

Deflection of High Energy Beams by Channeling in Bent Silicon Crystals

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Abstract

Experimental results on the deflection of a high energy positive beam by means of planar and axial channeling in a bent silicon crystal are presented. The primary 450 GeV/c H8 proton "microbeam" in the CERN SPS North Area as well as secondary 200 GeV/c positive hadrons in the H8 beamline were used in the present investigations. A silicon crystal was bent to deflect the beam horizontally in a classical 3-point bender. Deflection efficiencies of up to 50 % were observed for planar (111) channeling at 450 GeV/c, in agreement with theoretical calculations.

1. INTRODUCTION

Deflection of high energy protons using the channeling effect in bent silicon crystals has been studied since several years [1,2]. Deflection efficiencies for a parallel incident proton beam were found to be above 10% in the first experiments at 450 GeV/c [3]. The features of such crystals as beam splitters, producing little background, are very attractive and are being used e.g. in the NA48 experiment at CERN [4]. Other investigations aim at extracting a high energy proton beam from a storage ring [5]. Moreover, it was found that bent crystals equipped with solid state detectors provided a unique tool to study energy loss under channeling conditions [6]. Experimental results obtained with a 5 cm long bent silicon crystal, both for planar and axial channeling and bending, are presented here.

2. CHANNELING and BENDING

Channeling of high energy particles in single crystals is now a well-established phenomenon. Positively charged particles entering a silicon crystal at small angles to a major plane or axis are channeled, i.e. reflected from the planes or strings of nuclei, and thus experience less energy loss, multiple scattering, nuclear interactions etc. than particles incident far away from such directions, i.e. at so-called "random directions". Critical angles are in the order of 10 and 30 microradians, respectively, for planar and axial channeling at $p = 200$ GeV/c, and scale with $1/\sqrt{p}$. The average dE/dx of particles channeled along major planes in silicon is about 60% of the normal "random" energy loss.

Particles once channeled, will be guided by the strong potential of the crystalline atoms, even if the crystal is

slightly bent. Losses due to so-called de-channeling will occur if the crystal is too long (multiple scattering de-channeling, dominant at low beam energies) or if it is bent too much (bending de-channeling, important at high energies). Nevertheless, for a suitably chosen crystal length and deflection angle, high deflection efficiencies for a parallel incident beam can be expected.

3. EXPERIMENT

The present experiment aims at testing the current understanding of planar channeling and de-channeling in bent silicon crystals, which is most relevant for applications. However, axial channeling and bending is also investigated.

The measurements were performed in continuation of our earlier tests [3,6] in the H8 beam in the North Area of the CERN SPS. A schematic view of the experimental arrangement is shown in Fig. 1. The bent silicon crystal is mounted on a goniometer turntable with $1.7 \mu\text{rad}$ step-size. The incident and exiting particle positions are defined in two drift-chambers, one 20 cm upstream, the other 4.1 metres downstream of the crystal. Two scintillators (SC1, SC2) are used for triggering the data acquisition on beam particles hitting near the crystal, while a third scintillation counter is used to veto events in which hadronic interactions in the crystal or bending device have occurred.

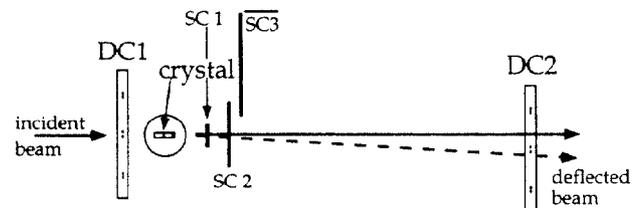


Figure 1: Schematic view of the experimental set-up for the bent crystal experiment. Two driftchambers (DC) are used to track the protons. The scintillation counters SC1,2, serve as trigger counters, SC3 is a veto counter.

The silicon crystal, 50 mm long in the beam direction, 10 mm high and 0.9 mm thick, was cut parallel to one of the (111) planes, with the $\langle 110 \rangle$ axis close to the beam direction. It is mounted in a classical 3-point bender for deflection in the horizontal plane (see Fig. 2). The bending is varied by a

thumbscrew. Four surface barrier detectors were implanted along the crystal, allowing to measure the dE/dx of protons passing the crystal. The variation in shape of the dE/dx spectrum of the first detector can be used to align the crystal with respect to the proton beam and to monitor the beam divergence. The other dE/dx detectors can be used to estimate dechanneling along the crystal and study energy loss phenomena for channeled particles [6,7].

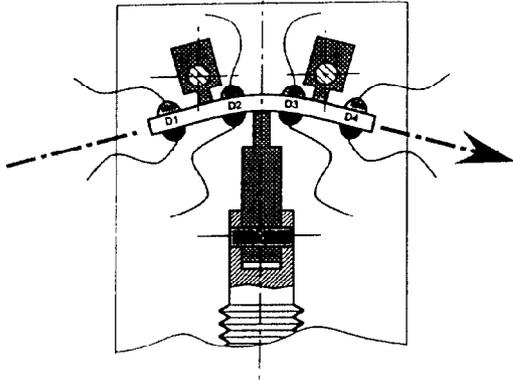


Figure 2: Schematic view of the crystal and the bending device. The four surface barrier detectors on the crystal are indicated.

4. RESULTS

A first set of measurements was performed with 450 GeV/c protons tuned to be parallel in the horizontal (bending) plane in order to maximize the number of particles channeled in the (111) plane. This provides ideal conditions to study the deflection efficiency and compare to calculations. For another series of measurements, the 450 GeV/c beam was set to be parallel in both planes, as required for the experiment using axial channeling. A secondary mixed pion/proton beam of 200 GeV/c, also parallel in both planes, was used for comparison with the planar channeling results at 450 GeV/c.

4.1 Planar channeling of 450 GeV/c protons

A series of measurements with the 450 GeV/c proton beam was performed at different deflection angles, i.e. different bendings of the silicon crystals. In order to avoid sensitivity to surface imperfections, only protons hitting within the central 0.3 mm on the crystal thickness were considered in the analysis, by cutting in DC1. Deflection efficiencies given are the ratios of the bent beam observed in DC2 to the incident beam selected in DC1. The results of the experiment are summarized and compared to theoretical estimates in Fig. 3. Deflection efficiencies of up to 50% were measured. The error bars indicate statistical errors only. Systematic errors due to mechanical or other instabilities may be deduced from the scattering of the data points - note that the experiment is sensitive to angular changes in the order of one microradian! The comparison of the measured and calculated deflection efficiencies is very satisfactory, but shows the well known imperfections of the bending device: a 3-point bender can not give a uniform curvature.

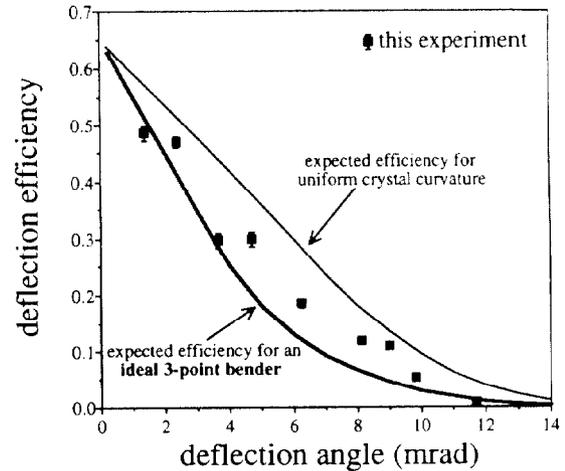


Figure 3: Comparison of experimental results (dots with bars indicating the statistical errors) with theoretical estimates for uniform curvature and an ideal 3-point bender. For further details, see [6].

4.2 Comparison of 200 and 450 GeV/c beam deflection

At a deflection angle of 3 mrad, measurements were performed with both 450 GeV/c and 200 GeV/c positive beams. The beam divergence of the two beams is expected to be quite different, the primary 450 GeV/c microbeam being more parallel. This is seen in the dE/dx spectra from the crystal entrance (Fig. 4).

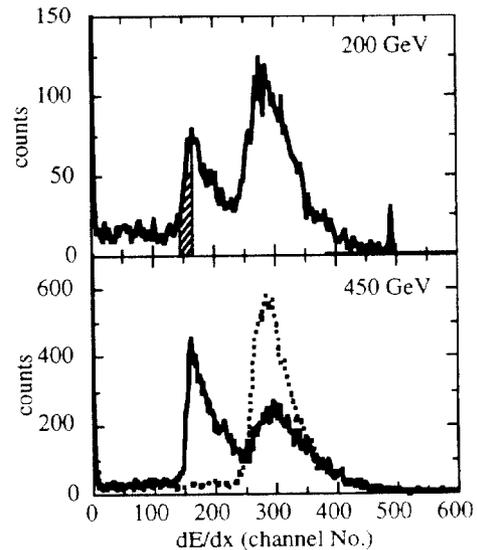


Figure 4: Energy loss spectra for the 200 and 450 GeV/c proton beams at the crystal entrance. The lower dE/dx peak corresponds to channeled particles. The region defining well-channeled particles is indicated in the upper part. For comparison, the dotted line in the lower part shows the dE/dx for random incidence, i.e. a non-aligned crystal.

Therefore, it is not surprising to find a lower deflection efficiency for the 200 GeV/c, as shown in Fig. 5 and Table 1. If only well-channeled events are selected at the crystal entrance by setting a window on dE/dx (see Fig. 4), the deflection efficiency is found to be similar for both energies. The region between undeflected and bent beam is populated by particles originally channeled, then lost during the passage through the crystal.

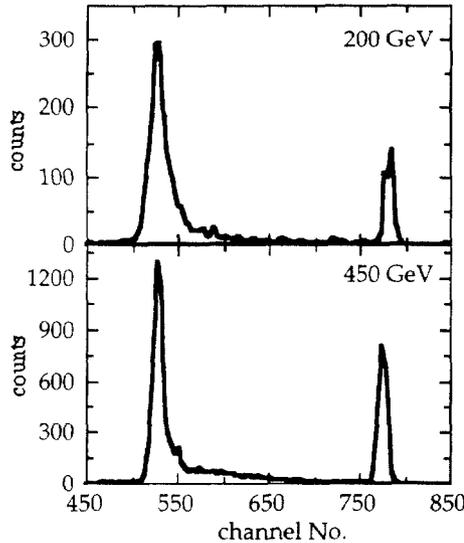


Figure 5: Comparison of 200 GeV/c and 450 GeV/c data on planar bending of positive particles. The horizontal profiles recorded in DC2 are shown. The peak on the right represents particles deflected by 3 mrad.

Table 1: Comparison of experimental results obtained at 3 mrad deflection angle with a 200 GeV/c secondary and a 450 GeV/c primary beam. Statistical errors are given.

	200 GeV/c	450 GeV/c
measured deflection efficiency (all particles)	$16 \pm 1\%$	$25 \pm 1\%$
deflection efficiency for well channeled particles, off-line selected in detector D1 (Fig.4)	$75 \pm 5\%$	$83 \pm 4\%$

4.3 Axial channeling and bending

Preliminary data are given for an axially channeled 450 GeV/c proton beam. As an example, the resulting pattern in DC2 for a total bending angle of 3 mrad is shown in Fig. 6. While there is clearly some beam deflected by the full horizontal deflection angle, set by the bending device, several other beams are produced, too. These can be attributed to skew planes in the crystalline structure, as shown in the stereogram inserted in Fig. 6. The analysis is under way, to identify the remaining beam spots and to study the deflected intensities in view of expected higher deflection efficiencies than observed for the planar (111) channeling [2].

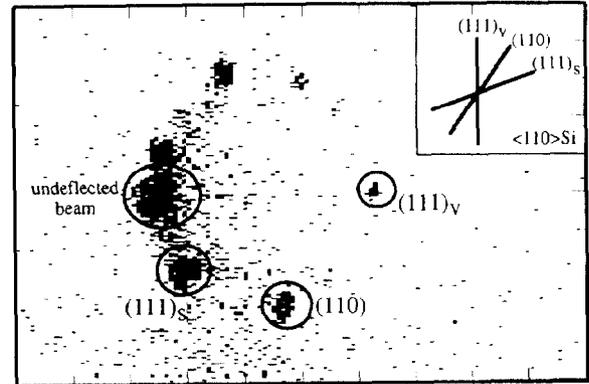


Figure 6: Preliminary result from axial channeling and bending through a deflection angle of 3 mrad. The two-dimensional spectrum recorded in DC2 shows different deflected beams, corresponding to particles "fed" into the planes of the crystal from the axis. The insert shows the stereogram of the major planes identified here.

5. CONCLUSION

The experiments on deflection of a 450 GeV/c proton beam in a bent silicon crystal show that by choosing the appropriate crystal curvature for a given energy, efficiencies as high as 50% can be obtained in a parallel beam, in agreement with the theoretical expectations. The present results confirm the validity of the channeling and de-channeling models also at the highest energies available today. The comparison of 200 and 450 GeV/c positive beams further confirms the models: For similar incident beam divergence, the deflection efficiency is only slightly different at 200 GeV/c. While an application of a silicon crystal as a beam splitter and deflector for 450 GeV/c protons is operational for NA48 at CERN, the results presented here also give confidence in extrapolations to higher energies. Extraction of protons from the halo of a high energy collider can be envisaged, too [5], e.g. for an external fixed target experiment, for beam monitoring or calibration of forward detectors.

6. REFERENCES

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