PYROELECTRIC ELECTRON BEAM DEFLECTOR AND UNDULATOR

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Abstract

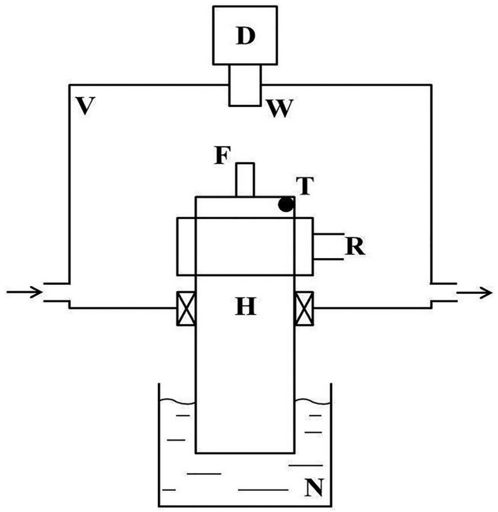
Deflection of a relativistic electron beam by means of the pyroelectric deflector is demonstrated experimentally for the first time [1]. The operating principle of the pyroelectric deflector is based on the generation of a strong transverse electric field in a vacuum in the gap between a pair of pyroelectric crystals due to the pyroelectric effect [2]. The experiments on observation of deflection of 7 MeV electron beam for 26 mrad in the transverse electric field with a strength of about 100 kV/cm arising at a variation of the temperature of a pair of pyroelectric crystals in vacuum are described. The possibility for application of the installed sequentially pyroelectric deflectors in pyroelectric undulator for production of undulator radiation by relativistic electron beam without any external high voltage power supply is discussed.

- This project has received funding through the MSCA4Ukraine project, which is funded by the European Union.

- [1]. V.I. Alekseev, A.N. Eliseev, O.O. Ivashchuk, I.A. Kishin, A.S. Kubankin, A.N. Oleinik, V.S. Sotnikova, A.S. Chepurnov, Y.V. Grigoriev, A.V. Shchagin. Pyroelectric deflector of relativistic electron beam. Chinese Journal of Physics 77 (2022) 2298-2306.
- [2] A.N. Oleinik, A.S. Kubankin, R.M. Nazhmudinov, K.A. Vokhmyanina, A.V. Shchagin and P.V. Karataev. Pyroelectric deflector of charged particle beam. Journal of Instrumentation 11 (2016) P08007

Electric field strength in miniature pyroelectric accelerator can reach about 100 kV/cm.

A.V. Shchagin, V.S. Miroshnik, V.I. Volkov, and A.N. Oleinik, Ferroelectric ceramics in a pyroelectric accelerator, Applied Physics Letters 107, 233505 (2015).



After our research of the pyroelectric accelerator, we decided to try pyroelectric deflector and undulator.

• Deflection of non-relativistic 30 keV electron beam

Experiment in Belgorod radiation laboratory

A.N. Oleinik, A.S. Kubankin, R.M. Nazhmudinov, K.A. Vokhmyanina, A.V. Shchagin and P.V. Karataev. Pyroelectric deflector of charged particle beam. Journal of Instrumentation 11 (2016) P08007

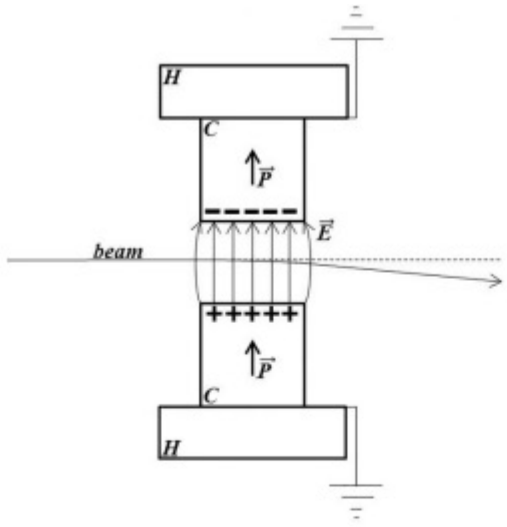


Figure 1. The principle diagram of the pyroelectric beam deflector.

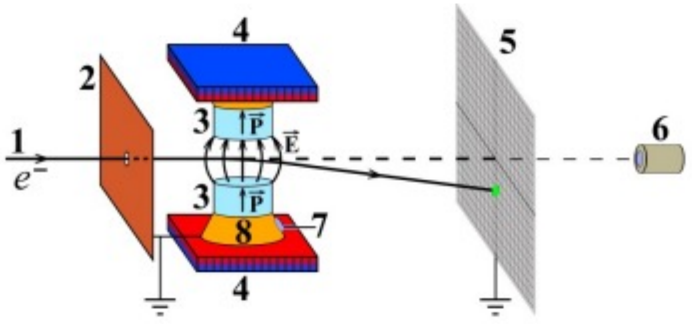


Figure 2. The experimental layout: the 30 keV electron beam (1) passes through the diaphragm (4.2) and the gap between the pyroelectric crystals (3). The position of the beam spot on the transparent screen (5) is observed by the camera (6). Pyroelectric crystals (3) are glued to conical metallic heat-conductors (8) installed on Peltier elements (4). The temperature is controlled by digital DS18B20 type thermometers (7).

Beam position as functions of the pyroelectrics temperature and time

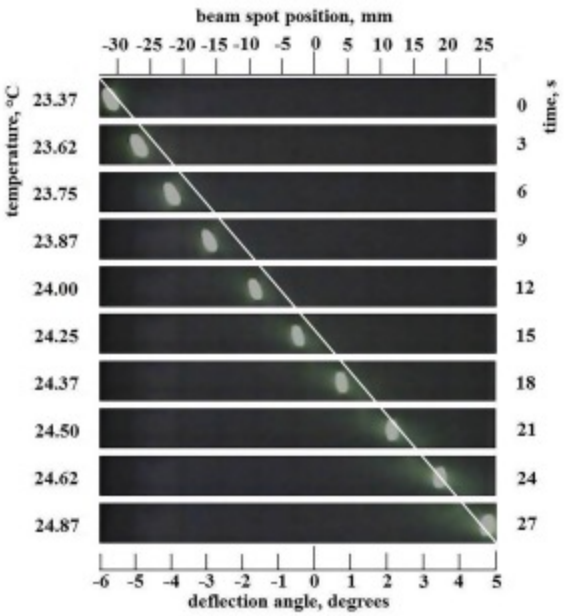


Figure 3. Images of the 30 keV electron beam observed every 3 seconds during heating of the pyroelectric crystals. The straight diagonal line is given in the figure to see a slight nonlinearity of the beam deflection.

Results of deflection of 30 keV electron beam

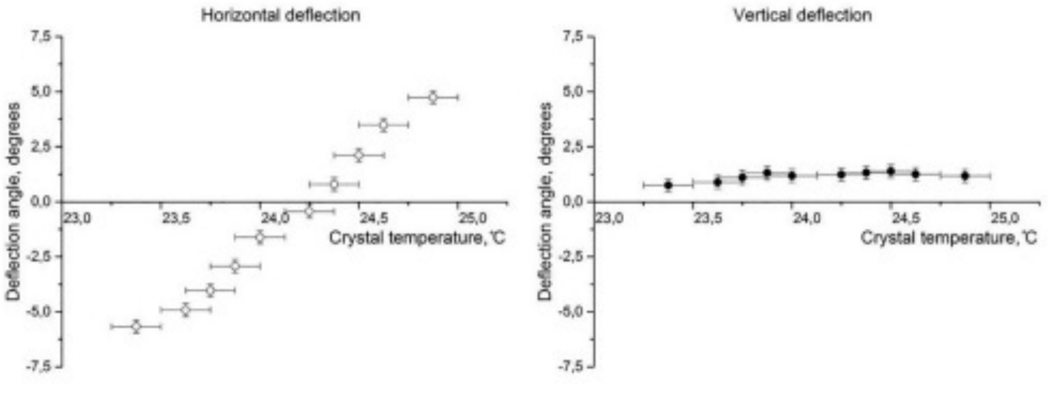


Figure 4. Dependence of the beam deflection angle as a function of the temperature.

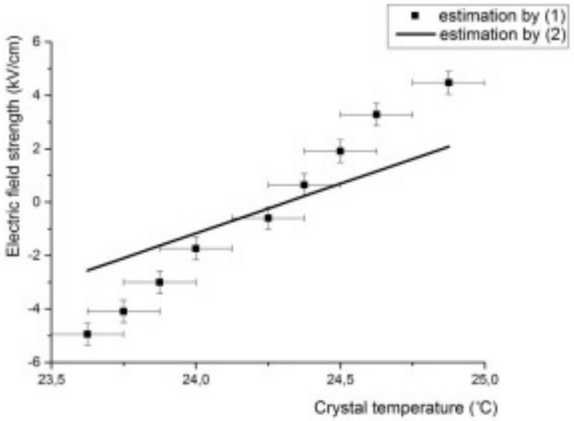


Figure 6. Dependence of the electric field strength versus crystal temperature estimated using eq. (4.1) and eq. (4.2).

• Deflection of relativistic 7 MeV electron beam

V.I. Alekseev, A.N. Eliseev, O.O. Ivashchuk, I.A. Kishin, A.S. Kubankin, A.N. Oleinik, V.S. Sotnikova, A.S. Chepurnov, Y.V. Grigoriev, A.V. Shchagin. Pyroelectric deflector of relativistic electron beam. Chinese Journal of Physics 77 (2022) 2298-2306.

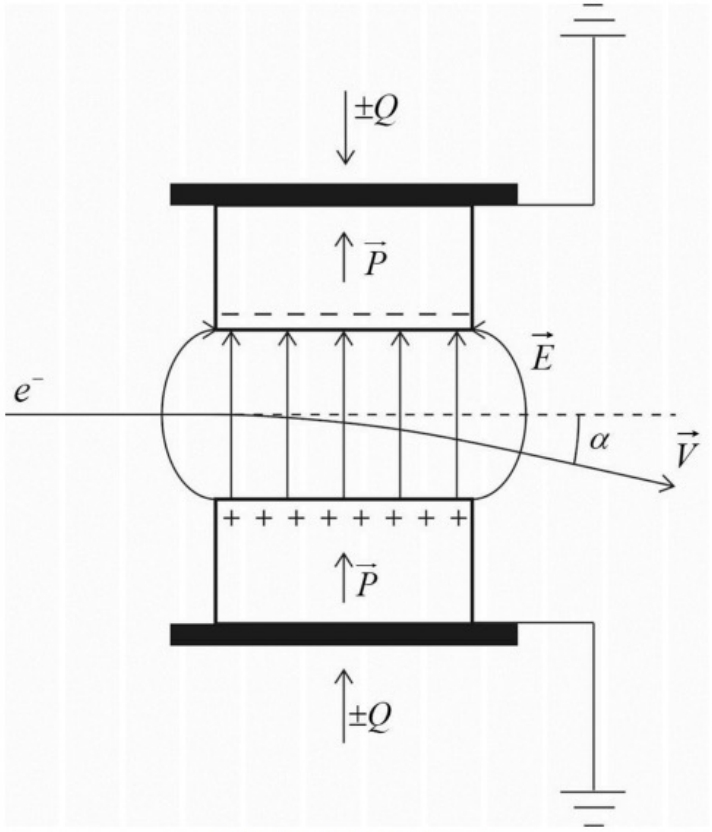


Fig. 1. Pyroelectric deflector circuit diagram.

2. Deflection of charged particle in transverse electric field

At the motion of the particle with charge q, mass m, velocity V, and momentum p in the transverse electric field E, the centrifugal force $\frac{pV}{R}$ should be equal to the force acting on the particle from the field qE. Therefore, one can write the following equation

$$\frac{pV}{R} = qE \tag{1}$$

where R is the radius of the particle's trajectory curvature. One can find the radius of the curvature from Eq. (1)

$$R = \frac{\varepsilon\beta^2}{qE} \tag{2}$$

where $\varepsilon = \frac{mc^2}{\sqrt{1-\beta^2}}$ is the full energy of the particle, $\beta = \frac{V}{c}$, c is the light velocity Eq. (2). can be written as a function of the kinetic energy ε_{kin} of an accelerated particle

$$R = \frac{\varepsilon_{kin}}{qE} \cdot \frac{\varepsilon_{kin} + 2mc^2}{\varepsilon_{kin} + mc^2} \tag{3}$$

The deflection angle $\alpha = \frac{l}{R}$ of the particle which passed path l in the transverse electric field E is

$$\alpha = \frac{qEl}{\varepsilon_{kin}} \frac{\gamma}{\gamma + 1} = \frac{qEl}{\varepsilon_{kin}} \frac{\varepsilon_{kin} + mc^2}{\varepsilon_{kin} + 2mc^2} \tag{4}$$

where γ is the relativistic factor, α is in radian units. In the non-relativistic case at $\varepsilon_{kin} << mc^2$, Eq. (4) takes the form

$$\alpha = \frac{qEl}{2\varepsilon_{kin}} \tag{5}$$

Eq. (5) has been used in the analysis of the deflection of the non-relativistic electron beam in [8]. In the ultra-relativistic case at $\varepsilon_{kin} >> mc^2$, Eq. (4) takes the form

$$\alpha = \frac{qEl}{\varepsilon_{kin}} \tag{6}$$

Below we describe our experiments on a deflection of the relativistic electron beam by the pyroelectric deflector.

Experimental setup 7 MeV electron beam

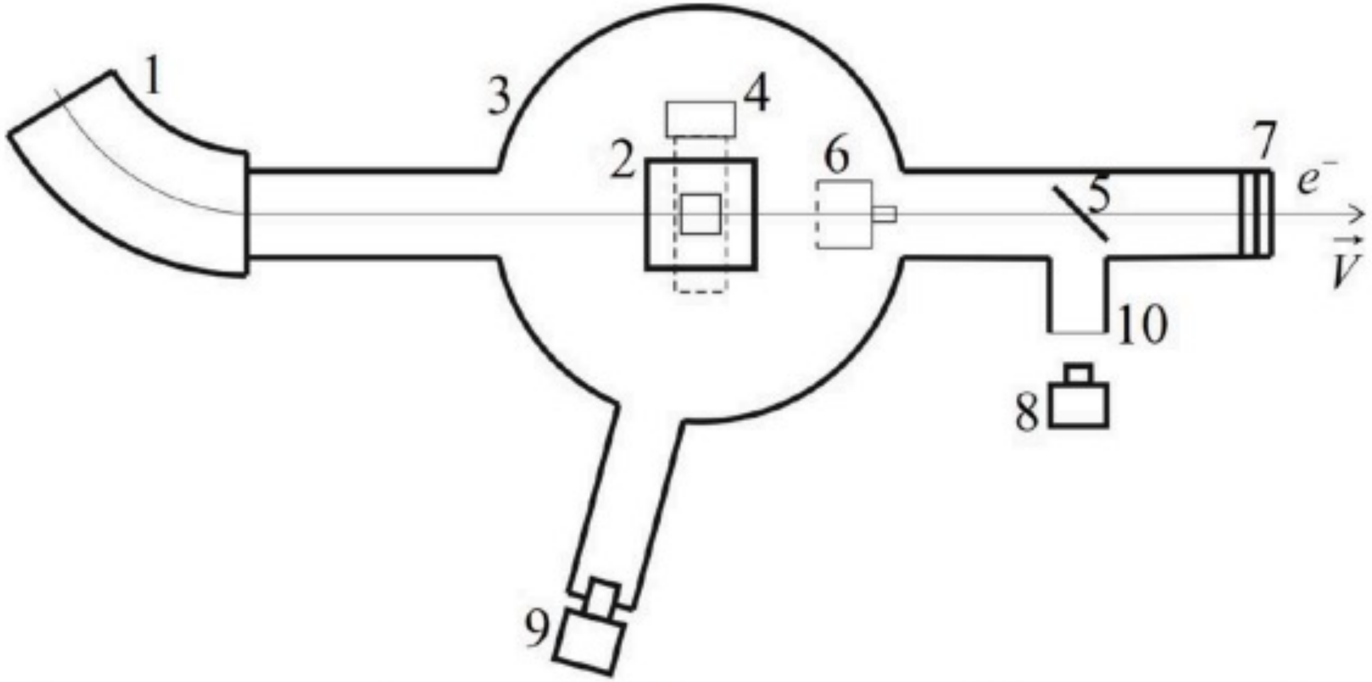


Fig. 2. The scheme of the experiment. 1 - Bending magnet, 2 - pyroelectric deflector, 3 - vacuum chamber, 4 – linear translator, 5 – removable scintillation screen, 6 – removable Faraday cup, 7 - proportional chamber, 8 - web camera, 9 - X-ray detector, 10 – glass window.

Construction of the pyroelectric deflector
Pyroelectric crystals are $LiNbO_3$

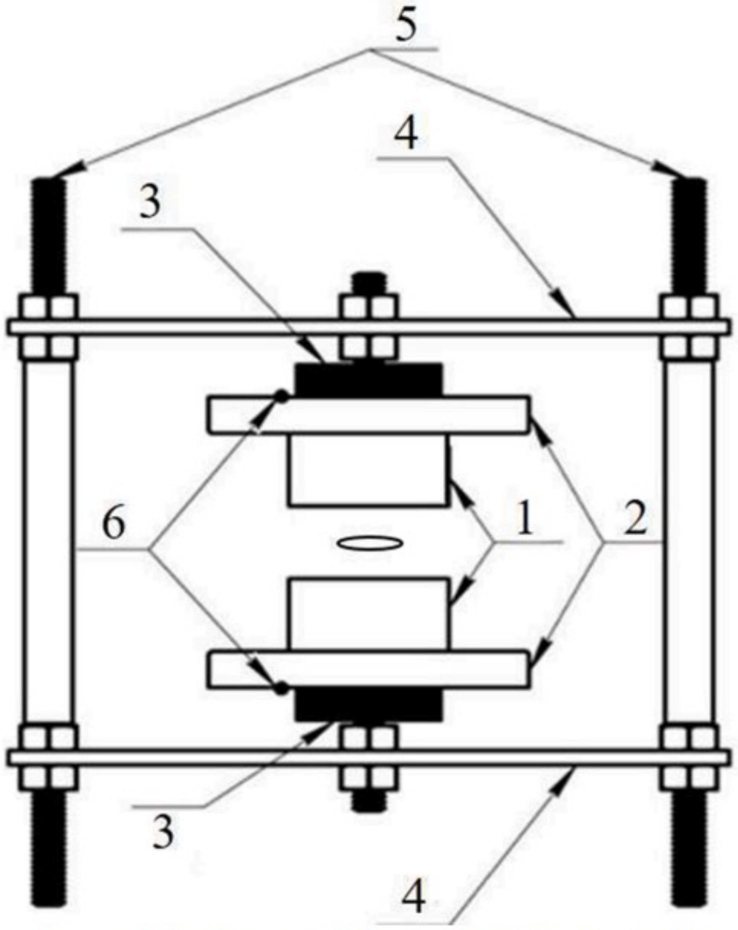
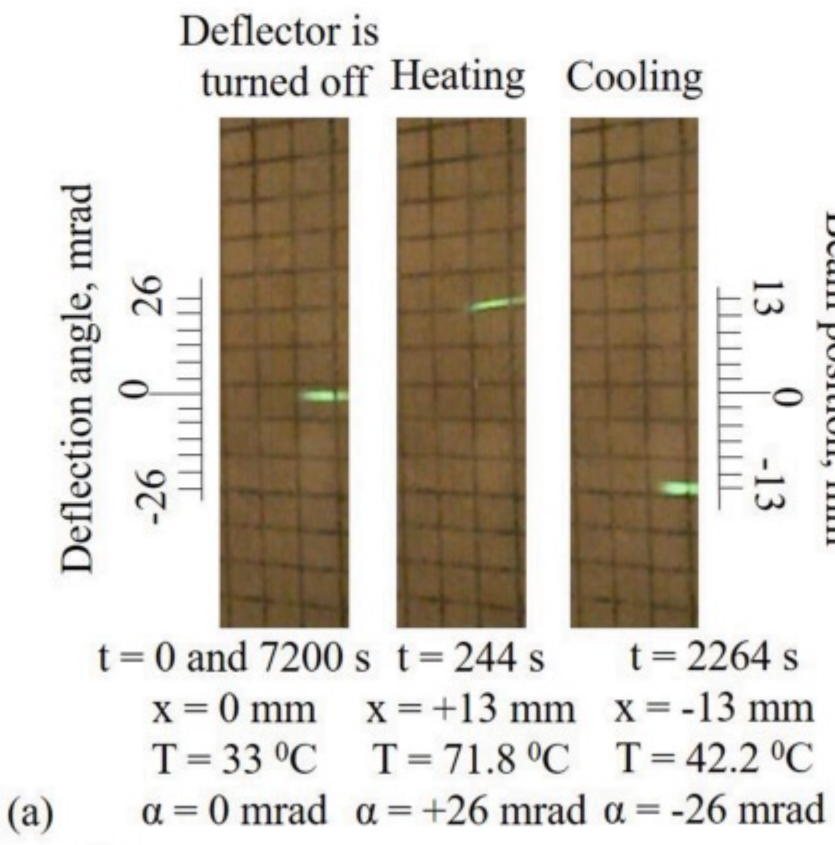


Fig. 3. The design of the pyroelectric deflector. 1 - Pyroelectric crystals, 2 – duralumin heat-conductors, 3 – heating diodes, 4 –metal plates, 5 – metal rods, 6 – K-type thermocouples. The ellipse shows the position of the incident electron beam in the deflector.

Deflection of the electron beam. Maximum electric field strength is 100 kV/cm.



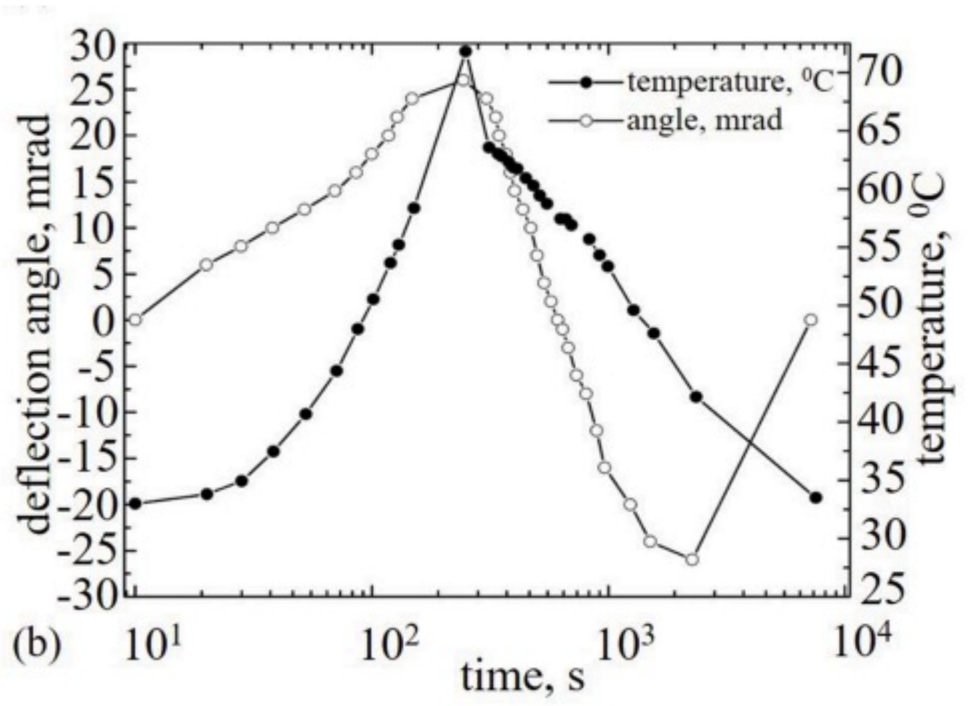


Fig. 4. The deflection of an electron beam. (a) Three photographic imagines of the electron beam spot on the screen when the deflector was turned off and at maximum deflection angles at heating and cooling of pyroelectric crystals. (b) The deflection angle of the electron beam and measured temperature as functions of time. Experimental points are connected by lines for clarity.

Electrons accelerating from one crystal to another produce bremsstrahlung and characteristic X-ray radiation. One can say, that they provide low-current perpendicular electron beam between pyroelectric crystal.

The spectrum of X-ray radiation from the perpendicular electron beam.
7 MeV electron beam is turned off. This is independent confirmation of the electric field strength 100 kV/cm.

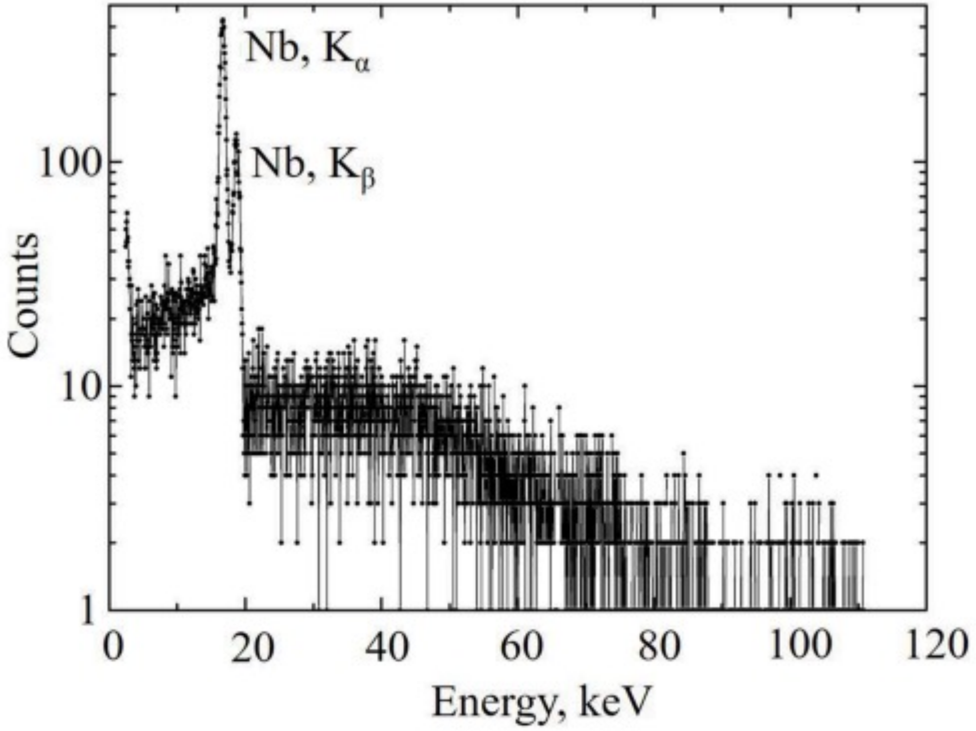


Fig. 5. The spectrum of X-ray radiation from the pyroelectric deflector measured during one cycle of heating and cooling without an external electron beam.

Discussion

The concept of a pyroelectric deflector can be as the basis for the development of a pyroelectric undulator. Several installed sequentially pyroelectric deflectors with opposite directions of crystals polarization can lead to undulatory motion of relativistic charged particles and to the emission of undulator radiation. Such undulator can be considered as a kind of electrostatic undulator. The electrostatic undulator was first proposed by V.L. Ginzburg in 40ies. The project of the electrostatic undulator of the ultra-relativistic beam with conductive electrodes and external high voltage power supply was proposed in Stanford in 90ies.

In the present paper, we demonstrated experimentally operation of the pyroelectric deflector with the relativistic electron beam. Undulator parameter K~0.2 in ultra-relativistic case. External power supply is absent (excluding only heating).

The pyroelectric undulator can be used when we will need in a light, cheap simple undulator. **For instance, in the space**

- This project has received funding through the MSCA4Ukraine project, which is funded by the European Union.