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**DEFLECTION OF 450 GeV PROTONS BY PLANAR
CHANNELING IN A BENT SILICON CRYSTAL**

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Abstract

A 450 GeV proton beam has been bent by various angles from 4 to 14 mrad using planar channeling in a (111) silicon crystal. Detailed investigations of the deflected beam as well as the unbent and scattered particles have been performed. The incident beam had a divergence of about 35 μ rad (FWHM). 20% of the protons hitting the crystal front face were found to be initially channeled. The measured bending efficiencies range from 5% to 2% (for increasing deflection angles) and are compared to theoretical estimates including surface acceptance and dechanneling in bent silicon crystals.

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Channeling of high energy protons through single crystals of silicon has been investigated since a few years [1]. Particles entering the crystal under small angles of incidence with respect to major crystalline axes or planes are found to be steered through the crystal by the strong coherent field created by the strings and planes of atoms in a crystal lattice. The classical criteria derived by Lindhard for low energy channeling, e.g. the planar critical angle ψ_p [2], hold also for high energy beams. For planar channeling of 450 GeV protons in (111) silicon, the critical angle is $\psi_p \approx 7 \mu\text{rad}$. In addition to attractive features of channeling in straight crystals, it was also shown [1] that channeled high energy protons can be efficiently guided through **bent** crystals, the losses being related to the type of crystal used, the beam momentum and divergence, and the radius of curvature of the crystal [3]. The efficiency of such crystal deflectors is determined first of all by the surface acceptance (i.e. the fraction of particles channeled initially), and by the multiple scattering losses for particles which were initially channeled - both effects are well known from channeling in straight crystals. In a bent crystal, an additional bending dechanneling, stemming from the centrifugal force acting on the deflected particle inside the crystal, has to be taken into account [3]. Moreover, the multiple scattering dechanneling is modified due to the curvature of the crystal lattice.

Channeling in bent crystals allows e.g. to split a high energy proton beam without major background production: most of the protons hitting the crystal inside the critical angle are channeled and deflected, while the non-channeled beam is hardly affected by a few centimetres of silicon. This principle is intended to be applied for a CP violation experiment at CERN (NA48), which will use a crystal for the production of nearly parallel K^0 beams [4]: a small fraction of the proton beam is deflected by a crystal, and sent to a production target for K_S downstream of the target in which the K_L originate. Other applications include e.g. the production of low intensity test beams [1] or the focussing of high energy protons by means of a specially polished crystal exit face [5].

Very recently, there has been strong interest in channeling in bent crystals at TeV energies, mainly motivated by the perspectives of extracting a beam from the future high energy proton colliders (LHC and SSC) [6,7]. According to these ideas, the bent crystal would peel off particles from the beam halo before they could hit a collimator, thus providing an extracted beam of multi TeV protons for fixed target experiments in an entirely parasitic fashion, i.e. unnoticed by the collider experiments.

Experiments to extract protons from circulating beams by means of a bent crystal have so far only been performed at a relatively low energy, up to 70 GeV at IHEP Protvino, and the extraction efficiencies were found to be modest (8×10^{-5}) [8]. However, the physics of channeling in bent crystals has been studied in extracted beams up to 800 GeV [9,10,11]. While in general the beam divergence in these experiments made it difficult to investigate bending with a high efficiency, our recent measurement with a highly parallel beam of 450 GeV protons at CERN [12] provided for the first time an experimental bending efficiency of around 10% (at about 7 mrad deflection angle). Therefore, there is hope that in future extraction experiments efficiencies in excess of 10%, as they would be needed for example in CP violation studies in the B system [6,7], may be obtained. Until the next generation of proton accelerators comes into operation, a number of experimental studies are still needed in order to corroborate our understanding of channeling and the dechanneling losses in bent crystals and to allow a safer extrapolation from today's multi-hundred GeV beams to the multi TeV domain.

The experiment described here investigates the angular dependence of the bending efficiency for 450 GeV protons incident on a bent (111) silicon crystal. The measurements were a continuation of our earlier work [12] in the H8 beam at the CERN SPS. The experimental arrangement is schematically shown in Fig. 1a. The bent crystal was mounted on a goniometer turntable for horizontal rotation, located near the drift chamber DC1, which was used to define the incident beam hitting the crystal. A second drift chamber (DC2) measured the position of the protons at 4.1 metres distance downstream from the crystal. The $15 \times 15 \text{ cm}^2$ drift chambers are equipped with three pairs of double sense wires to avoid sign ambiguities, interspaced by 50 mm. (The position resolution of these chambers is about $100 \mu\text{m}$ (rms.), thus the angular resolution between DC1 and DC2 does not allow a measurement of the beam divergence with

sufficient accuracy). Two scintillation counters (SC) in coincidence provide the trigger signal for the data acquisition system.

The crystal was bent for horizontal beam deflection with a device shown in Fig. 1b, based on a design developed at Serpukhov [13]. Ideally, such benders should result in a uniform curvature along the crystal, thus yielding a maximum bending efficiency (see below). However, for the present experiment, no means to measure this curvature with sufficient precision were available. The crystal was fixed on the bending device by three aluminum clamps on a "bridge" fabricated of the same material. The whole "bridge" was then bent by pushing with a linear motor on the translating mechanics. The device allows to let all beam particles pass without touching any material except for those protons which hit the crystal, thus reducing background in the downstream detectors.

The silicon crystal used was 52 mm long (in beam direction), 9 mm high and 0.9 mm thick. It was mounted asymmetrically in the bending device, leaving an 8 mm straight section at the beam entrance end (see Fig. 1b), as a precaution to avoid strain on the front detector (see below). The crystal was cut roughly parallel to the (111) planes used for channeling, the miscut angle was measured to be about 4 mrad. In all measurements only particles hitting the central area of the crystal were selected by offline cuts in the drift chamber DC1 (see Fig. 1a), thus rejecting channeled particles which would leave the crystal due to the miscut of the planes with respect to the surface.

Three surface barrier detectors of about (4×4) mm² were produced on the front, centre and exit parts of the crystal. Due to the large leakage current, these detectors were not fully depleted. In fact, only the front detector in the unbent part of the crystal gave useful information in this experiment: As in earlier measurements [12], the reduced energy loss for channeled particles in this front detector was used to align the crystal with the beam direction. Fig. 2 shows two superimposed energy loss spectra for protons traversing the front detector for a non-aligned and an aligned crystal. While in the non-aligned case, which corresponds to an amorphous detector, the usual Landau dE/dx distribution (on some background) is observed, the aligned crystalline detector features an additional peak at about 60% of the random energy loss, indicating the presence of channeled particles. A comparison of the two spectra allows a first conclusion: roughly 20% of the incident particles are initially channeled inside the silicon crystal - those are lacking in the higher dE/dx peak and appear instead in the low energy loss region. The remaining part of the beam consists of particles which cross the crystal planes and hence give a normal energy loss signal. Measurements of the beam profiles in the drift chamber DC2 also show that about 20% of the incident particles are initially channeled (see below).

A comparison of the spectrum for an aligned crystal in Fig. 2 with our earlier experiments [12] gives an indication that the proton beam in the present work was not tuned to the same parallelism. About 50% of the incident protons were initially channeled in the earlier runs (see Fig. 3a in [12]). Additional information on beam divergence can be obtained by observing the intensity of the bent beam in DC2 as a function of the angular position of the goniometer turntable. The result of such a scan is shown in Fig. 3 for a deflection angle of 4.5 mrad. The observed width of the distribution is about 40 μ rad (FWHM), much more than expected from the critical angle for planar channeling, $2\psi_p \approx 14 \mu$ rad, therefore a beam divergence of about 35 μ rad (FWHM) can be inferred. Again, the same type of measurement indicated a much more parallel beam in our earlier experiments (see Fig. 3c in [12]). This comparison partly explains the lower bending efficiency measured in this work (see below) - the cause for the larger beam divergence is under investigation.

While the first drift chamber (DC1) was used to define protons hitting the central part of the crystal, the DC2 served to investigate in detail the beam profile of the bent and unbent particles. A measurement for a deflection angle of 5 mrad is shown in Fig. 4: The horizontal beam profile in DC2 for an aligned and a non-aligned crystal are superimposed, normalized to the same number of protons in DC1. The insert shows the same spectrum, with an expanded vertical scale. The spectra clearly show the intense peak of the straight beam. Two more features are readily observed: (a) the bent beam appears as a sharp peak at $x=78$ mm, and (b) there is a "foot" observed in the profile of the unbent beam ($x=57$ mm), pointing away from the bent beam direction. The origin of this "foot" is likely to stem from an unwanted curvature,

produced by the way the crystal was mounted on the bending device (see Fig. 1): the first clamp, pressing on the "straight" part, leads to a much smaller curvature of the opposite sign, and therefore large bending dechanneling after the 8 mm "straight" section of the crystal. (Note that in an earlier experiment by Forster et al. [5], a somewhat similar "foot" was observed and explained by their bending technique). Furthermore, it is seen in Fig. 4 that the profiles for the non-aligned and aligned crystal are essentially identical in the region between the bent and straight beams, allowing the conclusion that there are little contributions by dechanneling all along the crystal. A comparison of the number of protons in the different areas of the spectra in Fig. 4 shows the following:

- about 20% of the incident proton beam is initially channeled - this is the reduction in the area of the straight beam when comparing non-aligned and aligned crystal;
- of these 20%, roughly 3/4 have been bent into the "foot" region near the straight beam, and 1/5 in the bent beam, the latter yielding a bending efficiency of 4% (see below);
- less than 1% of the incident particles are found in the range between bent and unbent beam - this is below the uncertainty of the present experiment.

(For clarity, it should be mentioned that the slight increase in counting rate near the bent beam in Fig. 4 does not originate from the crystal: both spectra for the non-aligned and aligned crystal show the same "bump". It can be attributed to the increase of background counts near the sense wires of the drift chamber, and it is observed exactly at the position corresponding to a pair of sense wires. Note that in this experiment all beam particles were used to trigger the data-acquisition system.)

The deflection angle obtained in this channeling experiment could be varied continuously with a linear motor (see Fig. 1b), and data were taken at various angles. Fig. 5 shows data from three runs with increasing deflection angle, superimposed in one spectrum of DC2. All spectra are normalised to the same number of incident protons. It should be noted that the straight beam area stays essentially unchanged, and that also the "foot" remains the same for all three deflection angles (see insert in Fig. 5), indicating its relation to the first part of the crystal. Once again, the "bump" due to the increased background near the sense wires is seen, and the counting rates between the straight and bent beam peaks correspond essentially to background rates.

The experimental bending efficiency for different deflection angles was evaluated by counting the number of protons in the bent beam for a given number of beam particles hitting the central part of the crystal front face (offline cut in DC1). Linear background subtraction was applied in all spectra. The resulting experimental efficiencies are shown in Fig. 6. The theoretical estimate for a uniformly bent crystal, shown as dashed line in Fig. 6, was obtained considering

- the surface acceptance of a (111) silicon crystal for a 450 GeV proton beam with a divergence of 35 μ rad, found to be 32 %;
- the multiple scattering dechanneling length ($L_D = 35$ cm in the present case) in the straight part of the crystal [10], which introduces negligible losses and yields an efficiency of $e^{-L/L_D} = 99$ %.
- The efficiency $(1-F)$ due to bending dechanneling, where F describes the dechanneling losses as a function of the radius of curvature, for uniformly bent crystals [3,14];
- the modified multiple scattering dechanneling length for the bent part of the crystals, according to the empirical rule $L_D^* = L_D(1-F)^2$ [3,10].

The resulting curve was normalized by an arbitrary factor of 0.5 in order to facilitate the comparison of the experimental and calculated angular dependence. Clearly, the poor agreement between measured and calculated values asks for an explanation: firstly, the finite beam divergence in the present experiment leads to a limited acceptance of particles into crystal channels. This has been calculated to be 32 %, however the experimental data from the dE/dx detector and

the DC2 drift chamber seem to indicate a somewhat smaller value of about 20 % (see above). Further disagreement between calculation and experiment stems from the imperfections in the bending device, leading to a strong variation in crystal curvature, which in turn might produce the "foot". Such particle losses are not described by the models in [3], which have been developed for uniform curvature. However, if we introduce a strong, local curvature of variable size, as might be caused by the first clamp of the bending device (see Fig. 1b), good agreement between calculation and experiment can be reached. This is shown by the solid line in Fig. 6 for a local curvature 5 times larger than the one expected for uniform bending and a deflection angle of 5 mrad. This assumption leads to a bending dechanneling of $F=0.83$ at the point of maximum curvature. The other contributions to the efficiency (see above) were left unchanged in the calculation, which corresponds to the assumption that the crystal curvature was uniform after the "edge" produced by the first clamp of the bending device.

In conclusion, we present detailed measurements of bending experiments with 450 GeV protons using planar channeling in a bent silicon crystal, with deflection angles reaching up to 14 mrad. The results show good agreement with theoretical estimates, if a non-uniform curvature of the crystal is assumed. The absolute efficiencies are somewhat smaller than measured in the previous work [12], suggesting a number of improvements needed (and being prepared) for future experiments: (a) an optical test bench with laser equipment to measure the crystal bending angle and the behaviour of the curvature along the crystal (b) crystals with at least two fully depleted detectors to give more information about surface acceptance, bending dechanneling and feed-in, and (c) the re-establishing of the very parallel proton beam, which would further facilitate the investigations. With these improvements in the experimental technique, we hope to obtain bending efficiencies close to the theoretically expected values.

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Figure Captions

- Fig. 1 a) Schematic view of the experimental arrangement at the SPS H8 beam at CERN: The bent silicon crystal (Xtal) is mounted on a goniometer turntable with $1.7 \mu\text{rad}$ stepsize. Two drift chambers (DC, resolution $100 \mu\text{m rms.}$) are used to track the undeflected and the bent beam particles. Two scintillators (SC) in coincidence serve as trigger counters.

 b) Details of the bender used to curve the crystal to variable radii by pushing with a linear motor (lower part). This device allows beam particles which do not hit the crystal to pass without traversing any material.
- Fig. 2 Energy loss spectrum of protons entering the crystal for random incidence (dotted line) and for a crystal aligned with the beam direction (solid line). From a comparison of the two spectra one can deduce that in the aligned case about 20% of the incident protons are channeled.
- Fig. 3 Intensity of bent beam particles for different angular positions of the goniometer. This scan, when combined with the information on the critical angle for channeling ($\pm 7 \mu\text{rad}$ for 450 GeV protons on (111) planes in Silicon) gives indirect information on the divergence of the beam hitting the crystal.
- Fig. 4 Horizontal beam profile as seen by the downstream drift chamber DC2 (see Fig. 1). The solid line is for a crystal aligned with the proton beam, the dotted line is for random incidence. Inserted is the same spectrum, vertically enlarged (for details see text).
- Fig. 5 Overlay of three horizontal beam profiles measured in DC2 for a sequence of measurements with decreasing crystal curvature, i.e. increasing beam bending angle. Inserted is the same spectrum, vertically enlarged.
- Fig. 6 Efficiency of bending 450 GeV protons by means of planar channeling in the bent Si crystal as a function of the deflection angle. Experimental efficiencies are obtained by dividing the intensity of the bent beam (in drift chamber DC2) by the number of particles hitting the crystal (defined in DC1, used as a cut on all events in the analysis). The dashed line represents the theoretical efficiency for a uniform crystal curvature, normalized with a factor 0.5. The solid line is calculated with an arbitrary, strong curvature to explain the "foot" in the DC2 spectra. For further details, see text.

a

b

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6