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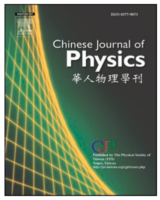

Pyroelectric deflector of relativistic electron beam

V.I. Alekseev [a], A.N. Eliseev [a], O.O. Ivashchuk [a,b], I.A. Kishin [a,b], A.S. Kubankin [a,b], A.N. Oleinik [b,c], V.S. Sotnikova [b,d], A.S. Chepurnov [e], Y.V. Grigoriev [f], A.V. Shchagin [b,g,*]

[a] *P. N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow 119991, Russian Federation*
[b] *Laboratory of Radiation Physics, Belgorod National Research University, Belgorod 308015, Russian Federation*
[c] *John Adams Institute at Royal Holloway, University of London, Egham TW20 0EX, UK*
[d] *Belgorod State Technological University named after V.G. Shukhov, Belgorod 308012, Russian Federation*
[e] *Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow 119991, Russian Federation*
[f] *Shubnikov Institute of Crystallography, Moscow 119333, Russia*
[g] *National Science Centre Kharkov Institute of Physics and Technology, Kharkov 61108, Ukraine*

A R T I C L E I N F O

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A B S T R A C T

Deflection of a relativistic electron beam by means of the pyroelectric deflector is demonstrated experimentally for the first time. 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. 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.

1. Introduction

Usually, a beam of accelerated charged particles is controlled by a transverse magnetic or electric field. For instance, dipole magnets are used to control beam turning [1]. The transverse electric field is used, for example, to control low-energy beams or in kickers of high-energy beams [2]. A natural transverse electric field between crystallographic planes or rows in crystals is used for beam~~s~~ steering due to channel~~l~~ing or above-barrier motion of particles in a crystal [3,4]. Besides, steering of the low energy beam is possible due to surface charge, which is produced on dielectrics by incident beam [5–7]. Recently, the pyroelectric deflector of charged particles beam has been proposed in Ref [8]., where the deflection of the non-relativistic electron beam was demonstrated experimentally. Here we describe our first experiments on the deflection of the relativistic electron beam by the pyroelectric deflector and discuss the possibility for application of pyroelectric deflectors in the pyroelectric undulator.

* Corresponding author.
E-mail address: shchagin@kipt.kharkov.ua (A.V. Shchagin).

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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.

3. Pyroelectric deflector

The electric field can be created in a vacuum due to the pyroelectric effect at the variation of the temperature of pyroelectrics installed in vacuum [9,10]. The circuit diagram of the pyroelectric deflector is shown in Fig.1.

Two pyroelectric crystals with parallel polarization vectors $\overrightarrow{P}$ are installed on grounded metal plates at some distance one from another in a vacuum. Both crystals can be heated or cooled simultaneously by adding and reducing some amount of heat Q. Surface charges of opposite signs arise on free crystal surfaces at the variation of the temperature. The electric field $\overrightarrow{E}$ appears between free crystal surfaces. A similar configuration of crystals was proposed in Ref [11]. for the production of X-rays by electrons accelerated along vector $\overrightarrow{E}$ between free crystal surfaces. Here we use the electric field as the transverse electric field for deflection of external relativistic electron beam moving along the crystal surfaces between crystals. The electron beam is deflected for angle α in the transverse electric field.

4. Experimental

The experiment was carried out on a modified ROENTGEN setup [12] at the exit of electron microtron of the synchrotron complex "Pakhra" [13] in the Lebedev Physical Institute in Troitsk, Russia. The microtron provided a pulsed electron beam of energy of 7 MeV at an average beam current of 2 nA. The repetition rate was 50 Hz, the duration of each pulse was 4 μs. The transverse size of the beam was about 1 × 5 mm.

Fig. 2 shows the general scheme of the experiment. Accelerated electron beam passed bending magnet 1 and penetrated to the vacuum chamber 3. The pyroelectric deflector 2 was installed in the middle of vacuum chamber 3 on the linear translator 4, which allowed to regulate the position of the deflector relative to the electron beam. Pyroelectric crystals are shown by the square in the centre of the deflector. The removable screen 5 was installed at an angle of 45° relative to the electron beam. Screen 5 consists of a powder zinc sulfide scintillator (ZnS:Cu) deposited on 1 mm thick aluminium plate. The grid with rectangles $5 \times 5\sqrt{2}$ mm in size was drown on the surface of the scintillator. The distance between the centre of the pyroelectric deflector 2 and the screen 5 was 500 mm. The position of the electron beam spot on the screen was observed through glass window 10 by web camera 8 installed at the right angle relative to the primary beam axis. The removable Faraday cup 6 made it possible to measure the beam current. The gas-filled position-sensitive proportional chamber 7 monitored the beam position and profile. The proportional chamber was used for preliminary tuning of the electron beam.

The semiconductor X-ray detector 9 of type Amptek XR-100T CdTe was used to measure spectra of X-ray radiation generated by electrons accelerated in the deflector between free surfaces of pyroelectric crystals. The distance between the centre of deflector 2 and the entrance window of the detector 9 was 500 mm. The 100 μm beryllium entrance window of the detector was inserted in a vacuum. The area of the detector is 25 mm^2, the registration efficiency of the X-ray detector is close to 100% in the energy range from 3 to 100 keV. X-rays emitted from free surfaces of both crystals at grazing angles only could penetrate to the detector. The signals from the detector were processed by the digital processor PX-5. The X-ray spectrometer was calibrated by energy with the use of the X-ray lines of the ^{237}Np isotope before performing the experiments.

The pyroelectric deflector is made as a separate assembly. The design of the pyroelectric deflector is shown in Fig. 3. Two pyroelectric crystals 1 are glued by conductive epoxy to the duralumin disks 2 of diameter 38 mm and height 5 mm which served as heat conductors. Two thermocouples of K-type 6 were installed at the heat-conductors 2 and used to measure the temperature. Both measured temperatures were practically equal in the experiments. Therefore, in the following discussions of the temperature, we mean both temperatures. The heating of pyroelectric crystals in a vacuum was performed by semiconductor elements. Application of semiconductor elements for heating of the pyroelectrics in vacuum was proposed recently [14]. Crystals 1 were heated by diodes 3 through duralumin heat-conductors 2. We used commercially available silicon diodes of type MUR1560 with maximum current of 15 Amps and maximum junction temperature of 175 °C as heating diodes.

The units of crystal 1, heat conductor 2 and diode 3 are fixed on the metal plates 4. The metal plates served as heat radiators at the

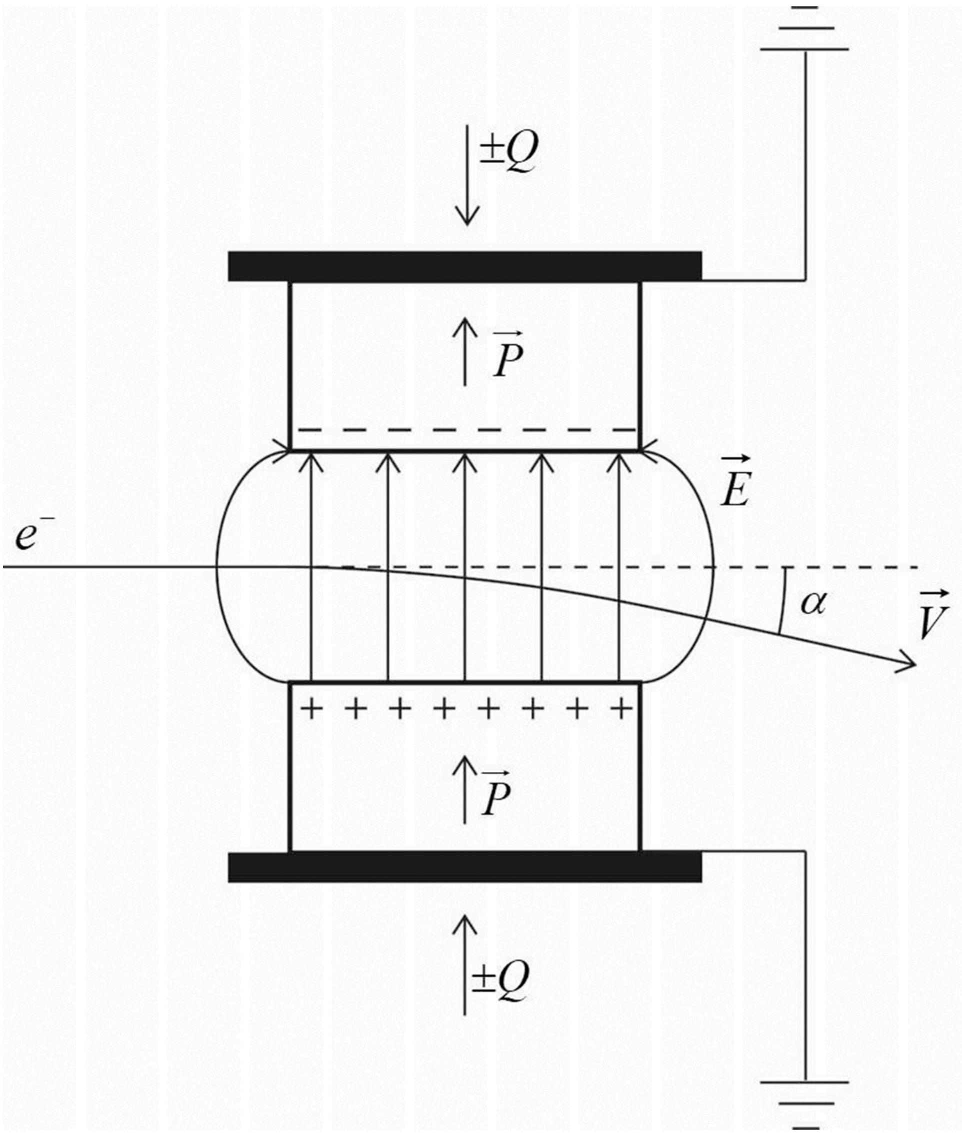

Fig. 1. Pyroelectric deflector circuit diagram.

cooling of the crystals after tuning off the current through diodes. Two such units are connected by brass rods 5. We used two identical pyroelectric single crystals $LiNbO_3$ in the form of a parallelepiped. The size of the crystal's base is 20 × 20 mm and the height of every crystal is 10 mm. The Z-axis of the $LiNbO_3$ crystal is perpendicular to the base of the parallelepiped. The distance between the free surfaces of the crystals was d=11 mm. The polarization vectors of both crystals were co-directed, as shown in Fig.1. Synchronous heating or cooling of both crystals leads to arising of a negative charge on the free surface of one crystal and a positive charge on the free surface of another crystal. The charges induce the electric field between crystals, as shown in Fig. 1. The back surfaces of the crystals were grounded through the heat conductors. Heating diodes 3 were electrically isolated from the heat-conductors 2.

The pressure of residual gas in the vacuum chamber during the experiments was about $5{\bullet}10^{-5}$ Torr. The beam parameters were tuned using the proportional chamber and Faraday cap to provide an ellipsoid-like shape of the beam passing through the middle of the deflector. Then, the current through the diodes was turned on and both crystals were synchronously heated. After that, the current was turned off and crystals were synchronously cooled due to thermal radiation. During heating and cooling, the transverse electric field arose in the deflector, the electron beam deflected, and the beam spot position on the screen was shifted.

5. Results

Some photographic images of the electron beam spots on the screen are shown in Fig. 4(a). The temperature of the pyroelectric crystals, the beam positions, and deflection angles of the electron beam in some moments of time are noted in the bottom of Fig. 4(a).

One can see from Fig. 4(a), that the electron beam is deflected in one direction at heating and in opposite direction at natural cooling of crystals of the pyroelectric deflector. More detailed results of measurements are given in Fig. 4(b), where the deflection angle and measured temperature are shown as functions of time.

The heating of crystals began from the initial temperature of the crystals 33 °C due to turning on stabilized current of 4.5 Amps through each diode. The voltage of 1.2 Volts was on each diode at the beginning of the heating and it was some reduced during the heating because of increasing of the temperature of the silicon junctions. The heating was stopped and natural cooling began by turning off the current through diodes at 244th second. The natural cooling in vacuum was mainly due to thermal radiation from crystals, and heat conductors, and metal plates.

The deflection angle increased for 244 s and reached maximum magnitude +26 mrad at increasing the temperature at about 38.8 °C. The reduction of the deflection angle began immediately after turning off the current through diodes and stopping the heating. The deflection angle and electric field strength became equal to zero on 610th second at the temperature of about 57.4 °C. During the natural cooling of the crystals, the signs of the charges on the crystal surfaces and electric field vectors became opposite and the deflection angle became negative. The deflection angle reached value −26 mrad at the 2264th second and the deflection angle became equal to zero again after following natural cooling up to temperature 33.5 °C during 7200 s. In the experiments, we observed that spark discharges appeared in the deflector at a sufficient increase of the range of the temperature variation relative to the above described one.

Thus, we experimentally observed maximum deflection angles α_{max}=±26 mrad with an accuracy of about 5%. One can find the maximum values of the strength of the transverse electric field E_{max} in the deflector from Eq. (4).

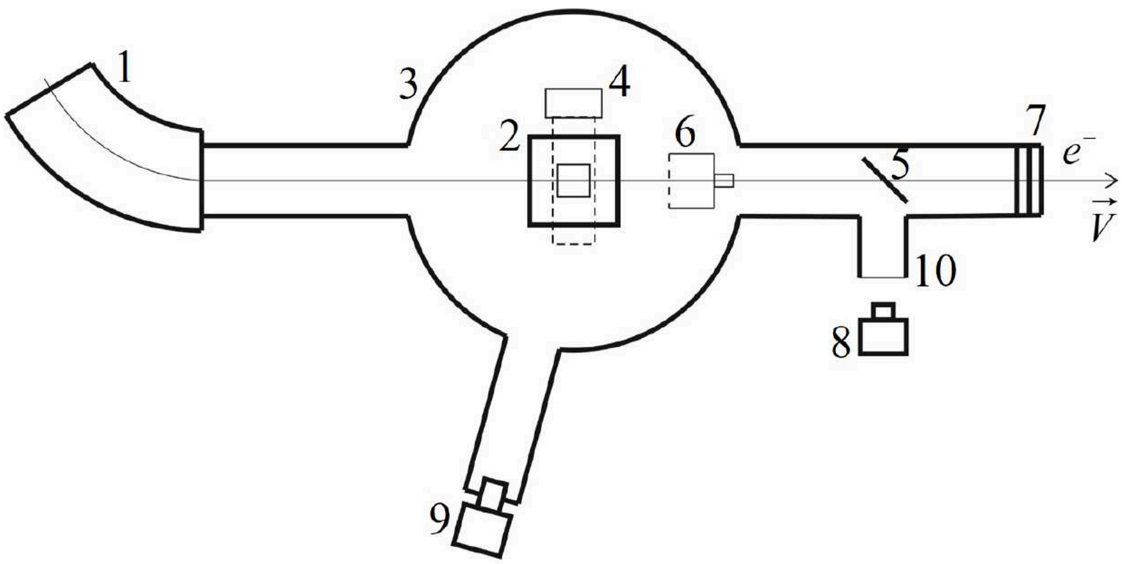

Fig. 2. The scheme of the experiment. 1 - Bending magnet, 2 - pyroelectric deflector, 3 - vacuum chamber, 4 – linear translator, 5 – removable scintillation screen, 6 – removable Faraday cup, 7 - proportional chamber, 8 - web camera, 9 - X-ray detector, 10 – glass window.

$$E_{\max} = \frac{\alpha_{\max}\varepsilon_{kin}}{el}\frac{\varepsilon_{kin}+2m_ec^2}{\varepsilon_{kin}+m_ec^2} \tag{7}$$

where e, m_e are electron charge and mass respectively. From Eq. (7) we find $E_{\max} = \pm 97.2\frac{kV}{cm}$ at $\varepsilon_{kin} = 7$ MeV, and the path of electrons between crystals $l = 2$ cm.

Independent measurement of the field strength between crystals was performed due to X-ray radiation of electrons accelerated between crystals. This radiation was observed in Ref [11]. The X-ray radiation is produced by electrons that are emitted from the negatively charged surface and are accelerate in the gap between crystals toward the positively charged surface. When accelerated electrons collide with the positively charged surface of the crystal, they produce characteristic and bremsstrahlung X-ray radiation. The maximum energy of the bremsstrahlung quanta $\hbar\omega_{\max}$ is practically equal to the maximum energy of the accelerated electrons eU, where U is the difference of the potentials between crystal surfaces. Thus, we can estimate the strength of the electric field $E_{\max}^{X-ray}$ from our X-ray data as

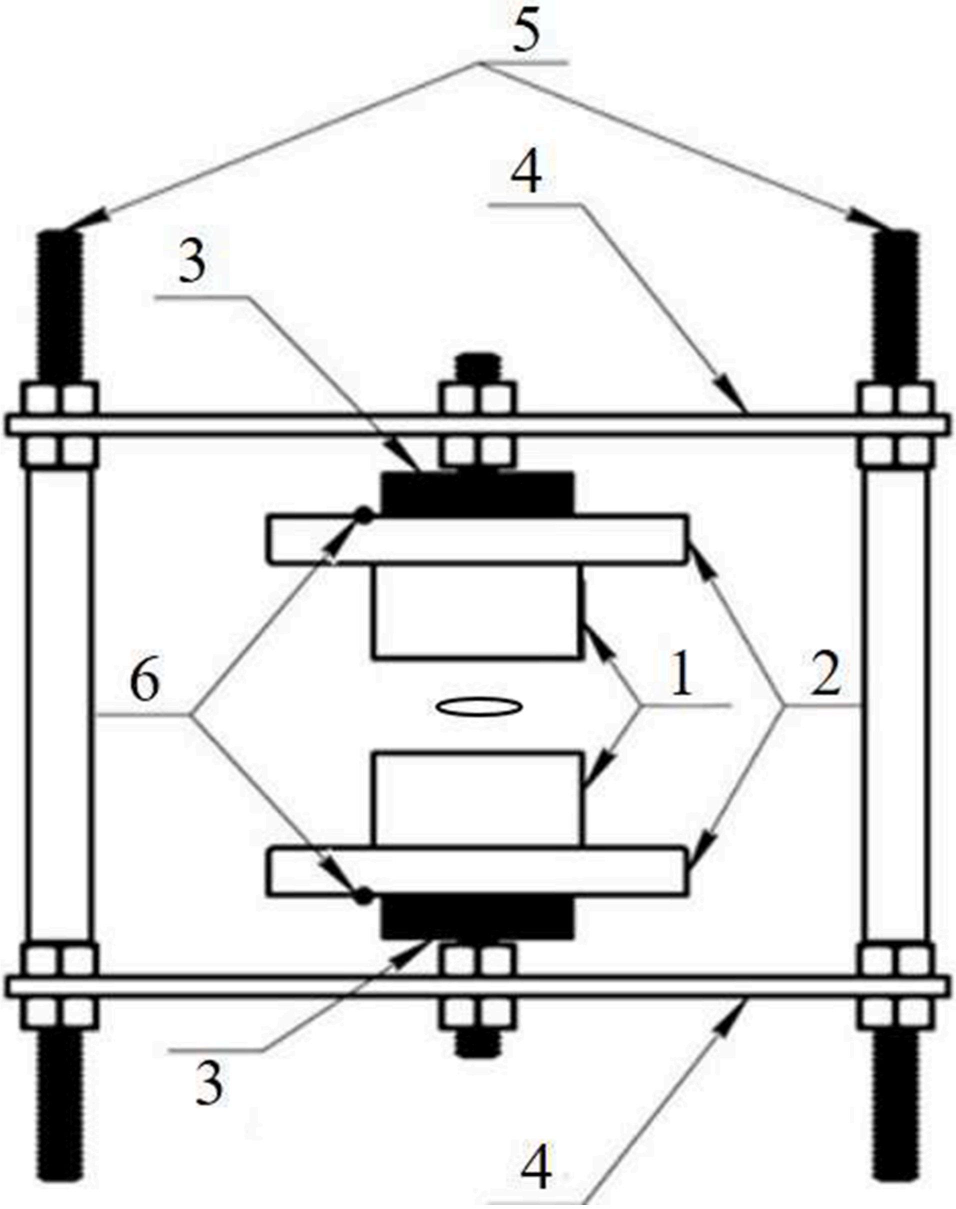

Fig. 3. The design of the pyroelectric deflector. 1 - Pyroelectric crystals, 2 – duralumin heat-conductors, 3 – heating diodes, 4 –metal plates, 5 – metal rods, 6 – K-type thermocouples. The ellipse shows the position of the incident electron beam in the deflector.

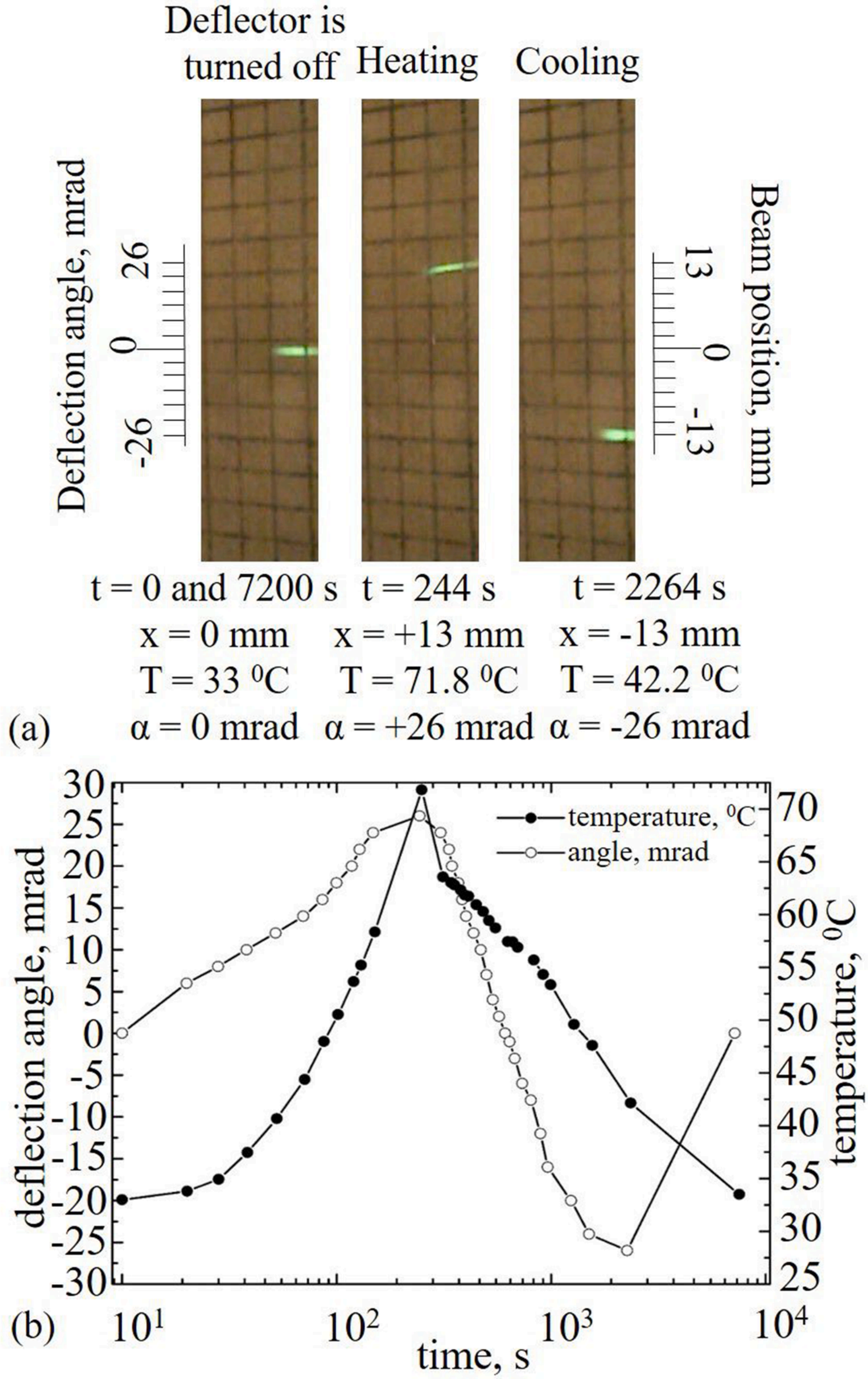

Fig. 4. The deflection of an electron beam. (a) Three photographic imagines of the electron beam spot on the screen when the deflector was turned off and at maximum deflection angles at heating and cooling of pyroelectric crystals. (b) The deflection angle of the electron beam and measured temperature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

$$E_{\max}^{X-ray} = \frac{eU}{ed} = \frac{\hbar\omega_{\max}}{ed} \quad (8)$$

where d is the distance between crystals. Unfortunately, our attempts to measure a spectrum of X-ray radiation by the X-ray detector shown in Fig. 2 during experiments with accelerated electron beam were not successful because of the low intensity of radiation and significant spectral background from the accelerator. Therefore, we performed measurements of spectrum of X-ray radiation from the pyroelectric deflector under the same conditions at the same variations of the temperature as described above but with tuned-off accelerator. The spectrum of X-ray radiation from the pyroelectric deflector measured during one cycle of heating and cooling is shown in Fig. 5.

The spectrum contains peaks with energies 16.62 keV and 18.62 keV which correspond to K_α and K_β lines respectively of characteristic X-ray radiation of Nb atoms from $LiNbO_3$ crystal. The bremsstrahlung radiation has maximum energy $\hbar\omega_{\max} = 110$ keV. With use of Eq. (8) we obtain $E_{\max}^{X-ray} = 100\frac{kV}{cm}$.

6. Discussion and perspectives

We measured the maximum strength of the electric field in the gap between pyroelectric crystals by two independent experimental methods. In the first one, where $E_{\max}$ is estimated by Eq. (7), the electric field strength is averaged along the incident electron beam trajectory. In the second one, where $E_{\max}^{X-ray}$ is estimated by Eq. (8), the electric field strength is averaged in the perpendicular direction along the symmetry axis of the deflector. In spite of so different methods and areas of averaging, results of both measurements of the electric field strength are in good agreement with an accuracy of about 3%. The agreement is because the electric field between free surfaces of crystals is almost uniform similar to one in a parallel-plate capacitor. Thus, the transverse electric field strength of about $100\ \frac{kV}{cm}$ was observed experimentally in the pyroelectric deflector.

Theoretical estimation of the electric field strength in the deflector can be performed using pyroelectric properties of the crystals using Eq. (4.2) from Ref [8]. This estimation at conditions described in the present paper gives strength $211\ \frac{kV}{cm}$ at the variation of the temperature of crystals by 38.8 °C. The calculated strength exceeds experimentally observed one in more than two times. The discrepancy may be because of a leakage of the charge from the free crystal surfaces and some difference of temperatures between crystals and heat-conductors, where the temperature probes are installed.

Note, that the deflecting field, produced by a transverse electric field with strength 100 kV/cm, is equivalent to the deflecting field produced by a transverse magnetic field with inductance 333 H or 0.0333 T for ultra-relativistic particles at $V \to c$.

As we noted above, the range of the temperature variation ΔT in the experiment was 38.8 °C. But we observed instability of the

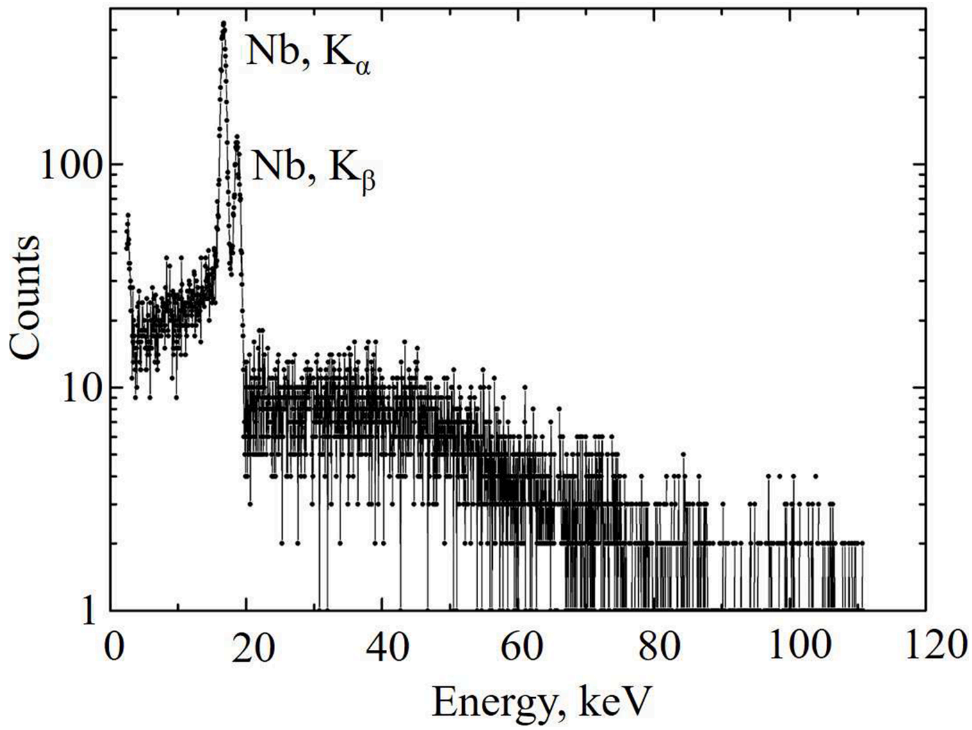

Fig. 5. The spectrum of X-ray radiation from the pyroelectric deflector measured during one cycle of heating and cooling without an external electron beam.

deflection angle and spark discharges at increasing the range at $\Delta T > 40$ °C. Therefore, the stability and reproducibility of the electric field strength should be studied as functions of the residual gas pressure, the range of the temperature variation, the state of pyroelectric crystals surfaces, the shape of the crystals.

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 in Refs [15,16]. The project of the electrostatic undulator of the ultra-relativistic beam with conductive electrodes and external high voltage power supply was proposed in Refs [17,18]. The undulator based on fringing E-field superlattice for electron beam with mildly relativistic energy was proposed in Ref [19]. The undulator based on separate pyroelectric deflectors was proposed in Refs [8,20]. In the present paper, we demonstrated experimentally operation of the pyroelectric deflector with the relativistic electron beam.

The pyroelectric undulator can produce radiation during heating or cooling of the undulator only and cannot operate continuously. However, the pyroelectric undulator could be light, small, cheap and it does not need any external high voltage power supply. The pyroelectric undulator can be applied for the production of electromagnetic radiation in conditions, where such properties of the undulator are acceptable. The pyroelectric undulator can operate during heating or cooling of all pyroelectric deflectors simultaneously. The phase of the undulator radiation should be changed by π at heating or cooling. Pyroelectric crystals or pyroelectric ceramics [21] can be applied in the pyroelectric undulator. Besides, the high voltage produced due to the piezoelectric effect in a vacuum [22] can be used for the power supply of the electrostatic undulator.

7. Conclusion

The obtained results allow concluding that a pyroelectric deflector can be used for slow steering of a relativistic electron beam. The slow operation of the deflector is due to the slow variation of the temperature of the pyroelectric crystals. The pyroelectric deflector does not need in any external high-voltage power supply because the high voltage is produced inside of the vacuum chamber due to the pyroelectric effect. The electric field strength of about 100 kV/cm was observed in the experiment. The power of several Watts from a low-voltage source is enough for the supply of the deflector. The possibility for the development of small, light, cheap pyroelectric undulator based on pyroelectric deflectors is discussed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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