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ON THE POSSIBILITY OF USING STRAIGHT AND BENT CRYSTALS FOR CHARGED PARTICLE BEAM STEERING AT THE FUTURE MULTIFUNCTIONAL ACCELERATOR COMPLEX OF NSC KIPT

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The scattering of electrons and positrons with energy of 500 MeV on straight and bent silicon crystals has been considered using numerical simulations. The selected particle energy corresponds to parameters that can be achieved at the future multifunctional accelerator complex of the NSC "Kharkiv Institute of Physics and Technology". It is shown that bent crystals, at certain orientations, allow deflecting charged particles at angles significantly exceeding the critical angle of axial channeling. It is also shown that experimental investigation of the effect of reducing incoherent scattering of high-energy positrons when orienting the crystal relative to the direction of particle incidence near one of the main crystal axes is of interest.

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INTRODUCTION

The National Science Center "Kharkiv Institute of Physics and Technology" has extensive experience in experimental work in the field of interaction of high-energy charged particles with amorphous and crystalline targets. In particular, this center previously operated a linear accelerator that accelerated electrons to an energy of 2 GeV. Currently, this accelerator is not in operation, but there is a plan to construct a new multifunctional accelerator complex that would be able to produce electron (and positron) beams with energies up to about 500 MeV [1–3]. In this work, using numerical simulations we consider the orientation effects in the scattering of 500 MeV electrons and positrons on crystalline targets. Scattering on atomic strings and atomic planes of a straight crystal is considered, as well as the possibilities of particle deflection during planar channeling and motion near the crystal axis in a bent crystal. In the case of particle motion in a bent crystal, the primary focus is on finding the optimal crystal parameters that correspond to the most efficient deflection of particles.

1. SCATTERING IN A STRAIGHT CRYSTAL

The process of scattering high-energy electrons and positrons in oriented crystals has been intensively studied in many accelerator centers in recent years (see e.g. [4–6]). The interest in this process is related both to the study of the characteristics of effects such as channeling and particle deflection by crystals, and to the potential application of these effects for beam manipulation, the creation of radiation sources, and pair production. Below in this section, we will analyze a number of interesting orientation effects that can be observed during the scattering of 500 MeV electrons and positrons in a straight crystal. Silicon is considered as the target crystal, since, on the one hand, this material has a densely packed diamond-like crystal lattice, and on the other hand, well-developed methods for producing such crystals with a very low number of defects are currently available. Let us begin by examining the effects that occur with the planar orientation of the crystal. As Lindhard demonstrated [7], in this orientation, planar channeling and over-barrier motion in the field of the atomic planes of the crystal are possible. The periodic arrangement of atomic planes in a crystal causes charged particles to move in a periodic potential field generated by these planes, which has maxima and minima. The difference between the maximum and minimum of this planar potential, multiplied by the absolute value of the particle charge, is referred to as the potential well depth U_0. Planar channeling occurs if the transverse energy of particle

$$E_{\mathrm{T}} = \frac{1}{2} p v \theta^2 + U(x) \tag{1}$$

does not exceed the depth of the potential well. Here p is the absolute value of particle momentum; v is the absolute value of its velocity; θ is the angle between the particle momentum and the crystal planes, and $U(x)$ is the potential energy of the particle in the field of the planes, with its minimum value set to zero. From Eq. (1) we see that if

$$|\theta| > \sqrt{\frac{2U_0}{pv}} = \theta_c , \tag{2}$$

planar channeling is impossible. The angle θ_c is known as the critical angle of planar channeling. According to Eq. (2) it depends on the energy of the particle and on the choice of crystal orientation. Without loss of generality, we will choose the (110) plane of a silicon crystal for further consideration of the particle scattering process. For this plane $U_0 \approx 21.35$ eV and so for 500 MeV electrons and positrons $\theta_c \approx 292$ μrad.

In Fig. 1, the dependence of the deflection angle of 500 MeV positrons after passing through a 100 μm thick crystal on the incoming angle is shown. The choice of the crystal thickness will be explained in the next section, where the scattering of particles in a bent crystal will be discussed. To better understand the characteristics of the particle scattering process, the initial beam divergence was assumed to be zero here and in subsequent analyses. The simulation was performed using the code described in [8, 9]. On the abscissa axis, the initial angle θ_x between the particle momentum and the atomic plane (110) is plotted. On the ordinate axis, the difference between the angle θ between the particle momentum and the atomic plane (110) at the particle exit from the crystal and θ_x is shown: $\vartheta_x = \theta - \theta_x$. The simulation was conducted for various values of θ_x, ranging from -1.5 to +1.5 mrad, with a step of 25 μrad. For each value of θ_x, the passage of 10^4 particles through the crystal was simulated. The color represents the number of particles deflected by a given angle.

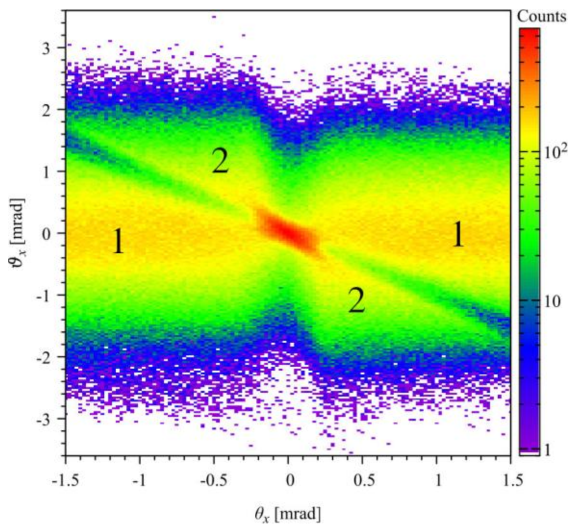

Fig. 1. The dependence of the deflection angle of 500 MeV positrons after passing through a 100 μm thick Si crystal with planar orientation on the incoming angle

To understand the distributions presented in Fig. 1 for different positron incoming angles, it is necessary to analyze equations (1) and (2). From these equations, it follows that, without taking into account incoherent scattering of positrons by atomic thermal vibrations and the electronic subsystem of the crystal, particles are captured into the planar channeling regime if the absolute value of the angle θ_x does not exceed θ_c. However, since incoherent scattering is accounted for in the simulation, we observe deflected particles even for $|\theta_x| > \theta_c$.

To study the scattering process without considering incoherent scattering, one must analyze thinner crystals where such scattering can be neglected. As an example, Fig. 2 shows the same deflection angle distributions as in Fig. 1, but for scattering in a 1 μm thick crystal. This thickness is very informative, as the thickness of the crystal that a particle passes through while making one oscillation in the planar channeling regime can be estimated as $\lambda = \pi d_p / \theta_c$ [11], where d_p is the distance between neighboring atomic planes, and in our case $\lambda \approx 2$ μm. We observe that capture into the planar channeling regime indeed occurs only at $|\theta_x| < \theta_c$. Particles with larger entry angles are scattered in the field of atomic planes as over-barrier particles. Additionally, as seen, there is a periodic structure in the distributions at $|\theta_x| > \theta_c$, which is due to the fact that, when approaching the atomic plane, positrons are decelerated by its field, and after passing through it, they accelerate. From equation (1), it follows that the maximum deflection angle for particles captured in the planar channeling regime is $\pm 2\theta_c$, which is exactly what we observe in Fig. 2 at $|\theta_x| = \theta_c$ (the slight exceeding of this angle in the figure is due to the fact that, even with a crystal thickness of 1 μm, incoherent scattering still makes a small contribution to the scattering process.). A more detailed analysis of the scattering process of positively charged particles in ultrathin crystals is provided in reference [10].

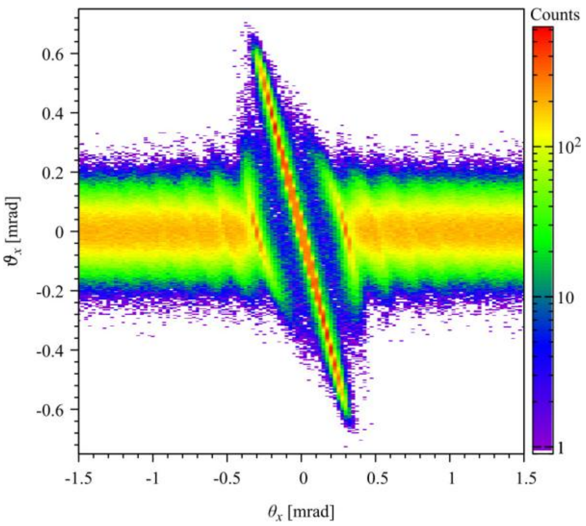

Fig. 2. The dependence of the deflection angle of 500 MeV positrons after passing through a 1 μm thick Si crystal with planar orientation on the incoming angle

Returning to Fig. 1, we can now observe that the shown distributions can be divided into several regions. The regions marked with the number 1 represent over-barrier particles not captured in the planar channeling regime. Their scattering in the crystal with thicknesses of 100 μm is mainly determined by incoherent scattering. The regions marked with the number 2 represent particles that were captured into the planar channeling regime at some point along their trajectory in the crystal and were significantly deflected from their initial entry direction into the crystal. It is worth noting that the absolute value of deflection angle for many such particles significantly exceeds $2\theta_c$, which can be explained by the influence of incoherent scattering. At the same time, in the region near the origin, the distribution resembles that shown in Fig. 2, but it is more "blurred" due to incoherent scattering.

Similar distributions for 500 MeV electrons are shown in Fig. 3. The crystal thickness is also 100 μm. Considering that electrons are attracted to the positively charged atomic nuclei of the crystal, incoherent scattering due to atomic thermal vibrations is more intense for them, as they spend more time near the nuclei when passing through an oriented crystal. This is confirmed in Fig. 3, where, due to strong incoherent scattering, the deflection of particles captured into the planar channeling regime is barely noticeable against the background of incoherent scattering. Nevertheless, the asymmetry of the distribution is caused precisely by the capture of particles into the planar channeling regime, making Fig. 3 similar to Fig. 1 in this regard. Note that due to incoherent scattering, even particles whose angle between their momentum and the atomic plane at entry exceeded the critical angle for planar channeling can be captured into the planar channeling regime inside the crystal.

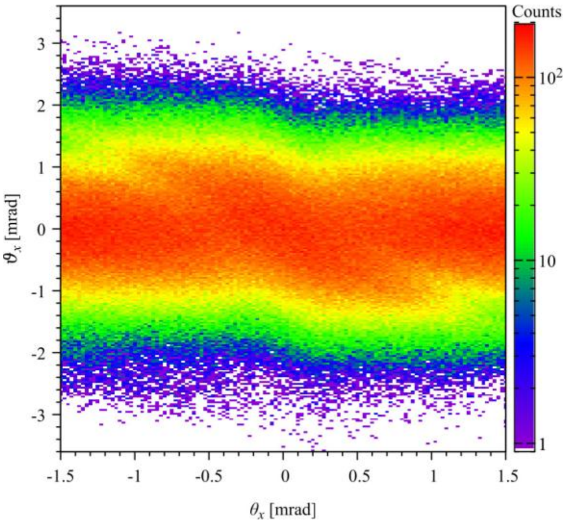

Fig. 3. The dependence of the deflection angle of 500 MeV electrons after passing through a 100 μm thick Si crystal with planar orientation on the incoming angle

Let us now move on to the consideration of particle scattering in the field of atomic strings of the crystal. Without loss of generality, we will examine the case of particles incident on the crystal near the crystalline axis $\langle 110 \rangle$. The *x*-axis lies in the (100) plane of the crystal, while the *y*-axis is in the (110) plane. The *z*-axis coincides with the $\langle 110 \rangle$ axis of the crystal. The critical angle for axial channeling in this case is

$$\psi_c = \sqrt{\frac{4Ze^2}{pvd}} \approx 648\ \mu\text{rad}, \qquad (3)$$

where *Z* is the atomic number of the nuclei, *e* is the positron charge, and *d* is the distance between neighboring atoms in the atomic string.

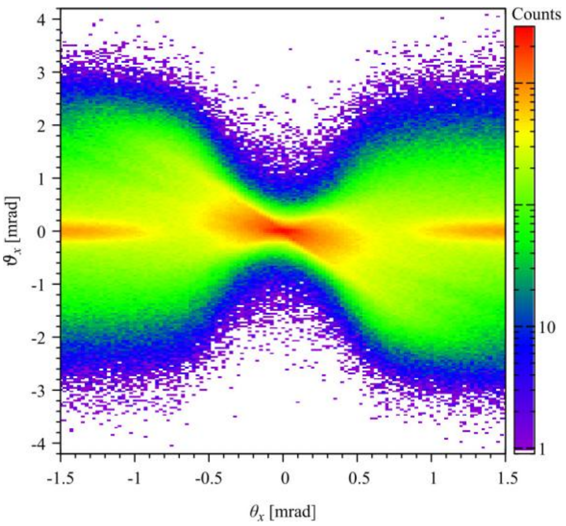

Fig. 4. The dependence of the deflection angle of 500 MeV positrons after passing through a 100 μm thick Si crystal with axial orientation on the incoming angle

The dependence of the deflection angle of 500 MeV positrons after passing through a 100 μm thick Si crystal in this case on the incoming angle is shown in Fig. 4. In this figure, as in the previous ones, the asymmetry caused by the capture of particles by the field of atomic strings (so called doughnut scattering) is noticeable, but the most interesting effect is the significant reduction of incoherent scattering of positrons when the incidence angle $|\theta_x| < \psi_c$ [12]. This suppression of incoherent scattering is related to the fact that the transverse energy of the particle at $|\theta_x| << \psi_c$, for those particles that impinge on the crystal in points significantly farther from the atomic strings than the root mean square deviation of atoms due to thermal vibrations $u_T \approx 0.075\,\text{Å}$, is insufficient for the particles to approach the strings closely. The farther the particle moves from the atomic strings within the crystal, the lower the probability of it being scattered at large angles due to incoherent scattering.

Finally, in Fig. 5 the dependence of the deflection angle of 500 MeV electrons after passing through a 100 μm thick axially orientated Si crystal on the incoming angle is shown. Since electrons are attracted to the positively charged atomic nuclei, the suppression of incoherent scattering that occurred in the case of positrons is not present. The asymmetry of the distribution is caused by the doughnut scattering of over-barrier particles in the field of atomic strings of the crystal.

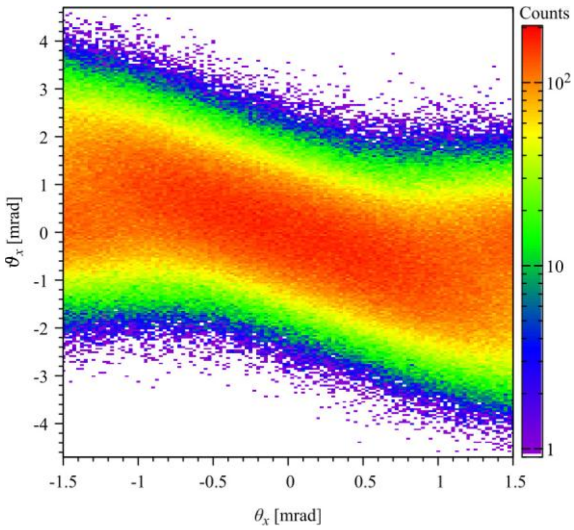

Fig. 5. The dependence of the deflection angle of 500 MeV electrons after passing through a 100 μm thick Si crystal with axial orientation on the incoming angle

2. SCATTERING IN A BENT CRYSTAL

Let us now consider the scattering of particles in a bent crystal. The bending of the crystal introduces asymmetry into the scattering problem. This asymmetry leads to the presence of a centrifugal force acting on the particle in the reference frame associated with the bent atomic planes or atomic strings of the crystal (meaning that the *x* and *y* axes remain the same as in the straight crystal, while the z-axis bends along with the crystal). In this reference frame, the transverse energy of the particle can be written as follows [11]:

$$E_T = \frac{1}{2} pv\theta^2 + U(x) + \frac{pv}{R} x, \quad (4)$$

where *R* is the radius of curvature of the crystal, and the *x*-axis lies in the plane of bending of the crystal.

The presence of centrifugal energy in (4) leads to faster dechanneling of particles captured in the planar channeling regime. On the other hand, the bending of the crystal planes causes the channeling particles to be deflected in the direction of the crystal bend. If the particle does not dechannel, it will be deflected by the full bending angle of the crystal. This angle should be reasonably chosen based on the tasks to be performed using the bent crystal. This could involve improving beam collimation, where the crystal needs to deflect halo particles onto an amorphous absorber, or the task of extracting part of the beam from the accelerator into a separate channel. To solve such tasks, deflection angles of several mrad are needed. Below we will consider the problem of deflecting 500 MeV positrons and electrons by an angle of 10 mrad while passing through bent crystals with planar and axial orientations.

An important question is what the bending radius of the crystal should be so that the maximum number of particles is deflected by the specified angle, which in our case is chosen to be 10 mrad. To answer this question, simulations were performed for particle scattering in crystals with different bending radii. The simulation was carried out for various values of *R*, ranging from 1 mm to 10 cm, with a step of 1 mm for small *R* and 0.5 cm for higher *R* (the step size is easily seen from the width of the bins in the figures). The results are shown in Fig. 6, where the bending radius of the crystal is plotted on the abscissa axis, and the deflection angle of the positrons is plotted on the ordinate axis. As before, color represents the number of particles deflected by a certain angle. Also, as before, the initial beam divergence was set to zero, and the simulation was conducted for 10^4 particles for each value of the bending radius. Since the bending angle of the crystal is fixed, the thickness of the crystal is a function of the bending radius and is equal to $L \approx 10^{-2} R$.

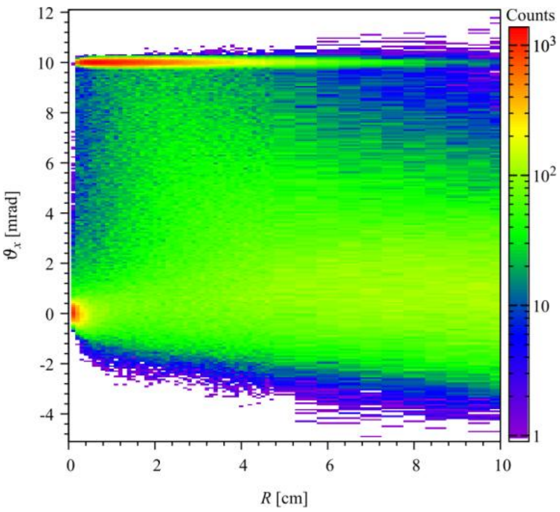

Fig. 6. The dependence of the deflection angle of 500 MeV positrons after passing through a bent Si crystal with planar orientation on the radius of curvature of the crystal

From the figure, we see that at small values of the bending radius, particles are not deflected by the bent crystal, as in equation (4) the centrifugal energy significantly exceeds the depth of the potential well of the planar channel. As the bending radius increases, the centrifugal energy decreases, and particles begin to deflect by the bending angle of the crystal. The maximum number of deflected particles corresponds to a bending radius from 0.5 to 2 cm, which corresponds to the crystal thicknesses from 50 to 200 μm. This is precisely why, in the previous section, we examined scattering in a straight crystal with a thickness of 100 μm. This now allows us to compare the deflection angles that can be achieved through scattering particles in straight and bent crystals. From Fig. 6, we see that with a reasonable choice of the bending radius of the crystal, the vast majority of the beam particles are deflected by 10 mrad. It should be noted that taking into account the divergence of the initial beam will lead to a decrease in the number of deflected particles, as only particles for which $E_T < U_0$ can be channeled. It is also important to note that a bending radius of a few centimeters is no longer something exotic. In particular, such bent crystals are produced by specialists at the University of Ferrara and INFN Ferrara (e.g., in experiment [4], the radius of curvature of the crystal was 3 cm). Let us emphasize that the existence of an optimal bending radius of the crystal, which corresponds to the highest fraction of positively charged particles deflected by a given angle, is similar to the analogous effect for negatively charged particles [13–16]. This phenomenon can be explained by the fact that if the bending radius is less than the critical radius of planar channeling (≈ 1 mm in our case), the particles are not deflected by the crystal and as the bending radius increases, the thickness of the crystal also increases (since the bending angle is fixed), and at a certain radius, the thickness reaches the dechanneling length of the particles [11] which is about 300 μm in our case (such thickness of the crystal corresponds to $R \approx 3$ cm).

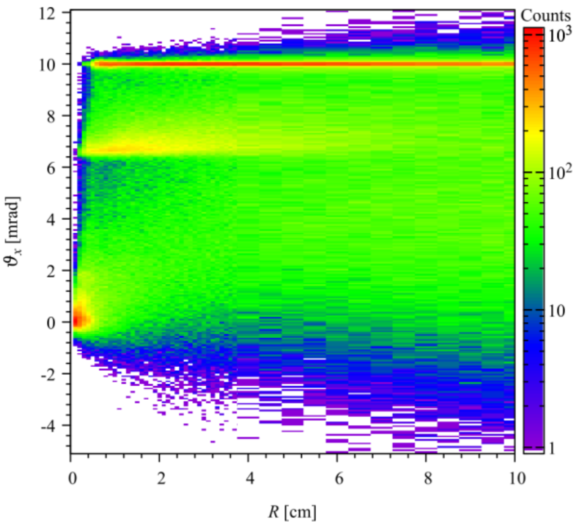

Fig. 7. The dependence of the deflection angle of 500 MeV positrons after passing through a bent Si crystal with axial orientation on the radius of curvature of the crystal

In Fig. 7 the dependence of the deflection angle of 500 MeV positrons after passing through a bent Si crystal with axial orientation on the radius of curvature of the crystal is shown. We see that, as with planar channeling, there is a fairly large range of bending radii of the crystal in which the majority of particles are deflected by the bending angle of the crystal. The difference is that this range is wider, and there is also a group of particles that are deflected by an angle of about 6.5 mrad. These are the particles that exited the axial deflection regime (the Grinenko-Shul'ga mechanism) and transitioned into the planar channeling regime in the (111) planes.

Overall, comparing the last two figures with Figs. 1 and 4 from the previous section, we can conclude that a bent crystal allows positrons with an energy of 500 MeV to be deflected at much larger angles than a straight one. Importantly, the deflected part of the beam is well-collimated, both in the case of planar channeling in the bent crystal and when particles are moving near the bent crystal axis. A distinctive feature of the Grinenko-Shul'ga mechanism is that after particles pass through the crystal, there are significantly fewer particles with $\vartheta_x < 0$ compared to planar channeling. This is due to the larger angular acceptance of the Grinenko-Shul'ga mechanism along the *x*-axis.

In Fig. 8 the dependence of the deflection angle of 500 MeV electrons after passing through a bent Si crystal with axial orientation on the radius of curvature of the crystal is shown. We see almost no particles deflected at 10 mrad. This is because, for electrons, the dechanneling length is much shorter than for positrons, and at the chosen particle energy, they dechannel before they can be deflected by a significant angle.

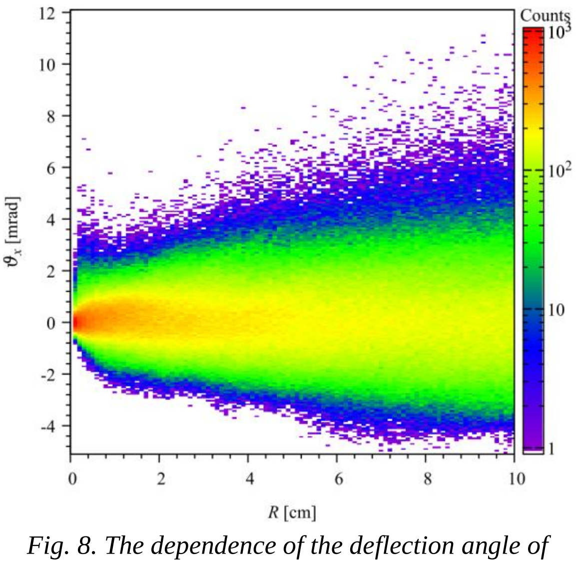

Fig. 8. The dependence of the deflection angle of 500 MeV electrons after passing through a bent Si crystal with planar orientation on the radius of curvature of the crystal

Finally, Fig. 9 shows the dependence of the deflection angle of 500 MeV electrons after passing through a bent Si crystal with axial orientation on the radius of curvature of the crystal. Due to strong incoherent scattering, the number of electrons deflected by the crystal's bending angle is significantly smaller than in the case of positrons. However, unlike planar channeling, the Grinenko-Shul'ga mechanism allows at least a small portion of the electrons to be deflected by 10 mrad, which can be used for the slow extraction of particles from the accelerator (as was proposed in [17]).

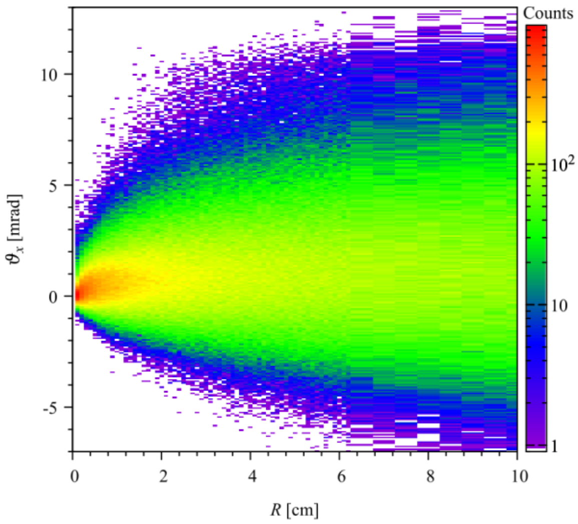

Fig. 9. The dependence of the deflection angle of 500 MeV electrons after passing through a bent Si crystal with axial orientation on the radius of curvature of the crystal

The conducted analysis has shown that at energies achievable at the future multifunctional accelerator complex of NSC KIPT, there are several interesting orientation effects in the scattering of electrons and positrons in straight and bent crystals. Experimental investigation of these effects is important both for deepening the understanding of the particle scattering process in oriented crystals and for developing methods of particle extraction from accelerators using compact bent crystals.

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ПРО МОЖЛИВІСТЬ ВИКОРИСТАННЯ ПРЯМИХ ТА ЗІГНУТИХ КРИСТАЛІВ ДЛЯ КЕРУВАННЯ ПУЧКОМ ЗАРЯДЖЕНИХ ЧАСТИНОК НА МАЙБУТНЬОМУ БАГАТОФУНКЦІОНАЛЬНОМУ ПРИСКОРЮВАЛЬНОМУ КОМПЛЕКСІ ННЦ ХФТІ

І.В. Кириллін, Г.Д. Коваленко

За допомогою числового моделювання було розглянуто розсіювання електронів і позитронів з енергією 500 МеВ у прямих і зігнутих кристалах кремнію. Обрана енергія частинок відповідає параметрам, які можуть бути досягнуті на майбутньому багатофункціональному прискорювальному комплексі ННЦ «Харківський фізико-технічний інститут». Показано, що зігнуті кристали при певних орієнтаціях дозволяють відхиляти заряджені частинки на кути, які значно перевищують критичний кут осьового каналювання. Також показано, що експериментальне дослідження ефекту зменшення некогерентного розсіяння високоенергетичних позитронів при орієнтації кристала відносно напрямку падіння частинок поблизу однієї з головних осей кристала є цікавим напрямком дослідження.