrons are accelerated from the working surface of the pyroelectric crystal to the copper target. Upon such interaction of accelerated electrons with target atoms, X-ray radiation is generated. During cooling, the pyroelectric crystal is repolarizes, which leads to appearance of free electrons in a cloud of ionized gas in vicinity of its working surface. In this case, the crystal itself becomes the target.

Such a source is operated in a quasi-continuous X-ray generation mode. The duration of one heating–cooling cycle of the pyroelectric crystal is about 3 min (Fig. 2). It is not possible to control and change the spectral characteristics of X-rays in such source.

2. PULSED PYROELECTRIC X-RAY SOURCE

In the radiation physics laboratory of Belgorod State University in Belgorod, Russia, a pulsed pyroelectric X-ray source was developed [7]. The circuit

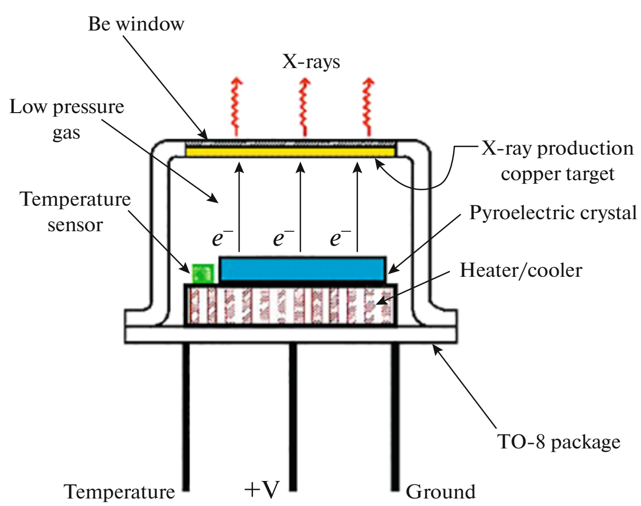

Fig. 1. The circuit diagram of the Amptek COOL-X pyroelectric X-ray source [6].

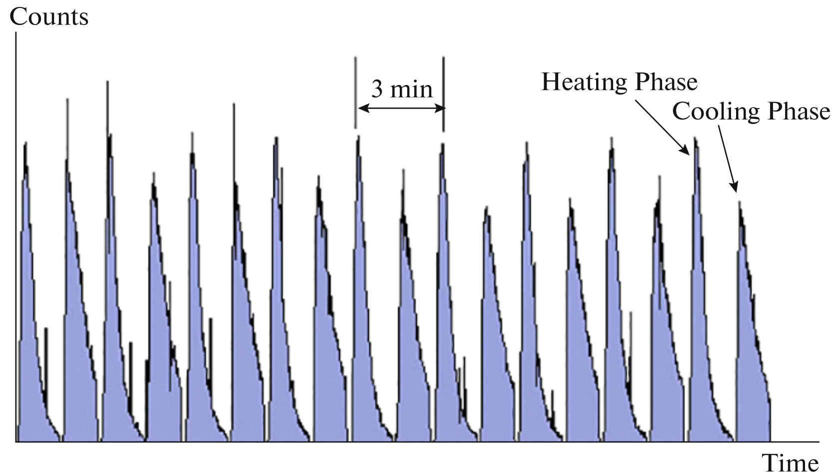

Fig. 2. Dependence of X-ray yield in the Amptek COOL-X pyroelectric X-ray source on time at the cyclic change in temperature [6].

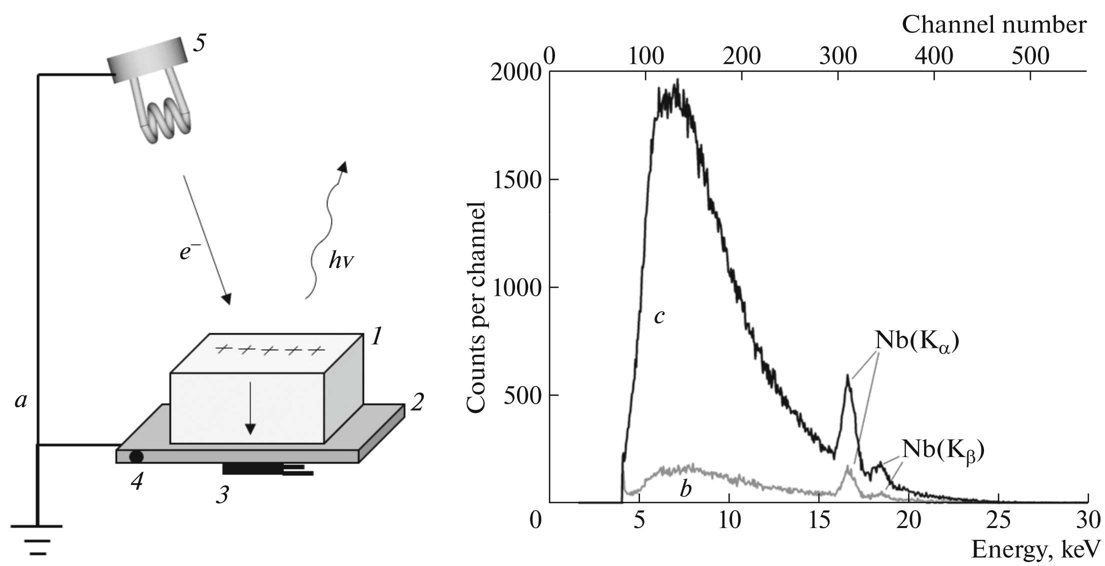

Fig. 3. Pulsed pyroelectric X-ray source: (*a*) the circuit diagram of such source ((*1*) pyroelectric crystal, (*2*) aluminum substrate, (*3*) silicon diode, (*4*) thermocouple K-type, (*5*) electron emitter); (*b*) the X-ray spectrum measured in the quasi-continuous mode of the pyroelectric X-ray source according to the scheme in Fig. 1; (*c*) the X-ray spectrum measured in the pulsed mode of the pyroelectric X-ray source.

diagram such a source is presented in Fig. 3a. The spectra of X-ray radiation in the quasi-continuous and pulsed generation modes are shown, respectively, in Figs. 3b and 3c.

The pulsed pyroelectric X-ray source contains an additional electron emitter—tungsten filament (5). Preliminarily, the pyroelectric crystal (1) was heated by the semiconductor [8] diode (3) in conditions of a high vacuum, which led to appearance of a high positive electrical potential on its surface. Then the current of 0.3 A passed through the filament (5), which provoked the process of electron emission. Free electrons accelerated in electric field, having reached the working pyroelectric crystal (1) surface, compensate for the positive charge. This process was accompanied by intense generation of X-rays for one second.

The number of registered X-ray quanta per 1 s during operation of the pyroelectric X-ray source in the pulsed mode (Fig. 3c) exceeds by more than two orders of magnitude the value during operation of the pyroelectric X-ray source in the quasi-continuous mode (Fig. 3b).

It is useful to note that the pulsed pyroelectric X-ray source theoretically has the possibility of changing the intensity of generation of X-rays through variation

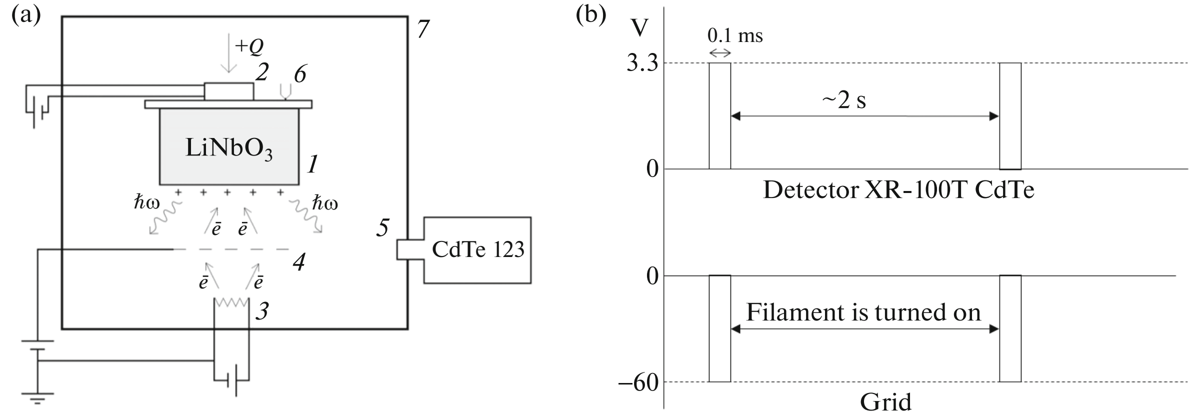

Fig. 4. Pulsed pyroelectric X-ray source with control of the duration of X-ray generation: (a) the circuit diagram of the source ((*1*) pyroelectric crystal, (*2*) silicon diode, (*3*) additional electron emitter, (*4*) grid electrode, (*5*) semiconductor X-ray detector, (*6*) thermocouple K-type, (*7*) vacuum chamber); (b) the coincidence mode of the X-ray detector and the grid electrode.

of the voltage supply of additional electron emitter. However, increase of the endpoint energy of X-ray radiation was not observed.

3. WAYS OF FUTURE DEVELOPMENT OF PULSED PYROELECTRIC X-RAY SOURCE

A significant disadvantage a pulsed pyroelectric X-ray source is impossibility to control and change the duration of X-ray generation. This problem is solved by implementing an additional grid electrode in the pulsed source [9]. The circuit diagram of a such source is shown in Fig. 4a. The grid electrode (4) is located between the electron emitter (3) and free pyroelectric crystal surface (1). The grid electrode in such configuration of the source is like a "tap"; when it is "turned on" (positive potential), electrons pass through it and reach the pyroelectric crystal surface, and when it "turned off" (negative potential), electrons are blocked. The operating principle of such a device can be compared with the operating principle of a triode lamp. Therefore, periodic change in the polarity of the grid electrode voltage (Fig. 4b) will make it possible to observe X-ray generation with the duration depending on the width of the pulse of positive voltage.

Another interesting possibility to generate short pulsed X-rays is using a nanosecond laser. In this case, the construction of the pyroelectric source must be modified; it is necessary to use a grounded photocathode and short pulsed laser instead of system for controlling the duration of X-ray generation (filament and grid electrode). In such a configuration, the source is able to generate ultrashort pulses of X-rays with the duration of several nanoseconds.

4. TWO-CRYSTAL PYROELECTRIC X-RAY SOURCE

Danon [10] first proposed a two-crystal pyroelectric X-ray source. In the first experiments, he observed generation of X-rays with a record value of endpoint energy of 160 keV at that time. Note that penetrating power of X-ray radiation depends on the magnitude of its endpoint energy.

Let us consider the circuit diagram of the source (Fig. 5). Two pyroelectric crystals (1) were located on the same axis parallel to each other. Spontaneous polarization vectors of each pyroelectric are codirectional. Simultaneous heating of both crystals leads to appearance of charges with opposite signs on the free surfaces of each of them. Cooling is accompanied by repolarization of each crystal. In a two-crystal X-ray source, the potential difference between crystals is double unlike a standard X-ray source. Generation of X-rays is due to electrons accelerated from the negative surface of one crystal interacting with the positive surface of the other crystal.

5. ELECTROSTATIC DEFLECTION AND FOCUSING SYSTEMS BASED ON PYROELECTRIC EFFECT

In 2005, Danon proposed a two-crystal pyroelectric X-ray source, but he did not even know that had given rise to a new scientific direction—electrostatic deflection and focusing systems based on the pyroelectric effect. In 2015, the scientists from the radiation physics laboratory of Belgorod State University initiated this direction.

5.1. Pyroelectric Deflector of a Nonrelativistic Electron Beam

In the radiation physics laboratory of Belgorod State University, a pyroelectric generator of a strong

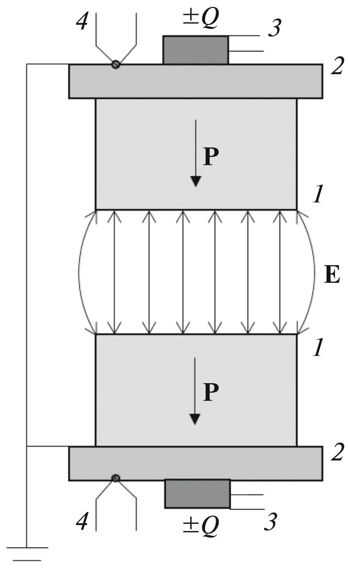

Fig. 5. The circuit diagram of the two-crystal pyroelectric source of X-rays: (*1*) pyroelectric crystal of lithium niobate, (*2*) metal substrate, (*3*) heating element, (*4*) thermocouple.

electric field was developed. In 2016, the idea of a pyroelectric deflector of a beam of charged particles was patented [11]. In [12], the possibility of deflection of a beam of nonrelativistic electrons using a pyroelectric deflector was investigated. For that purpose, an experimental setup was developed (Fig. 6a). Electron beam (*1*) passed through diaphragm (*2*) and between pyroelectric lithium niobate crystals (*3*), which were heated preliminarily by Peltier elements (*4*). On the luminophore screen (*5*) with the help of webcam (*6*), deflection of the electron beam with energy 30 keV in the transverse electric field of the pyroelectric deflector by an angle 10.6° relative to its initial direction (Fig. 6b) at the change of temperature of the pyroelectric crystals in vacuum by 1.5°C was observed.

This proposed version of the pyroelectric deflector of charged particles has such construction imperfections as weak heaters and small size of the pyroelectric crystals that defines the magnitude of electric charge on its surface. To realize the deflection of a relativistic electron beam, significant modernization of the pyroelectric deflector of the first generation is necessary.

5.2. Pyroelectric Deflector of a Relativistic Electron Beam

In the radiation physics laboratory of Belgorod State University, a new kind of pyroelectric deflector (second generation) of a relativistic electron beam was developed. A semiconductor diode served as heater of the pyroelectric crystal, providing a change in temperature in wide range of temperatures (several tens of degrees Celcius). The first experimental studies of the possibility of relativistic electron beam deflection by means of a pyroelectric deflector of the second generation were carried out at the Roentgen 1 setup (Fig. 7a) [13]. The electron beam with the energy of 7 MeV is transported into vacuum chamber (3), on the central axis of which the pyroelectric deflector (Fig. 7b) of the second generation (2) is located. At the operation of the pyroelectric deflector, the electron beam passing

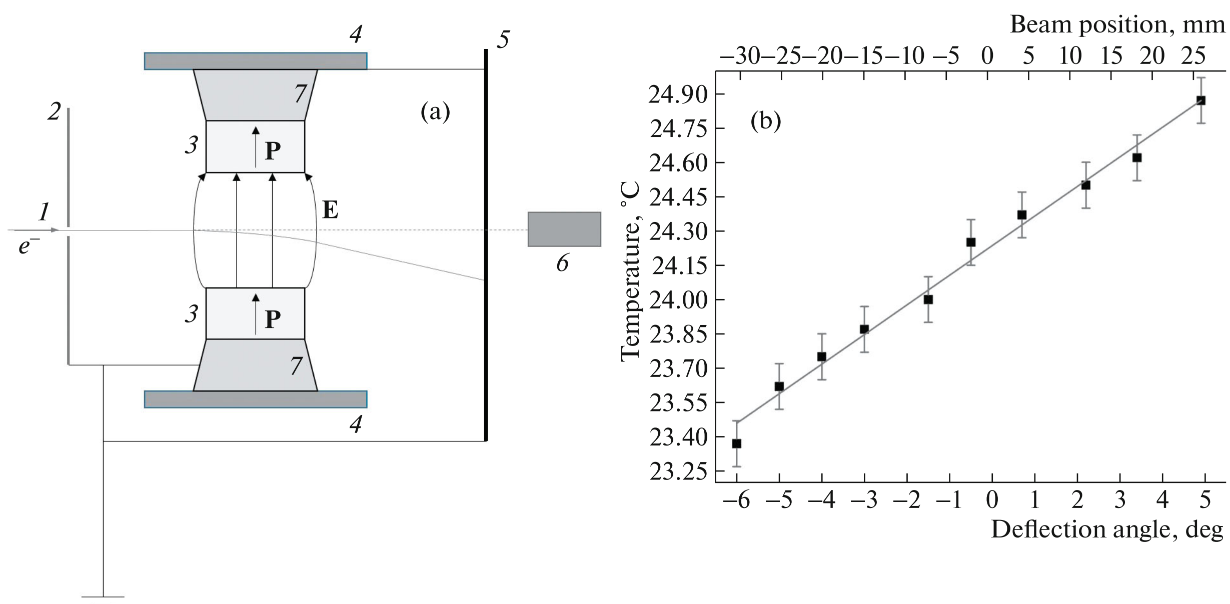

Fig. 6. Investigation of the possibility of electron beam deflection by a pyroelectric deflector: (a) schematic of the experimental setup; (b) results of the experimental investigations.

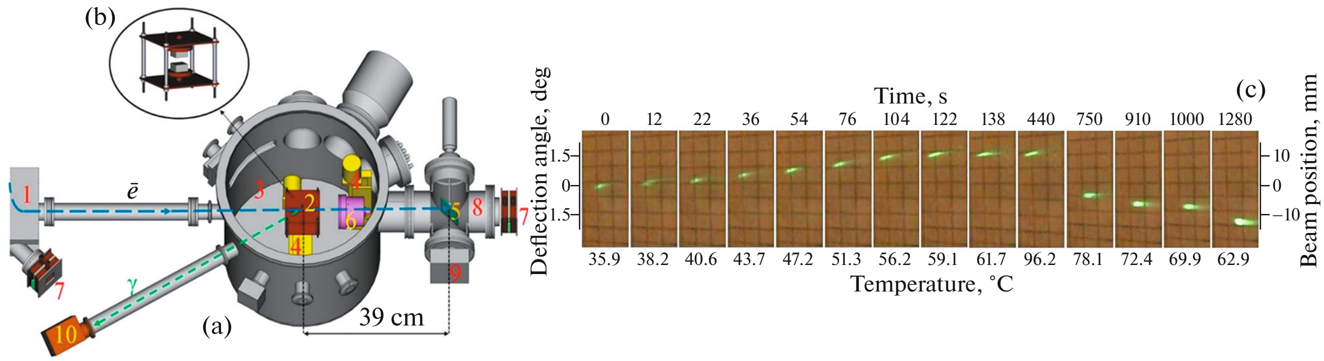

Fig. 7. Testing the pyroelectric deflector of a relativistic electron beam with the energy of 7 MeV at the Roentgen 1 setup: (a) experimental setup; (b) pyroelectric deflector; (c) experimental results.

through the gap between pyroelectric crystals with the energy of 7 MeV was deflected. Experimental results (Fig. 7c) confirmed the possibility of the deflection of a relativistic electron beam with the energy of 7 MeV in an electric field (100 kV/cm) by an angle of 1.45° at the change of temperature of the pyroelectric crystals in a vacuum by 20°C [14].

A curious fact in this experiment is prolonged stabilization of the electric field upon subsequent heating of the pyroelectric crystals after they reach the temperature of 56.2°C. For identification of the nature of this physical phenomenon, it is necessary to carry out more experiments.

5.3. Prospects for the Development of a Pyroelectric Deflector

The experimentally demonstrated possibility of the deflection of charged particle beams by means of a pyroelectric deflector allows one to speak about a great promise of its application in accelerator physics.

In the modern world, electronic optics is based predominantly on magnetic systems [15–17]. However, such systems have limitations, such as the necessity of a cooling system and current stabilization for their operation and the overall mass and size characteristics. In 2017, in the radiation physics laboratory of Belgorod State University, the idea of creating a quadrupole electrostatic lens on the basis of a pyroelectric deflector (Fig. 8) was proposed [18]. It consists of two pyroelectric deflectors located perpendicular to each other. For a proper focusing of the electron beam, it is necessary to use pair of quadrupole pyroelectric lenses reversed relative to each other by 90° around the axis passing through their centers.

The peak of development of the pyroelectric deflector will occur when it can be transformed in the creation of a pyroelectric undulator (Fig. 9) [19]. A pyroelectric undulator is a series of the pyroelectric deflectors located sequentially. The directions of strong lines of electric fields in neighboring deflectors are opposite. The electron beam moves along a sinusoidal trajectory in a pyroelectric undulator. The loss of electron energy at the change of its trajectory is accompanied by coherent radiation in narrow cone along the beam axis. According to preliminary theoretical estimates, in the electric field with the strength of 100 kV/cm, the undulator radiation generation in an X-ray range at electron energy of several hundred MeV is expected.

6. PYROELECTRIC NEUTRON SOURCE FOR ULTRALOW BACKGROUND DETECTORS

Today there is an urgent need for environmentally, miniature, and safe sources of fast neutrons for calibration of ultralow background detectors [20].

In [21], the possibility of generation of fast neutrons with energy of 2.5 MeV at the operation of a two-crystal pyroelectric source of charged particles is

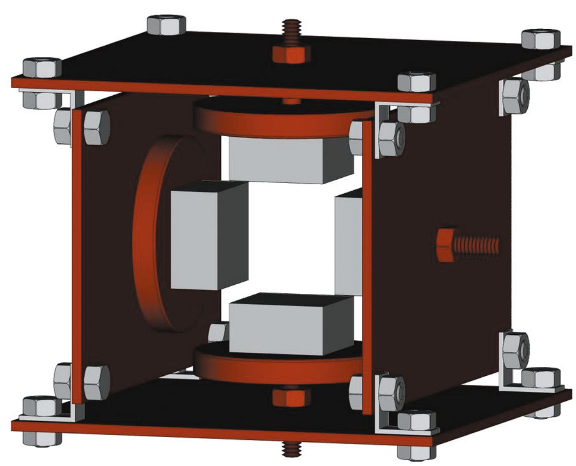

Fig. 8. Quadrupole pyroelectric lens.

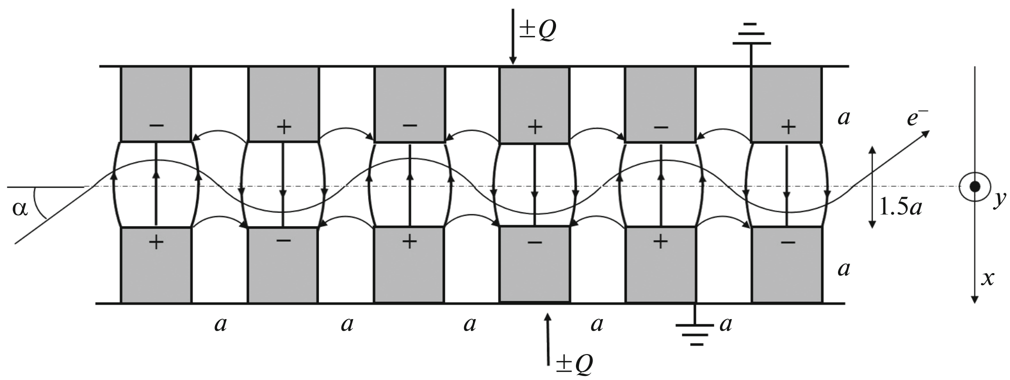

Fig. 9. Pyroelectric source of undulator radiation.

investigated. Since 2015, the radiation physics laboratory of Belgorod State University has actively taken part in development of the direction of creating miniature fast neutron sources based on the pyroelectric effect. In 2016, in [22], the generation of fast neutrons with an energy by 2.45 MeV and with intensity by a several tens of neutrons per second was observed at the operation of a single crystal pyroelectric source in a vacuum. The pyroelectric neutron generator developed in the radiation physics laboratory of Belgorod State University is presented in Fig. 10. The pyroelectric fast neutron generator consisting of pyroelectric crystal (*1*), metal substrate (*2*), and grounded deuterium target (*4*) on titanium substrate (*3*) is located in a vacuum chamber. The crystal has such orientation that, at its heating, a positive potential of about +50 kV arises on its free surface. In a strong electric field between crystal surface and target, ionization of residual gas (deuterium) atoms occurs. Neutron generation is due to D–D reaction at the interaction of accelerated deuterium ions up to energy 50 keV with the deuterium grounded target.

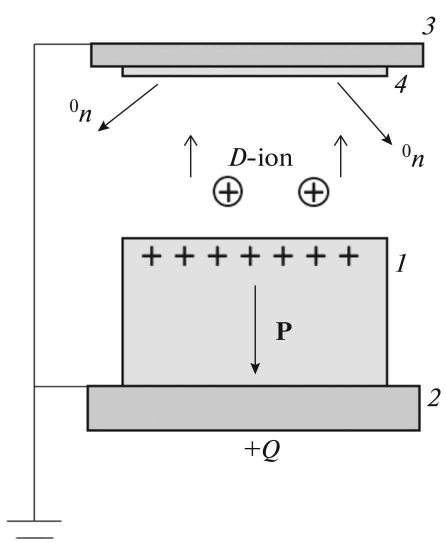

Fig. 10. Pyroelectric fast neutron generator.

CONCLUSIONS

The presented overview of the pyroelectric technology confirmed the possibility of application of pyroelectric crystals as a base element in an X-ray, undulator radiation, and fast neutron generator, which allows one to speak about the prospects of development of the direction of creating pyroelectric elements for electron and ion optics.

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