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HIGH EFFICIENCY BENDING OF 450 GeV PROTONS USING CHANNELING

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Abstract

For the first time more than 10% of a 450 GeV proton beam has been bent using planar channeling in a 5 cm long single crystal of silicon. The bent beam is very narrow in angle ($\pm 5 \mu\text{rad}$), symmetrical and has suffered an energy loss of $\sim 60\%$ of random energy loss. Some of the unbent particles, however, lose more energy than random particles and the straggling is 50% larger than random. From the unbent fraction the bending dechanneling is inferred and found to be in agreement with calculations. The bending efficiency is in good agreement with theoretical dechanneling estimates. The results present very interesting perspectives for extracting beams from future TeV accelerators.

(Submitted to Physics Letters B)

Geneva, February 1991

A very interesting new technique for bending multi-GeV beams has been demonstrated experimentally the last few years¹⁻⁹. The technique is based on the channeling effect in perfect crystals¹⁰⁻¹². Particles entering a crystal nearly parallel to a planar direction will be trapped and oscillate between very steep potential walls with field gradients of 10^{11} V/cm or more. Even in a bent crystal the particles remain trapped between planes unless the bending radius becomes very small or the beam momentum very high. Radii of curvature less than 1 m are easily obtained for GeV beams and with an appreciable bending efficiency, but the inevitable loss due to the bending dechanneling will increase as the radius of curvature is decreased. Detailed calculations on channeling phenomena in bent crystals have been performed^{3, 13-15}. Computer simulation^{3, 13} has been used to investigate dechanneling, but comparison of calculated and measured bending dechanneling has been difficult because the experimental results are influenced by variable radius of curvature and crystal distortions caused by the pins in the bending devices. Bending efficiencies up to 20% have been found for incidence along axial directions^{2, 3}. For bending by planar channeling, however, the efficiency until now was only around 10^{-4} and for the multi-hundred GeV experiments the experimental efficiency was lower than theoretical estimates¹⁶ by a large factor. In the experiment reported here 450 GeV/c protons were bent 7 mrad with an efficiency of 10% - the highest obtained until now.

In this experiment the H8 beam line in the North Area at CERN was used. This beam is capable of transporting primary protons of 450 GeV/c momentum from the SPS. Recently, a so-called micro-beam option was implemented in this beam line in order to produce very small spot sizes. Beam spots in the 10 μ m (sigma) range were obtained¹⁷. This was achieved by cutting down the phase space in successive optical stages, making use of specially constructed "micro" collimators. In this manner, the 10^{12} extracted protons per burst were diminished to the 10^4 - 10^6 level and the emittance was correspondingly drastically reduced. Making use of the very small emittance and with some modifications of the optics, a highly parallel beam in the horizontal plane at the position of an intermediate vertical focus could be obtained. The horizontal divergence obtained was 3 μ rad. This is less than the critical angle for channeling at 450 GeV, thus making this beam unique for channeling studies.

Fig. 1 shows the part of the H8 beam where the channeling experiment was performed. The crystal is located in between two dipole magnets (B5a and B5b). The positions of the delay wire chambers (DWC) used to detect the beam upstream and downstream of the crystal are also indicated in the figure. The horizontal and vertical beam size as measured with the chambers was 2 mm and 1 mm (FWHM), respectively.

The bending crystal was a $\langle 110 \rangle$ Silicon crystal 0.9 mm thick, 10 mm wide and 50 mm long. The bending was perpendicular to the $\{110\}$ planes. The front and back ends were made into (3×8) mm² fully depleted solid state detectors. Two different bending devices were used. In the first stage of the experiment a classical 3-point bender⁹ was used as shown in Fig. 2a. The silicon crystal was supported by two ceramic cylinders at $\pm \sim 15$ mm from the center. In the centre a cylinder presses against the crystal to create a bending angle of 7 mrad. In a later stage of the experiment a different bending device was used (fig. 2b) in order to take away the above mentioned variation in bending curvature resulting from a 3-point bender. In the second device the Si crystal was pressed up against a precisely machined cylindrical aluminum block. The bending pressure from below was performed by 0.5 mm stainless steel balls acting as "fluid" with a piston in the middle. Although this last device gives a constant

bending curvature, all the material around the crystal gives a serious background in the solid state detectors - especially the exit one.

The bending device was mounted in a (x,y) goniometer, and the crystal alignment was performed by observing the energy loss spectrum in the front detector as a function of the goniometer setting. Planar channelled protons only deposit around half the energy in the detector as compared to random incidence. The reduced energy loss for channelled particles in crystalline solid state detectors has turned out to give a fast technique for aligning crystals in high energy beams^{11, 12}.

In fig. 3a is shown energy loss from the front detector for well-aligned incident protons. It can be seen that ~ 50% of the incident beam is captured in planar channels. The large fraction of planar channelled protons in the incident beam is due to the very small angular divergence of the H8 beam. In fig. 3c is shown the intensity of the bent beam as a function of the tilt angle with respect to the {110} bending planes. The FWHM is around 15 μ rad which is two times the planar channelling angle ψ_p ^{10, 11} for 450 GeV/c protons incident along <110> planes in Si; here ψ_p is 7 μ rad. The very steep sides of the distribution show that the horizontal beam divergence is less than around $\pm 3 \mu$ rad.

In fig. 3b is shown the energy loss spectrum for the back detector when the front detector is aligned. From the figure it is clear that a large fraction of the original planar channelled protons are bent through the full angle of 7 mrad. One can estimate that about 10% of the beam entering the crystal is bent the full amount. This implies that the fraction of particles being dechannelled is about 80%, taking into account that roughly 50% of the incident beam is captured in the channeling phase space.

Dechanneling has been described as a kind of diffusion in transverse momentum space. Well-channelled particles gain transverse energy mostly by scattering on electrons and to less extent by nuclei. In a bent crystal the trajectories are shifted closer to nuclear planes so bent particles see higher electron densities. In a bent crystal the "centrifugal" force gives an extra contribution to dechanneling. The theoretical treatment of these effects can be found in ref. 12-16. For 450 GeV protons in Si the ordinary dechanneling length $l_{1/e}$ is around 350 mm, so after 50 mm of crystal passage ~ 11% of the particles should be dechannelled. The fraction F of particles dechannelled by the bending can be estimated from ref. 13 where F is calculated as a function of the dimensionless parameter Γ which is given as $\Gamma = pv\kappa/2\pi Z_1 Z_2 e^2 n$ where p and v is beam momentum and velocity respectively, κ is bending curvature, Z_1 and Z_2 atomic numbers of projectile and target respectively and n is areal density of each plane. For a bending angle of 7 mrad the estimates show that $F \sim 70\%$ which is much more severe than the normal dechanneling. These theoretical considerations compare well with our observation of ~ 80% of the particles being dechannelled.

In the second phase of the experiment delay-wire chambers (DWC) were introduced in front of and behind the crystal to detect the direct and bent beams, as indicated in fig. 1. The results are shown in fig. 4, where a) shows the beam distribution for random incidence and b) the distribution of transmitted particles for aligned incidence. The unbent and bent beams are clearly separated. A comparison of the particle content in the two beams shows that ~ 10% of the whole incident beam was bent. Contrary to the unbent beam the bent one is symmetric without any tails in the distribution.

In fig. 5 is shown the energy loss distribution in the front detector for each of the three beam components shown in fig. 4. Fig. 5a corresponds to random incidence, fig. 5b) and c) correspond to the bent and unbent beams in the aligned case. A comparison between figs. 5a) and b) shows that the most probable energy loss for the bent particles is only 60% of that for random particles which is somewhat lower ($\sim 10\%$) that was found for 15 GeV/c protons traversing the same planes in a straight Si-crystal¹⁸. Also the straggling and the Landau tail is strongly reduced for the bent particles -the FWHM is only 50% of that for random incidence. This shows that only well-channeled particles in the straight front part of the crystal will survive the bending - they move in strongly reduced electron densities resulting in a reduced energy loss during the passage through the front detector.

The energy loss distribution for the unbent particles (fig. 5c) shows interesting aspects. The most probable energy loss is 10% higher and the straggling (FWHM) is 50% larger than for the random ones. Group II has reduced energy loss as compared to random and represents particles original channeled but dechanneled during passage of the bent crystal. The fact that the unbent particles experience more than random energy loss and straggling can be explained as follows: These high-loss particles enter the crystal with angles to the $\{110\}$ planes around the planar channeling angle ψ_p and up to a $2\psi_p$ - the so-called "quasi-channeled". After entering the crystal they make a number of very close collisions with the atomic planes before suffering a dechanneling encounter after which their energy loss reverts to normal. By travelling for some way in trajectories which lie in regions of consistently high electron densities these protons loose energy more rapidly than in random. Earlier CERN-experiments¹⁹ on δ -ray yields from planar channeled particles also gave more than random yields for incident angles between ψ_p and $2\psi_p$.

Good agreement has been found between measurement and theoreticl calculations concerning the bending dechanneling. According to the rule of reversibility¹⁰, the probability for a channeled particle to be dechanneled is equal to the probability for a random particle to become channeled. This so-called "feed in" process was shown experimentally in straight crystals³. The fact that very few of the present bent particles experience random energy loss in the front detector (fig. 5b) implies that here the "feed ind" during passage of the bent crystal is small. The question about "feed in" in bent crystals will be investigated in more detail in future experiments.

The original motivation for the present bending experiment came from an idea of creating simultaneous K_L and K_S beams for a precision CP-violation experiment²⁰. Part of the proton beam, used to create the K_L component, is intended to be recuperated by a bent crystal and subsequently used to produce the K_S beam. The crystal provides a clean way of attenuating the proton flux and selecting a small emittance beam suitable for the K_S production.

The high efficiency bending found in the present experiment also offers interesting alternatives for extracting beam for fixed target experiments around future TeV-accelerators²¹. Crystals used for bending require only a few centimetres of space in contrast to tens of metres of conventional septa. Detailed predictions for TeV bending will, however, require more investigation in the multi-hundred GeV region concerning dechanneling, radiation damage, and type of crystal.

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Figure Captions.

- Fig. 1 Part of the H8 beam and experimental set-up for the channeling experiment. Q designates quadrupoles, B bending magnets and DWC delay-wire chambers.
- Fig. 2 a) A schematic drawing of the first bending device. The beam enters from the left. The front and back end of the crystal is made into solid state detectors.
 b) Second bending device.
- Fig. 3 a) Energy loss spectrum in the front detector for aligned incidence of the 450 GeV/c protons.
 b) Energy loss spectrum in the back detector for aligned incidence.
 c) Intensity of bent beam as a function of tilt angle to the $\langle 110 \rangle$ vertical plane.
- Fig. 4 Intensity distributions of the transmitted beam measured 4 m behind the crystal,
 a) for random incidence,
 b) for aligned incidence.
- Fig. 5 Energy loss distribution in the front detector, for
 a) random incidence,
 b) bent particles for aligned incidence,
 c) unbent particles for aligned incidence.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5