FIRST OBSERVATION OF PROTON REFLECTION FROM BENT CRYSTALS *

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Abstract

We recently suggested using short bent crystals as primary collimators in a two stage cleaning system for hadron colliders, with the aim of providing larger impact parameters in the secondary bulk absorber, through coherent beam-halo deflection [1]. Tests with crystals a few mm long, performed with 70 GeV proton beams at IEHP in Protvino, showed a channeling efficiency exceeding 85 %. We also observed disturbing phenomena such as dechannelling at large impact angle, insufficient bending induced by volume capture inside the crystal, multiple scattering of non-channeled protons and, for the first time, a proton flux reflected by the crystalline planes. Indeed, protons with a tangent path to the curved planes somewhere inside the crystal itself are deflected in the opposite direction with respect to the channeled particles, with an angle almost twice as large as the critical angle. This effect, up to now only predicted by computer simulations [2], produces a flux of particles in the wrong direction with respect to the absorber, which may hamper the collimation efficiency if neglected.

PROTON-CRYSTAL INTERACTIONS

Channelling [3] is a well-known phenomenon in which charged particles, incident to a bent crystal [4 5], are trapped in the potential well of the atomic lattice and follow the crystal curvature, deviating from the initial path. Capture occurs with the particles travelling in a direction tangential to the atomic planes. The maximal angular deviation from the tangent path below which the particle is still trapped, and above which the particle crosses the crystal along an almost unperturbed trajectory only suffering multiple scattering, is called the critical angle for channelling. As the tangency point lies at the entry face of the crystal, surface capture occurs, which produced an angular deviation equal the crystal bend within the critical angle. For volume capture [6] the tangency point is inside the crystal volume and the angular deviation is reduced proportionally to the fraction of the crystal length traversed afterwards. Most of the particles with the right parameters for being volume captured are in fact not channelled. These particles are called reflected particles [7] and the interaction they have with the crystal is called volume reflection effect. The volume capture process essentially results from the multiple scattering of the incident particles on electrons and nuclei of the crystal material [8]. The volume reflection process leads to a deflection of the reflected particles in the direction of the atomic plane concavity, i.e. in the opposite direction respect to channeling [2,9]. This effect can be described either as the result of the oscillatory motion induced by the curved potential well at the tangency point or as a single coherent scattering event induced by the crystal lattice in the vicinity of the tangency point. The volume reflection becomes the dominant effect only if the angular deflection induced by multiple scattering on the incoming particles up to the tangency point is small enough in comparison to the critical angle. Volume reflection inside the crystal bulk induces deviations not exceeding twice the critical angle, and at the entry or at the exit face deviations twice as small, i.e. within the critical angle. When reflected at the entry face, the particles, in traversing the remaining of the crystal volume, will also suffer multiple scattering effect.

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THE CRYSTAL

The silicon crystal was prepared and bent using the elastic quasimosaicity effect [10-13], which depends on how the plate is cut respect to the crystallographic planes.

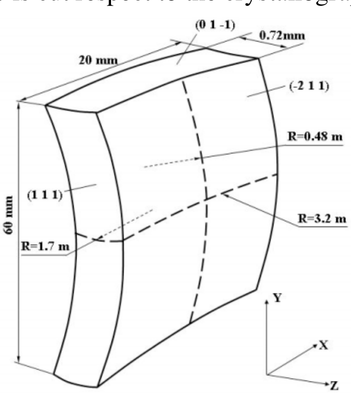

Figure 1: Bent crystal shape and atomic planes.

As shown in Figure 1, the XYZ directions were oriented parallel the crystallographic planes, with the planes (111) parallel to the XY. The plate was cut in the XYZ directions from a silicon ingot with this special orientation as described in [13]. The resulting sizes were $0.72\times20\times60$ mm^3. When curving mechanically the large XY face, the quasimosaicity effect could induce an almost uniform bend of all the normal cross sections YZ and of all the (111) crystal planes. The 20×60 mm^2 vertical face was mechanically bent with a 48 cm radius of curvature, inducing a quasimosaic curvature in the (111) atomic planes of 1.7 m radius and 423 μrad angle [13].

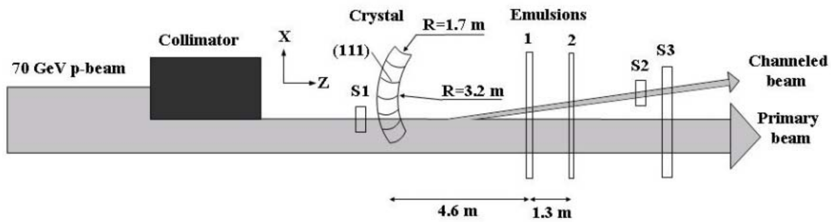

Figure 2: Layout of the experimental set-up (top view).

The properties of the bend crystal were also investigated with X-rays, and the bend angle of atomic planes (111) was indeed found to be equal to (413±10) μrad in different points of the horizontal mid-plane. A saddle shape, induced by anticlastic effects, was also observed in the major face 20×60 mm^2. The horizontal saddle radius in the middle of XY plane was found to be 3.2-m, with slightly increasing values in going above or below the center of the crystal in the Y-direction. Finally, the thickness of the damaged layer of the crystal surface was found to be less than 1 μm.

THE EXPERIMENT

The crystal was irradiated with 70 GeV protons at the U-70 in IHEP. The beam intensity was of 10^5 proton/sec and the total angular spread of 15 μrad [14]. The protons were travelling in the Z-direction. The rms angular deviation induced by multiple scattering in traversing the full crystal length of the 0.72 mm was equal to 13.5 μrad and the critical angle for channelling θ_c to 24 μrad. Indeed, the critical angle overcomes both the beam spread and the rms spread induced by multiple scattering. In these conditions, whenever the crystal is properly oriented for channelling, the volume reflection should become the dominant proton-crystal interaction.

The experimental layout is shown in Figure 2. The crystal was mounted on a turntable, and irradiated with protons in a 4 mm long spot surrounding the X-axis in the mid-plane next to the Y-Z end-face. The turntable was adjusted to an initial angle using a laser beam reflected by the crystal into appropriate marks aligned respect to the proton beam axis. The final crystal orientation was found eventually by performing a trial-and-error angular scanning of the turntable, using the counting rates of the scintillation counters S1, S2, and S3 to identify the onset of the channeling process. The beam profile in XY plane transmitted through the crystal in channeling orientation was measured using two emulsion plates of type R-100 respectively located 4.6 m and 5.9 m downstream. The traces detected by emulsion 1 are shown in Figure 3. Three curved lines are visible in the background. Similar shapes also appear in emulsion 2. Various channeling effects occur as shown in Figure 4.

The irradiated area has a horizontal curvature due to anticlastic effect. As a consequence, the (111) planes have a changing orientation along the X-direction (largely exaggerated in Fig. 2 and 4). In the X-axis range where incident protons are tangent to the (111) planes on the entrance face, channeling occurs and more than half of the protons are deflected by an angle equal to the lattice curvature, with an angular spread θ_c (rays 5 to 6 producing the spot C in Fig. 4). The remaining protons are reflected within the critical angle, suffering multiple scattering afterwards (rays 1 to 2 in Fig. 4).

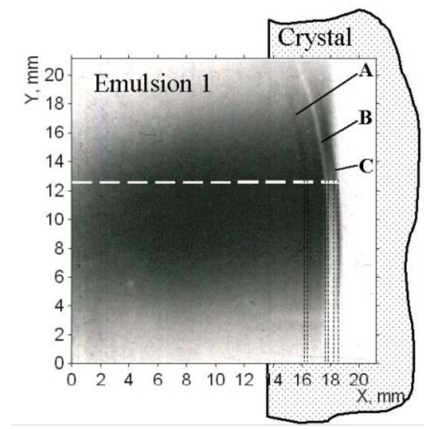

Figure 3: Part of emulsion 1. The white dashed line represents the path of a microscope. The black dashed lines show X-readings, given in Table 1, which correspond to the borders of the lines A, B, and C.

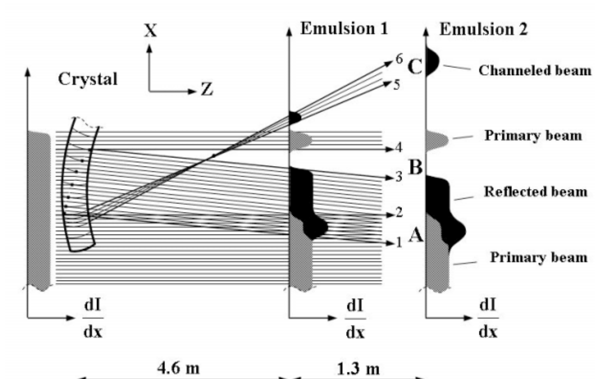

Figure 4: Schematic top view of the horizontal trajectories crossing the crystal and emulsions.

For points at larger X coordinates, volume reflection occurs, since the trajectories are tangent to the crystal array inside the volume. This process occurs with an expected probability of 1, consequently all these proton's trajectories should deviate by twice the critical angle θ_c, in the opposite direction respect to the channeling one (all the reflected rays are almost parallel and lie in between ray 1 and ray 3 in Fig. 4, producing a vide reflected beam spot in the emulsions). Beside the X-range for volume reflection and the X-range for channeling, the incident protons pass through the crystal and experience only multiple scattering. Their direction of motion is practically unchanged (ray 4 and above and rays below the channeling area in Fig. 4 producing two distinct spots of primary beams). In this scenario, there is an area depleted of protons in between the reflected and the primary beam (spot B in Fig. 4) and another area where primary and reflected protons mix (spot A in Fig. 4).

In this analysis, the dark line C in Fig. 3 results from channeled protons hitting the crystal at different heights. The light line B, and dark line A instead result from reflected protons. All the three lines A, B and C have the same slightly curved shape, caused by change with Y of the horizontal saddle radius. The positions and widths of the A, B and C lines were measured with a microscope by identifying the rays 1 to 6 along the white dashed lines in Fig. 4 (and in the analogous Figure of emulsion 2, not shown here). The results are summarized in Table I. The quoted error is the combination of the rms of repeated measurements and of a reading error of 5 μm.

The consistency of the above interpretation with experimental data comes from the following crosschecks.

The bending angle of the (111) planes is the ratio of the distance between A and C centers to the distance between the crystal and the corresponding emulsion. Using the data in Table 1 one finds an average value of 435 μrad, in excellent agreement the previous estimate of 423 μrad and with the X-ray estimate of 413 μrad.

The horizontal size of the crystal area where channeling occurs was estimated by adding the product of the critical angle θ_c by the horizontal saddle radius to the horizontal spread induced by the beam divergence. The resulting estimate is 174 μm. This value and the value of θ_c can be used to compute the expected width of C. the resulting estimate is of 297 μm and 430 μm, for emulsion 1 and 2 respectively, in excellent agreement with measured values in Table 1.

Table 1: Positions of the line centers and line widths in μm, referred to the center of line A.

	Emulsion 1		Emulsion 2	
Line	Position	Width	Position	Width
A	0 ± 10	190 ± 10	0 ± 11	260 ± 11
B	1420 ± 6	183 ± 19	1447 ± 13	213 ± 16
C	2025 ± 10	260 ± 8	2530 ± 23	433 ± 16

Furthermore, the distance between A and B depends on the beam divergence and on the horizontal size of the crystal area where reflection occurs. Using geometrical considerations, the size of the “reflection zone” can be computed from the bending angle of (111) planes and from the horizontal saddle radius of the crystal. However one has to take into account the smear introduced by the divergence of the incident protons. The resulting estimate is 1165-μm. We should then consider that the reflected protons emerge with a divergence of 58-μrad. The separation between A and B will increase to 1432 μm and 1507 μm, in emulsion 1 and 2 respectively, in excellent agreement with the values of Table I.

The deflection angle of the reflected protons is also the ratio of the A and B line-width to the distance from the crystal in each emulsion. Using the data of Table I one can compute the average angular width of A and B, which is equal to 42.7 μrad and 37.2 μrad, respectively. The protons producing the spot A are reflected at the entry face of the crystal, and suffer of the multiple scattering along the full crystal length. Hence one should subtract the rms angle of 13.5 μrad from the width of A. One can compute the reflection angle $2\theta_R$ as the average of the widths of A and B. The resulting value is $2\theta_R$ = (39.5 ± 2.0) μrad. By expressing it in terms of the critical angle one finds the following expression: $2\theta_R$ = (1.65 ± 0.08) θ_c, fully compatible with the expectation that the reflection angle is within twice the critical angle.

The presented data confirm that the reflection effect occurs with high probability and can produce a flux of particles in the opposite direction respect to channelling. The reflection angle is small however sufficient to enhance the directivity of a crystal as primary collimator. If neglected this effect may hamper crystal collimation. Further studies will be launched to make the best use of it.

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