AXIAL CHANNELING OF POSITIVELY CHARGED HIGH-ENERGY PROTON BEAMS

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Abstract

Deflection of protons under axial channeling in a silicon crystal bent along the <111> axis was observed on experiment with 400-GeV protons at the CERN Super Proton Synchrotron. The deflection efficiency due to axial channeling of protons for the crystal with the bend angle 50 μrad was about 30 %. Axial channeling deflection occurred by means of doughnut scattering and hyper-channeling, this latter involving about 2% of the particles.

INTRODUCTION

The deflection of high-energy positively charged particles through planar channeling in a bent crystal is an established effect, [1,2]. A particle under planar channeling performs a finite transverse motion between two bent crystallographic planes of a crystal. The deflection angle of the particles channeled through a crystal with length L is determined by crystal bending angle $\alpha=L/R$, where R is the bending radius.

In addition to planar channeling, it was predicted by simulations [3], the possibility to confine and deflect beam particles along a bent crystallographic axis (axial channeling).

AXIAL CHANNELING

The motion of a high-energy charged particle entering a crystal with small angle to one of the main crystallographic axes, $\psi_o \leq \psi_1$, where ψ_1 is the critical angle of axial channeling [4], is governed by the potential of the lattice of atomic strings averaged along the axis. The potential barrier separating the axial channels formed by the neighboring atomic strings is very low. Only a small fraction of the particles can be captured by the axial channels (a hyper-channeled fraction) even for perfect alignment of the crystal axis with the beam. For silicon crystal such potential barrier equals about 6 eV for the <110> direction and only about 1 eV for the <111> direction. Particles with a transverse energy higher than the potential barrier wander in the lattice of atomic strings changing the transverse momentum direction in collisions with the strings. For particles with small angles to an axis, $\psi\leq\psi_1$, the uniform distribution of the transverse momentum directions of particles is realized after some distance λ (equalization length) [4]. The process of scattering by atomic strings, which leads to such a distribution, is called doughnut scattering. Both hyper-channeling and doughnut scattering are different states of particles under axial channeling in the crystals. Under some limitations on the crystal bending, binary-collision simulations showed that even doughnut scattering ensures a dynamical keeping of the transverse momentum direction of over-barrier particles near a bent axis direction, thereby deflecting the particles. Thus, at an axial orientation of a bent crystal the deflection of particles is possible due to not only bound-motion of particles (hyper-channeling) but also to unbound motion (doughnut scattering). The condition for particle deflection in a bent crystal due to doughnut scattering was first formulated in [5]. However, previous experiments [5,6] mainly showed a strong feed-in of particles into skew planar channels. In fact the deflection of only a small beam fraction at full bending angle observed in experiment [6] was ascribed to hyper-channeling of particles in Ref. [7]. The sufficient condition for the deflection of particles due to doughnut scattering was formulated in [8]

$$k = k_1 k_2 = \frac{\lambda}{R\psi_1}\frac{L}{R\psi_1} < 1 \,, \quad (1)$$

$$\psi_1 = \sqrt{\frac{4Z_1 Z_2 e^2}{pvd}} \,, \quad \lambda(\psi_1) = \frac{4}{\pi^2 N d a \psi_1} \,,$$

where Z_1 and Z_2 are the atomic numbers of particle and crystal atom, respectively, p and v are the momentum and velocity of the particle, d is the distance between atoms in the strings, N is the density of the crystal atoms, a is a screening length for the particle-atom potential, a=0.194 A for our case. Besides the limitation of the bend angle along the equalization length, $k_1<1$, the condition (1) limits also a full bend angle of the crystal.

EXPERIMENTAL

In this work we present the results of the recent experiment at the CERN SPS on the deflection of 400-GeV protons due to doughnut scattering at the <111> axial orientation of a bent silicon crystal. The silicon strip with the dimension 70×2×0.5 mm^3 and the large faces parallel to the (110) crystallographic planes was used. Its side faces were cut parallel to (111) planes. The crystal was placed in a vertical position in such a way that the proton beam enters the crystal through its side face nearly parallel to the large faces (see Figure1). Thus, the <111> axis direction, which is normal to the side crystal faces, became close to the beam direction. The anticlastic

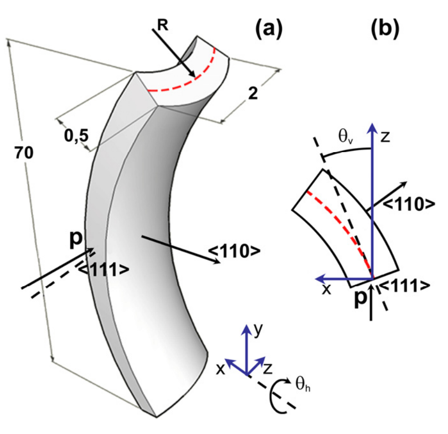

Figure 1: (*a*) Schematic picture of a silicon crystal bent by anticlastic deformation along the <111> axis. (*b*) Cross-sectional view of the crystal. Dimensions are expressed in mm.

curvature produced by the bending device along the crystal width was used for the beam deflection in a horizontal direction. The corresponding bend angle α=50 μrad and the bend radius R=40 m. The critical angle for axial channeling of 400-GeV protons ψ_1=20.7 μrad, the equalization length λ=15.8 μm. Thus, the condition (1) was satisfied. The experimental setup represents an improvement with respect to the one described in [9]. The goniometer system was upgraded with an additional rotational (cradle) stage, which allowed orienting the crystal with respect to a horizontal axis. The cradle stage has ±6.3° total range, 0.25 μrad resolution, about 1 μrad repeatability and 2 μrad accuracy. The deflection angles of protons due to interaction with the crystal were measured using microstrip detectors with very high angular resolution (about 3 μrad). The angular divergence of the primary beam of 400-GeV protons measured along the horizontal (bending) and vertical planes was characterised by the RMS deviations σ_x=8.8 μrad and σ_y=5.2 μrad, respectively. After installation, a precise angular scan of the crystal around the vertical axis (θ_{rot}) was done using the rotational stage in order to fix the crystal orientation when its vertical (110) planes crossing the <111> axis are parallel to the beam direction. This orientation was fixed by finding the deflection maximum of protons due to channelling in the (110) bent channels. Then similar angular scans were performed for different cradle angles (θ_{crad}) to reach the best possible alignment of the <111> crystal axis with the beam. Figure2 shows the beam intensity distribution as a function of the particle deflection in the horizontal (X) and vertical (Y) planes due to the interaction with the crystal for three different rotational angles (θ_{rot}). When the beam direction is far from the axial direction the beam is un-deflected. When the angle θ_{rot} becomes close to the alignment condition, a distribution shown in Fig. 2a is observed. A big fraction of the beam is still un-deflected but the other part is partially deflected due to scattering by atomic strings and feeding

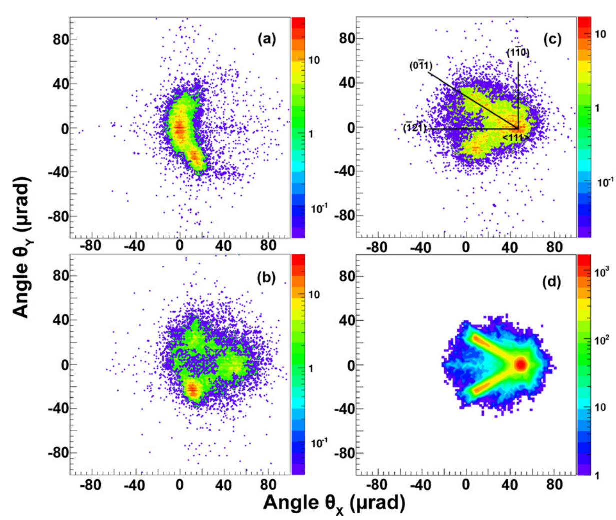

Figure 2: Beam intensity distribution as a function of horizontal and vertical deflections at some orientation angles (θ_v) of the <111> axis with respect to the incident beam direction: (*a*) -θ_v = 40 μrad, (*b*) θ_v = -15 μrad, (*c*) θ_v = 0 μrad. Only the particles hitting the crystal are shown in the pictures. The angular distribution obtained by simulation for the experimental conditions, in case of perfect alignment of the <111> axis with the beam direction and of a large number of particles hitting the crystal, is shown in (*d*) for comparison with the experimental case (*c*).

particles into the skew planar channels, which are stretched to the side opposite to the bend with small angles Y'. The bottom spot is much more intense due to the not perfect alignment of the crystal with respect to the beam in the direction of θ_{crad}. With increasing θ_{rot} the distribution is further modified, Fig. 2b. Only a small fraction of the beam remains un-deflected. Axial channeling along the <111> axis deflects the beam by the angle of about 50 μrad. A fraction of the initially axially channeled particles is leaked into skew planar channels because the <111> axis is intersection of different planes. Scattering of a particle by <111> atomic strings can accidentally direct it parallel to one of the skew planes, then the crystal bending increases stability of this planar motion. Deflection of particles due to channeling in the strongest (110) skew channels is clearly observed as two tails departing from the axial spot. The best alignment condition is shown in Fig. 2c. The un-deflected part of the beam is now completely disappeared and the spot corresponding to axial channeling is the most populated by beam particles. The clearly observed form of a "swallow" tail, which is formed by deflection of particles due to axial channeling and channeling into skew planar channels, was predicted by simulation [7]. The horizontal projection of the last distribution is shown in Figure3. The deflection efficiency due to axial channeling can be estimated through the beam part whose X deflection angles exceed 40 μrad. The particles with smaller deflection angles have orientation angles with the axis direction at the crystal exit greater than 10 μrad and

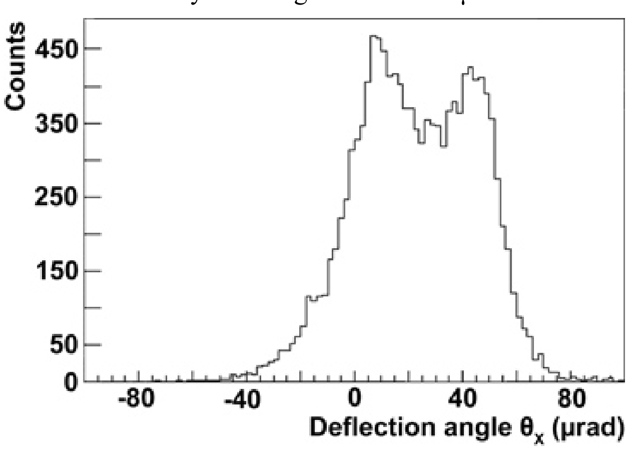

Figure 3: Horizontal projection of the two-dimensional distribution shown in Fig. 2c.

should be dechanneled or captured by the skew channels with a high probability. The deflection efficiency due to axial channelling is about 30%. Figure4 shows the angular distribution for 400-GeV protons deflected at a perfect alignment with the <111> axis of a bent silicon crystal received by simulation for the conditions of our experiment. The simulation has been made in the model of the atomic string lattice [10] using the atomic potential and electron density from the Doyle-Turner approximation for the atomic scattering factors. There is a good agreement of the calculated distribution with the experimental one. As it was shown by simulation the contribution of hyper-channeled particles to the distribution peak near the bend angle is smaller than 2% even for the perfect alignment of the crystal axis with the beam because of a small potential barrier between the axial channels for the <111> orientation of a silicon crystal. Thus, the deflection of high-energy protons at axial channeling in a bent crystal due to the mechanism of doughnut scattering was clearly observed in our experiment.

CONCLUSIONS

Beam deflection by means of axial channeling has been firmly observed with 400 GeV protons. Deflection efficiency at full bending angle was about 30%, while the capability to shift the beam from its initial direction towards a given direction, i.e., outward in an accelerator, is about 90%. This result envisages new possibilities to steer and collimate high energy beams.

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