Pyroelectric deflector of charged particle beam

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ABSTRACT: A new type deflector of a charged particle beam based on pyroelectric crystals is proposed and demonstrated experimentally. The transverse electric field arises in the gap between two pyroelectric crystals in vacuum because of the pyroelectric effect appearing when a temperature gradient is applied to both crystals. In a proof-of-principle experiment, we demonstrated deflection of a low-energy electron beam. The application of pyroelectric deflectors as bending elements in the pyroelectric undulator for production of the undulator radiation is proposed.

KEYWORDS: Beam-line instrumentation; beam optics; beam dynamics.

Contents

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1. Introduction

Techniques to control a trajectory of accelerated charged particle beams were developed ever since the invention of accelerators [1] for either steering or focusing the beams or for radiation production. The methods used to control the beams are based on transverse magnetic or electric fields. Dipole magnets are used to steer the beam trajectory, quadrupole magnets are used for strong focusing to concentrate the charged particles around the centroid trajectory, and the other multipole magnets such as skew quadrupoles, sextipoles or even octupoles are used for various beam parameter corrections [2]. Electric field in a capacitor supplied by an outer high voltage source is usually used for steering low- and high-energy beams, e.g. in oscilloscopic tubes or kickers in modern accelerators used to stabilize the particle beam in circular machines or to extract the beams from them. New methods utilizing strong electric fields inside natural crystals have been successfully applied for steering of multi-GeV particle beams [3]. This method is very attractive as the crystal is a passive element, i.e. not requiring any power supply. Experiments on application of dielectrics with surface charge for the steering of low-energy beams are ongoing as well [4,5]. In this paper, we propose a new method for steering the particle beams in vacuum using the electric field generated by pyroelectric crystals when their temperature changes.

Pyroelectric crystals of about 1 cm^3 can generate electric field in vacuum with strength over a 100 kV/cm when heating or cooling the crystals [6]. Since the pioneering experiment [7], pyroelectric crystals are applied in miniature so-called pyroelectric accelerators to produce electron and ion beams with energies up to hundreds of keVs, to generate X-ray radiation [7-14] or neutrons [15]. In the pyroelectric accelerator the particles are accelerated in mTorr vacuum in the electric field produced by charges accumulated on the surfaces of the crystals that arises due to the pyroelectric effect when heating or cooling it. Recently, the feasibility of the ferroelectric ceramics in pyroelectric accelerators instead of crystals was demonstrated in [16].

In this paper we propose and experimentally verify an idea to use the electric field produced due to the pyroelectric effect in the sub-mTorr vacuum between two crystals to steer an outer beam of particles moving across the field. We described a scheme of a pyroelectric beam deflector, presented our first experimental results obtained with a non-relativistic electron beam, and discussed the deflector performance.

2. Pyroelectric deflector

The principle diagram of the pyroelectric deflector for charged particles is illustrated in figure 1. Pyroelectric crystals C are installed on heater/coolers H in vacuum. Polarization vectors $\vec{P}$ of both crystals are parallel to each other and perpendicular to the incoming beam. The beam of charged particles is deflected (kicked) in the transverse direction by electric field $\vec{E}$ that arises in the gap between the free crystal ends when simultaneously heating or cooling both crystals. Directions of the vector $\vec{E}$ and the beam deflection will be opposite at the cooling or at the heating. The potential in the plane of symmetry of the deflector shown with a dashed line is supposed to be zero.

One can install crystals with opposite directions of the polarization vectors. But in this case it will be necessary to simultaneously heat one of crystals and cool the other to obtain transverse electric field.

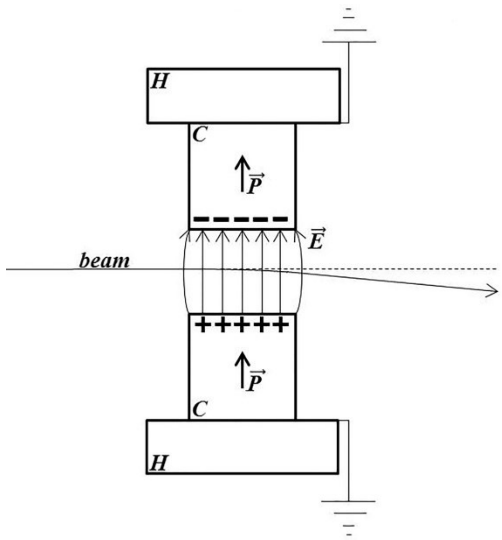

Figure. 1. The principle diagram of the pyroelectric beam deflector.

3. Experiment

The experiment has been performed in the Laboratory of radiation physics of the Belgorod National Research University. The experimental layout is shown in figure 2. The pyroelectric deflector is installed in a vacuum chamber with pressure of about 10^{-6} Torr. Two cylindrical $LiNbO_3$ pyroelectric crystals of diameter l = 11 mm and h = 9 mm in height are mounted on grounded metallic heat-conductors by a conductive adhesive via Peltier elements. The gap between the crystals is d = 14 mm. The Z-axes of both crystals are collinear, parallel to the cylinder axes and perpendicular to the incident electron beam trajectory.

As a source of electrons we used a thermionic electron gun with accelerating voltage of up to 60 kV and filamentary tungsten cathode. The gun can provide the current density of up to 1 A/cm^2. The beam diameter before the diaphragm is 2 mm. The beam angular divergence is smaller than 0.2 mrad.

In our experiment, a 30 keV and 100 pA electron beam passes through a circular diaphragm of 1 mm diameter. Then the beam passes the gap between the pyroelectric crystals and hits the grounded fluoresceent transparent screen installed 30.5 cm away from the deflector. The transverse electric field deflecting the beam arises in the gap between the crystals when simultaneously heating or cooling them. The accuracy of the temperature measurements was 0.125 °C.

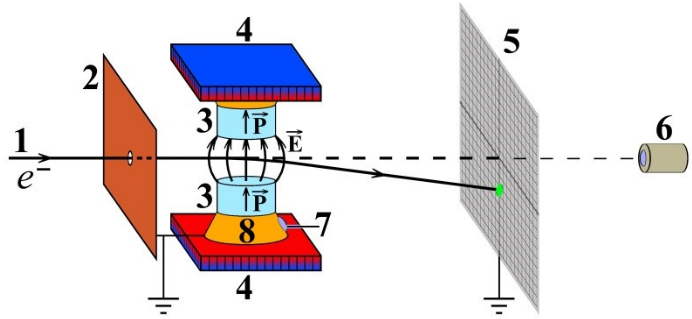

Figure. 2. The experimental layout: The 30 keV electron beam (1) passes through the diaphragm (2) and the gap between the pyroelectric crystals (3). The position of the beam spot on the transparent screen (5) is observed by the camera (6). Pyroelectric crystals (3) are glued to conical metallic heat-conductors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

In the experiment we observed the beam spot shift in the vertical transverse plane as a function of the temperature change of both crystals. The images of the beam spot on the screen measured every 3 seconds during the heating process are shown in figure 3. If the temperature of both crystals increases the beam shifts one way, if the temperature decreases the shift direction is reversed. As shown in figure 3, during these measurements the temperature was changing from 23.37 °C to 24.87 °C in 27 s, i.e. the temperature changed by 1.5 °C around room temperature. One can see that the total beam shift was 57mm. This means that the 30 keV electron beam was deflected by a total angle of α = 10.6°. The zero beam position on the screen corresponded to discharged crystals.

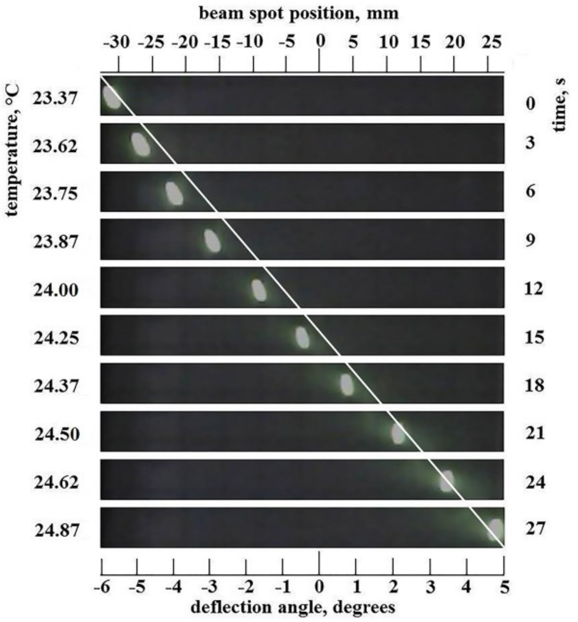

Figure. 3. Images of the 30 keV electron beam observed every 3 seconds during heating of the pyroelectric crystals. The straight diagonal line is given in the figure to see a slight nonlinearity of the beam deflection.

Figure 4 illustrates the dependence of the deflection angle versus crystal temperature. One can see that the beam shift in the plane of symmetry (vertical deflection in Figure 4 right) of the deflector during the heating is very small. This fact confirms the lack of a significant orthogonal component of the electric field in the gap due to edge effects. A small residual vertical offset can be explained by a small azimuthal misalignment of the double crystal system with respect to the vertical direction defined by the azimuthal orientation of the camera. A slight nonlinearity of the beam deflection as a function of temperature in horizontal direction (Figure 4 left) may be explained by the temperature inertia in the deflector. The inertia arises because the crystals temperature change is delayed relative to the temperature change of the heat-conductors, where the temperature probes are installed. The effect of the temperature inertia has been recently studied in [17].

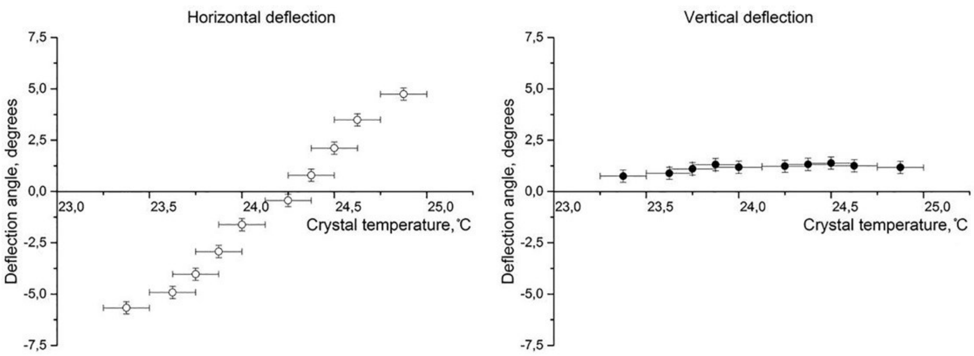

Figure. 4. Dependence of the beam deflection angle as a function of the temperature.

In figure 3 it is obvious that the azimuthal alignment of the ellipsoid of the beam spot changes at different temperatures. In other words, the upper part of the beam is deflected for some bigger angle in comparison to the lower part. Figure 5 shows the angle of rotation of the long axis of the beam spot ellipsoid as a function of the beam centroid deflection. The rotation might appear due to the beam offset with respect to the center of the deflector in the plane of symmetry. On the other hand, due to the edge effects, non-uniform distribution of the charge along the crystal surface and disorientation of the crystals relative to the symmetrical geometry the field distribution might be non-uniform and cause the beam rotation. This phenomenon requires additional dedicated studies.

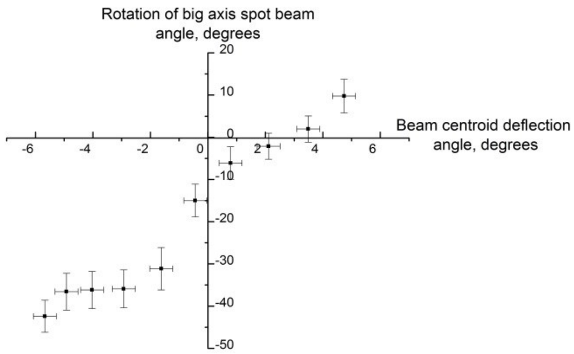

Figure. 5. Dependence of the angle of rotation of the long axis of the beam spot ellipsoid as a function of the beam centroid deflection angle.

4. Transverse electric field

The variation of the strength of the transverse electric field $\vec{E}$ in the deflector during the heating can be estimated from our experimental data by the non-relativistic formula at $\varepsilon_{kin} \ll mc^2$

$$E = \frac{2\varepsilon_{kin}}{q \cdot R} \tag{1}$$

where ε_{kin} is the kinetic energy of electrons, q is electron charge, R is the radius of the electron trajectory in the transverse plane. In our case the radius can be estimated as $R = \frac{l}{\alpha}$, where α is the small measured deflection angle, l is the path of electrons in the field. The path length is roughly estimated as equal to the crystal diameter $l \approx 11$ mm. The 30 keV electron beam was deflected by a total angle of α = 10.6°, see figure 3. Equation (1) returns the experimental transverse electric field strength variation in the gap of 10.1 kV/cm for the temperature change of ΔT = 1.5°C

For comparison the variation of the strength of the transverse electric field ΔE_c in the deflector can be estimated from the properties of the pyroelectric crystal using formula (9) from [6].

$$E_c = \frac{\gamma \cdot \Delta T}{\varepsilon_0 \cdot \varepsilon \cdot \frac{d_g}{h}}, \qquad (2)$$

where γ is the pyroelectric coefficient, ε_0 is the dielectric permittivity of free space, ε is the relative dielectric permittivity of the pyroelectric crystal, h is the height of the crystals, $d_g = d/2$ is the distance between the free ends of the crystals and the plane of symmetry of the deflector. In calculations we used values γ = 0.82·10^{-4} C/(m^2 K) and ε = 31 for $LiNbO_3$ using Table 1 from [3]. The electric field strength change in the deflector calculated by Eq. (2) is ΔE_c = 5.8 kV/cm at ΔT = 1.5°C.

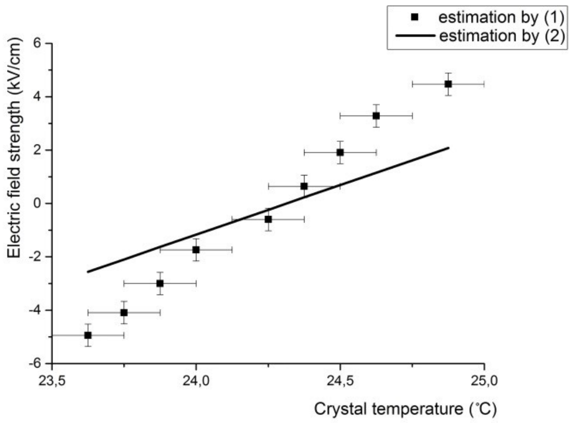

Figure. 6. Dependence of the electric field strength versus crystal temperature estimated using Eq. (1) and Eq. (2)

It is clear that the estimations of the transverse electric field performed using Eqs. (1) and (2) have the same order of magnitude, but the estimated maximum value using Eq. (1) exceeds the estimation by Eq. (2) almost twice as much. Figure 6 demonstrates the comparison of electric field strength in the gap between the free ends of the pyroelectric crystals as a function of the temperature. The points and curve are calculated using Eq. (1) and (2) in accordance with conditions for the experimental results presented in figure 3 (the values of the deflection angles and temperature gradient were extracted from figure 3). It is clear that the gradient of the curve calculated with (1) is nearly 2 times larger in comparison with ones calculated with (2). The reason of the discrepancy can be explained in the difference of the real crystal temperature and the temperature measured in the heat-conductor, and, also, by the influence of the field edge effects around of the deflector. It is well-known that the edge effects in any type of deflector are highly non-linear. Moreover the non-uniformity of charge distribution along the crystal surface [9] is determined by the roughness of the surface, the crystal uniformity and purity. In the estimations the edge effects and non-uniform charge distribution along the surface of the crystals were not taken into account.

5. Results and Discussion

In the paper we have proposed a new type of a pyroelectric deflector to control trajectory of a charged particle beam. We have demonstrated the deflection of a low-energy electron beam experimentally and studied some properties of the deflected beam. Note that the arrangement of the pyroelectric crystals in the deflector is similar to the one in a pyroelectric accelerator with paired crystals proposed in [13]. In the pyroelectric accelerator, the beam of particles is accelerated between two crystals at a residual gas pressure of few mTorr. In our experiment the vacuum of 10^{-6} Torr was achieved. Nevertheless residual particles might still be accelerated, discharge the potential between the crystals and distort the experimental results. To monitor any accelerated particles we installed an X-ray spectrometer (Amptek XR-100T Cd-Te X-ray detector with a 100 μm thickness Be window) sunk into the vacuum camera. However, no bremsstrahlung or characteristic X-rays excited by accelerated electrons in crystals were found during the experiment. This is not surprising because in our experiment the residual gas pressure was about 10^{-6} Torr instead of a few mTorr in [13] and the range of the temperature variation was much smaller than in [13] as well.

Due to miniature dimensions the pyroelectric deflector [18] can be integrated in any vacuum system to steer a beam and/or for radiation production. Besides, the deflector can be applied in miniature quadrupoles. A few-watt low-voltage power supply is needed to empower the heater/cooler. This fact makes it be attractive for various applications where the use of an outer high power voltage source is not desirable or in the case of lack of available space for a power supply.

High strength of the electric field is needed for deflection of relativistic particles. Now, the values about 100 kV/cm are achieved in pyroelectric accelerators [13]. One can hope to obtain similar values in pyroelectric deflector. However, problems of pyroelectrics discharge because of acceleration of particles between the crystals and possible spark discharges should be solved at increasing of the temperature range and field in the pyroelectric deflector. The electric field strength in the deflector can be corrected by adjusting the temperature of the crystals. The correction should be applied slowly to minimize the temperature inertia effect.

Usually, the potential at the pyroelectric crystal surface is evaluated as the endpoint of the bremsstrahlung spectrum, which is generated by accelerated electrons, see e.g. [7-13]. The deflection of an external beam of charged particles can also be used to measure the electric fields and potentials created due to the pyroelectric effect. Moreover this method enables to measure the electric field map across the gap by scanning the electron beam across it.

A set of pyroelectric deflectors can be applied as deflecting elements in a pyroelectric undulator, where the periodical transverse electric field is used instead of transverse periodical magnetic field in conventional undulators. A small, light, cheap pyroelectric undulator can be used for production of undulator radiation from relativistic electron beams. Experiments with high-energy beams are needed to prove the principle and demonstrate the emission of radiation.

Alternatively, ferroelectric ceramics [16] can be used in the pyroelectric deflector instead of pyroelectric crystals.

6. Acknowledgements

The research was supported by the grant from the Russian Science Foundation (project №16-19-10535). Authors are thankful to E. Irribarra for useful discussions.

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