High efficiency beam deflection by planar channeling in bent silicon crystals

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Abstract

Experimental results on the deflection of a 450 GeV proton beam by means of (111) planar channeling in a bent silicon crystal are presented. The H8 microbeam in the CERN SPS North Area was tuned to be highly parallel in the horizontal plane, i.e. to a divergence smaller than the critical angle for planar channeling at this proton energy, and focussed to less than 1 mm in the vertical plane. The Si crystal was bent to deflect the beam horizontally in a classical 3-point bender. Unprecedented deflection efficiencies of up to 50 % have been observed. Since channeling of positive particles is a well-understood phenomenon over many orders of magnitude in particle energy, the present data can be extrapolated to the TeV range. This opens exciting possibilites for the application of bent crystals, e.g. as small and tunable beam splitters or as extraction devices, in the future multi-TeV proton accelerators.

I. INTRODUCTION

Deflection of high energy protons using the channeling effect in bent silicon crystals has been studied since several years [1,2]. While the attractive features of bent crystals as beam splitters to produce low intensity test beams was of prime interest in the earlier studies at FERMILAB [3], the possible application for a new CP-violation experiment [4] lead to more detailed studies with 450 GeV protons at CERN [5-7]. Recently, the ultimate limitations of deflecting high energy protons in bent crystals have been much debated in the context of proposals to extract protons from the beam halo in the future multi-TeV hadron collidors SSC and LHC for fixed target experiments [8,9]. The expected flux of such a multi-TeV proton beam depends on simulations of the expected proton distribution in the halo of the collider [10] and on the theoretical estimates on the deflection efficiency for protons in bent crystals [11].

II. 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". Usually, for a quantitative description of channeling the transverse energy of particles in the crystal is considered: if this energy $E_\perp$ is low enough, particles are "trapped" in the channeling potential $Y_\perp$, the electric potential obtained from smearing the charges of all atoms in a crystal plane - the Lindhard "continuum approximation" (see [2] and references therein). For the planar case,

$$Y_\perp(y) = Nd_p \int_0^\infty 2\pi\rho d\rho V(\sqrt{y^2+\rho^2})$$

where y is the distance from the plane, Nd_p represents the number of atoms per unit area of the plane, d_p being the distance between planes. V(R) is the ion-atom potential and ρ the polar coordinate inside the plane. For example, one finds that 450 GeV protons inside a critical angle of $\pm$ 9 μrad to the (111) planar direction in silicon have an energy $E_\perp < Y_{\perp,max}$ and can be channeled.

Nevertheless, even for a perfectly parallel beam, the probability for channeling is not unity. The surface transmission, or in other words the "crystal acceptance", has to be considered. Assuming a uniform beam distribution in space, aligned with the crystal, the surface transmission at high energies is found to be typically 80% or less for planar orientation of the crystal.

In long straight crystals, the protons once channeled are lost only by multiple scattering - they are dechanneled. In a bent crystal, however, additional dechanneling may occur: due to the curvature of the crystal the potential $Y_\perp$ is asymmetrically lowered by a centrifugal term (κ is the crystal curvature, p and v are momentum and velocity of the beam particle, respectively),

$$Y_{eff}(x) = Y_\perp(x) - pv\kappa x$$

such that only particles with lower transverse energies may remain trapped and be channeled for the full length of the crystal. The bending dechanneling losses occur at the point of largest curvature of the crystal. At a given beam momemtum, the efficiency of deflection in a bent crystal is therefore determined by the length of the crystal and by the maximal curvature [2, 12].

III. EXPERIMENT

The present experiment aims at testing the current understanding of channeling and dechanneling in bent crystals and offers a quantitative comparison of measured deflection efficiencies with theoretical estimates for different crystal

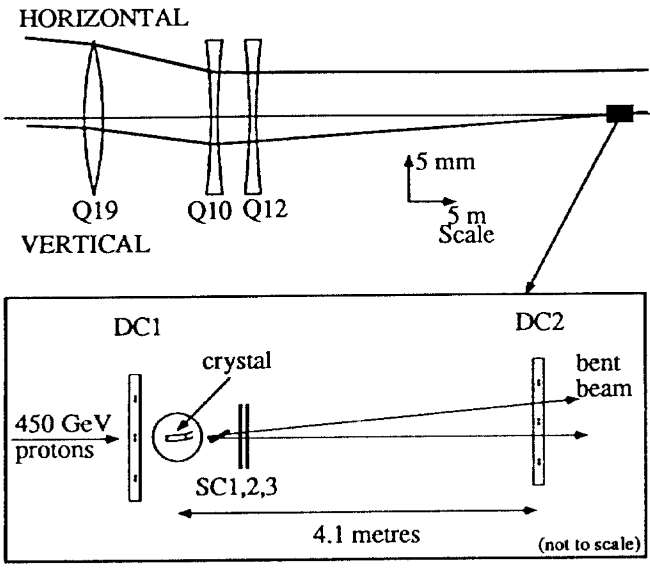

Figure. 1: Schematic view of a section of the SPS H8 beam (beam optics) and the experimental set-up for the bent crystal experiment. Two driftchambers (DC) are used to track the protons. The scintillation counters (SC1,2,3) serve as trigger counters.

curvatures. The measurements were performed in continuation of our earlier tests [5,6] in the H8 beam in the North Area of the CERN SPS. The experimental arrangement is schematically shown in Fig. 1. The 450 GeV proton beam was set up to be highly parallel in the horizontal (deflection) plane and focused in the vertical plane (for further details, see [5]). The bent silicon crystal is mounted on a goniometer turntable with 1.7 μrad step-size. The incident and exiting proton positions are measured in two drift-chambers, one 20 cm upstream, the other 4.1 metres downstream of the crystal. Scintillation counters are used to trigger on protons passing through or near the crystal.

The silicon crystal, 50 mm long in the beam direction, 10 mm wide and 0.9 mm thick, was cut parallel to one of the (111) planes. It was mounted in a classical 3-point bender for deflection in the horizontal plane (see Fig. 2). The bending

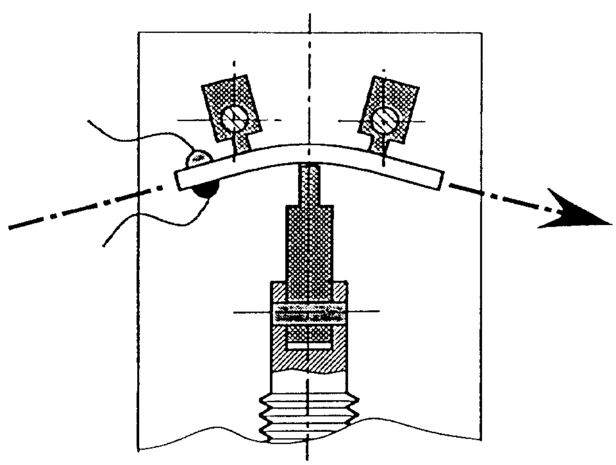

Figure 2: Detail of the 3-point bending device used to curve the crystal to variable radii. The dE/dx detector at the entrance side of the crystal is indicated.

was varied by a thumbscrew. A surface barrier detector was implanted on the entrance part of the crystal, allowing to measure the dE/dx of protons hitting the crystal. Channeled protons have about 60% of the energy loss of unchanneled ones - therefore, the variation of the dE/dx spectrum of this detector can be used to align the crystal with respect to the proton beam. Moreover, by maximizing the fraction of channeled protons in the dE/dx spectrum on the aligned silicon crystal, the beam was blown up horizontally (using Q19) in order to achieve the smallest possible angular spread for the fraction of protons hitting the crystal. Using the dE/dx information allows to tune the beam to an angular spread of a few microradians, beyond the accuracy reached with the standard beam instrumentation.

IV. MEASUREMENTS

Measurements were 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 entrance were considered in the analysis (i.e. cut in DC1). Horizontal beam profiles as measured in drift-chamber DC2 are shown in Fig. 3. For relatively modest deflection angles (e.g. 2.4 mrad), the intensity of the deflected beam is almost 50% of the total beam hitting the crystal, with about 35% of protons being undeflected and 15% being lost due to dechanneling in the bent crystal.For comparison, the dotted line in Fig. 3 shows the beam profile for an equal number of protons incident on a non-aligned crystal (random orientation), i.e. all particles are in the straight beam peak.

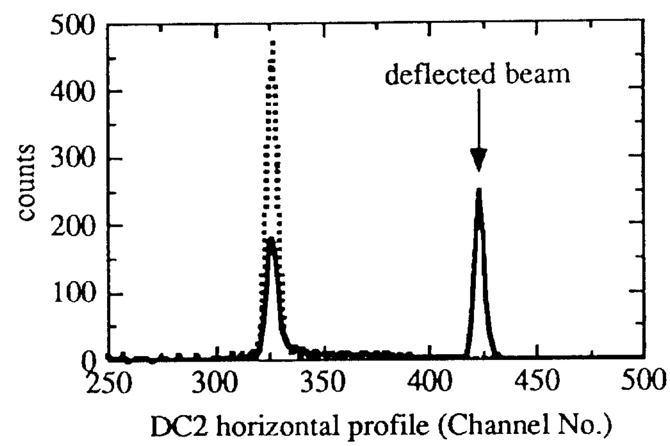

Figure 3: Horizontal beam profile as seen in the downstream drift-chamber DC2 for a deflection angle of 2.4 mrad. The dotted line indicates the beam profile as measured for a non-aligned crystal, when the full beam is undeflected.

The results of the present experiment are summarized and compared to theoretical estimates in Fig. 4. Measured deflection efficiencies for various deflection angles from 1.5 to 11.5 mrad show values up to 50 %. 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!

V. THEORETICAL ESTIMATES

The experimental results in Fig. 4 are compared to the expected efficiency for an ideally bent crystal (uniform curvature) - this is difficult to achieve in practice and was not attempted in the present experiment. The theoretical estimate involves the following factors:

a) The surface transmission was calculated for a perfectly parallel 450 GeV beam incident on a (111) silicon crystal and was found to be 0.75. This is the **ultimate** efficiency theoretically possible for bending a 450 GeV beam in a (111) silicon crystal.

b) The multiple scattering dechanneling in the straight parts of the crystal was included - this is an effect of a few percent at the present energies.

c) Bending dechanneling and multiple scattering dechanneling were considered in the bent part of the crystal - these effects determine the reduced efficiencies at the larger deflection angles.

In fact, in the present experiment, the crystal was bent in a 3-point bender, which was chosen for its simplicity (Fig. 2). Estimates of the expected deflection efficiency for an "ideal" 3-point bender (maximum curvature in the centre equals twice the average curvature) are also shown in Fig. 4. The calculation includes the same terms as described above for uniform curvature, with the change of the bending dechanneling term due to the larger maximum curvature. The data are seen to be bounded by the two theoretical estimates.

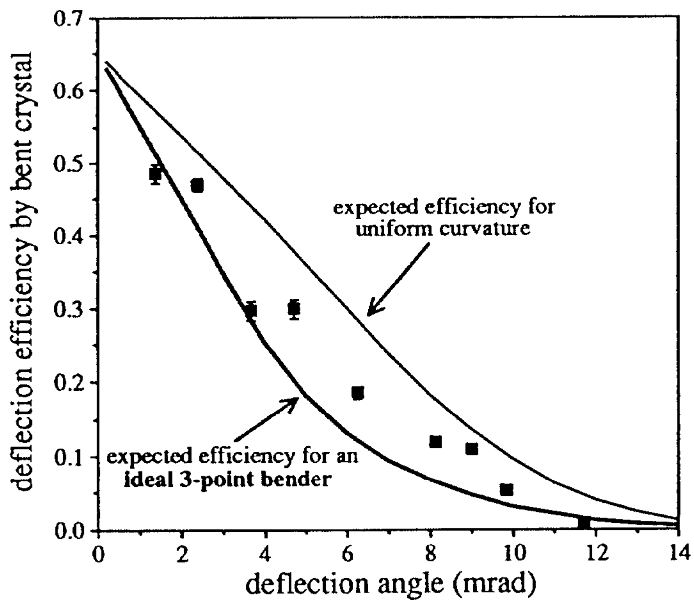

Figure 4: Comparison of experimental results (dots with bars indicating the statistical errors) with theoretical estimates for uniform curvature and an ideal 3-point bender. Details are explained in the text.

VI. CONCLUSION and PERSPECTIVES

In conclusion, the experiments on deflection of a 450 GeV proton beam in a bent silicon crystal show that by choosing the appropriate crystal curvature, efficiencies as high as 50% can be obtained in a parallel beam, in agreement with the expected values. The present results confirm the validity of the channeling and de-channeling models also at the highest energies available today. While an application of the silicon crystal as a beam splitter is already well advanced at CERN, the results presented here also give confidence in extrapolations to the higher energies available in future proton colliders. For example, a 7 TeV proton beam in a uniformly bent silicon crystal of 20 cm length could be deflected with an efficiency of 50% through an angle of 1 milliradian. Most crystal extraction schemes for LHC and SSC rely on a perfect crystalline surface. This represents a considerable technical challenge both for cutting and polishing the silicon crystals. Nevertheless, the present results show that if the surface layer can be made to resemble the bulk of the crystal, then high extraction efficiencies are not excluded for a beam, the divergence of which is matched to the critical angle for channeling (about one microradian for protons at 10 TeV energy).

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