DEPENDENCE OF 6 GeV ELECTRON DEFLECTION EFFICIENCY BY AXIALLY AND PLANARLY ORIENTED BENT CRYSTALS ON THE INITIAL BEAM DIVERGENCE

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Based on numerical simulations, an analysis was conducted on the dependence of the 6 GeV electron deflection efficiency at a given angle on the initial angular beam divergence for two crystal orientations: planar and axial. It is shown that in the case of axial orientation, the deflection efficiency is significantly higher, and as the initial angular beam divergence increases, it decreases much more slowly than in the case of planar crystal orientation.

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INTRODUCTION

This work is a continuation of the study [1], which investigated the possibility of using bent crystals with axial and planar orientations for extracting electrons from the beam halo of the DESY II booster synchrotron. In [1], optimal bending radii were determined for these crystal orientations to deflect the maximum number of electrons by a specified bending angle of 1.75 mrad, defined in [2] as the angle sufficient for electron extraction from the accelerator ring. In the present paper, we investigate the dependence of deflection efficiency on the angular divergence of the beam incident on the crystal. This is crucial because, in practical application, particles from the beam halo will strike the crystal at various angles.

DEFLECTION OF ELECTRONS

As high-energy charged particles move through an oriented crystal, correlations in scattering by neighboring lattice atoms appear. These correlations lead to an enhancement of the scattering angle. If the crystal is bent, the curvature introduces additional asymmetry into the problem. In cases where the crystal thickness is significantly smaller than its bending radius, and the particle motion is described in a non-inertial reference frame associated with the bent atomic planes or strings [3], the particle moves in the effective potential in which the effective potential energy of the particle is

$$U_{eff}(x,y) = U(x,y) + E\frac{x}{R}. \qquad (1)$$

Here $U(x,y)$ is the potential energy of the particle in the field of the atoms in a straight crystal, R is the bending radius, E is the particle energy, and x is the coordinate in the direction of the curvature vector. The second term in the right side of Eq. (1) represents the centrifugal energy. The smaller the bending radius, the more the potential in which the particle moves changes compared to the case of a straight crystal.

Fig. 1 shows the effective potential for the (111) planes of a silicon crystal at various values of R. A straight crystal corresponds to $R = \infty$, in which case the potential well depth is approximately 28.3 eV [4]. As the bending radius decreases, the depth of the potential well also decreases. For electrons with an energy of 6 GeV, the well disappears at $R = R_c \approx 0.9$ cm. In [1], it was shown that for deflecting 6 GeV electrons, the optimal curvature radius for a bent silicon crystal oriented near the (111) planes is about 8 cm, while for the axial orientation, the optimal radius is approximately 1 m. In this case, the bending angle is set to 2 mrad to ensure that the maximum possible number of particles is deflected by an angle exceeding 1.75 mrad. In the present work, for these optimal bending radii, the profiles of the beam scattered by the crystal were obtained for various values of the initial angular beam divergence using numerical simulation.

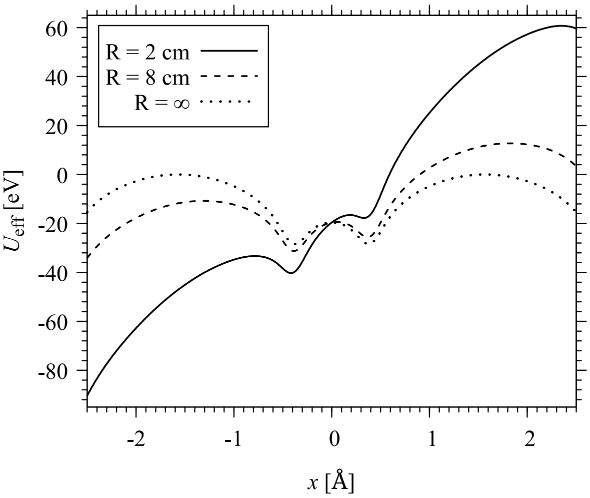

Fig. 1. The effective potential for the (111) planes of a silicon crystal at various values of bending radius

The initial angular divergence was defined by a uniform distribution. In the case of planar crystal orientation, it was a uniform distribution from $-\max(\theta_{in,x})$ to $\max(\theta_{in,x})$. In the case of axial crystal orientation, it was a uniform distribution within a circle of radius $\max(\theta_{in,x})$: $(\theta_{in,x})^2 + (\theta_{in,y})^2 \le (\max(\theta_{in,x}))^2$. The number of incident electrons in the simulation was 10^5.

Fig. 2 shows the numerically simulated dependence of the deflection efficiency on the angular beam divergence. Here, the deflection efficiency is defined as the ratio of the number of electrons deflected by an angle exceeding 1.75 mrad to the total number of incident electrons N_0. In the case of planar orientation, the crystal thickness was 160 μm, while for the axial orientation, it was 2 mm. Dividing these thicknesses by the respective bending radii (8 cm and 1 m) yields a bending angle of 2 mrad in both cases.

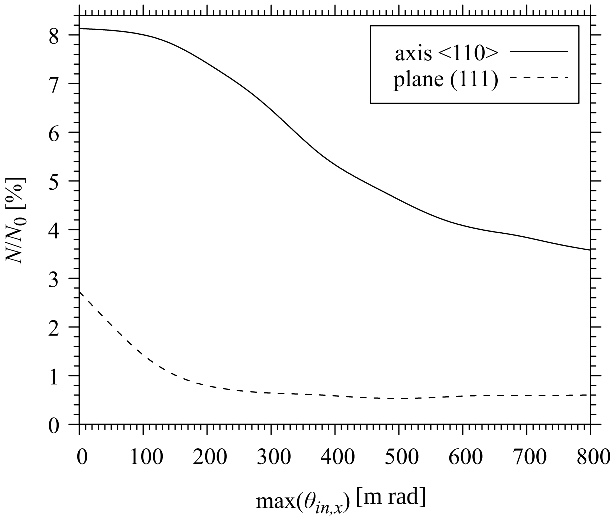

Fig. 2. The dependence of the number of electrons deflected by an angle exceeding 1.75 mrad to the total number of incident electrons on the angular beam divergence for two different orientations of the crystal

As seen in the figure, for a parallel beam, the deflection efficiency for the axial orientation is approximately 8%, whereas for the planar orientation, it is less than 3%. As the beam divergence increases, the deflection efficiency decreases. The characteristic angles determining the rate of efficiency decrease in this case are the critical angle for planar channeling ($\theta_c \approx 97.3$ μrad) and the critical angle for axial channeling ($\psi_c \approx 187.1$ μrad). It is observed that for the axial orientation, the deflection efficiency decreases by about a factor of two when $\max(\theta_{in,x})$ reaches $4\psi_c$. In contrast, for the planar orientation, the drop in efficiency is more abrupt. Already at $\max(\theta_{in,x})=2\theta_c$, the deflection efficiency falls below 1% and subsequently reaches a plateau. This saturation behavior warrants a separate discussion.

The fact that the electron deflection efficiency reaches a non-zero constant as the angular beam divergence increases could potentially be attributed to multiple incoherent scattering within the crystal. However, for a thickness of 160 μm, the characteristic angles of such scattering are significantly smaller than 1.75 mrad. In fact, the reason the deflection efficiency does not vanish with increasing angular divergence is explained by the volume capture of over-barrier particles into the channeling regime. This becomes evident when considering the angular distribution profiles of the particles in the θ_x angular coordinate after scattering by the crystal. These profiles are shown in Fig. 3 for three different values of $\max(\theta_{in,x})$. The solid vertical line indicates the angle of 1.75 mrad, which must be reached to allow for electron extraction from the accelerator ring, while the dashed line represents the crystal bending angle of 2 mrad. As seen in the figure, even when the angular beam divergence many times exceeds the critical angle for planar channeling, the shape of the deflected particle peak remains practically unchanged. This occurs because these particles are captured into the planar channel inside the crystal bulk (volume capture), rather than upon entry into the crystal. Furthermore, from the shape of the distributions at negative θ_x values, it is clearly seen that for this crystal thickness, multiple incoherent scattering does not allow for a significant number of particles to be deflected by an angle exceeding 1.75 mrad.

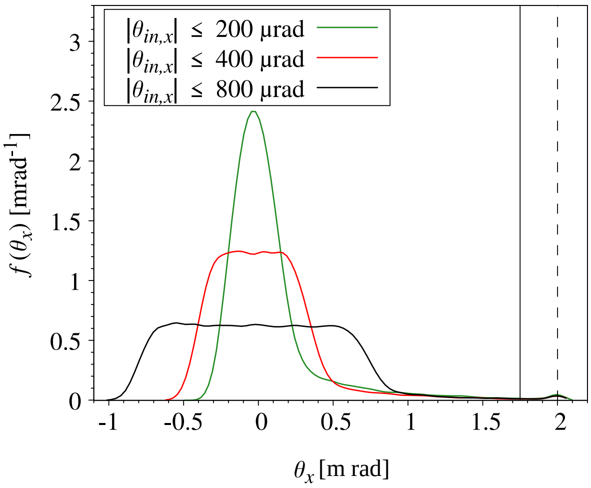

Fig. 3. Angular distribution profiles of electrons in θ_x after passing through a bent crystal for different values of the initial angular beam divergence

CONCLUSIONS

The dependence of the deflection efficiency of 6 GeV electrons by bent crystals at an angle of 1.75 mrad, enabling electron extraction from the DESY II accelerator, on the angular divergence of the electrons incident on the crystal was analyzed. It is shown that the axial orientation of the crystal provides a significantly higher deflection efficiency than the planar orientation. It is also demonstrated that the deflection efficiency in the axial orientation decreases substantially more slowly with increasing initial angular divergence of the beam than in the planar orientation.

ACKNOWLEDGEMENTS

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ЗАЛЕЖНІСТЬ ЕФЕКТИВНОСТІ ВІДХИЛЕННЯ ЕЛЕКТРОНІВ З ЕНЕРГІЄЮ 6 ГеВ ВИГНУТИМИ КРИСТАЛАМИ ОСЬОВОЇ ТА ПЛОЩИННОЇ ОРІЄНТАЦІЇ ВІД ПОЧАТКОВОЇ РОЗБІЖНОСТІ ПУЧКА

І.В. Кириллін

На основі числового моделювання було проведено аналіз залежності ефективності відхилення електронів з енергією 6 ГеВ на заданий кут від початкової кутової розбіжності пучка для двох орієнтацій кристалів: площинної та осьової. Показано, що у випадку осьової орієнтації ефективність відхилення значно вища, а зі збільшенням початкової кутової розбіжності пучка вона зменшується набагато повільніше, ніж у випадку площинної орієнтації кристала.