THE INFLUENCE OF RADIATION DAMAGE ON THE DEFLECTION OF HIGH ENERGY BEAMS IN BENT SILICON CRYSTALS

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Abstract

Experimental results obtained for deflection of 450 GeV/c protons channeling along the {111} planes in a bent, strongly irradiated silicon crystal are presented. A comparison between the deflection efficiencies in irradiated areas and non-irradiated areas in the crystal shows that irradiation by $2.4\cdot10^{20}$ protons/cm^2 leads to a reduction of around 30% in deflection efficiency. As a consequence, beam-splitting and extraction from an accelerator by means of a bent crystal are feasible solutions at high energies even for intense beams and during long periods.

1 INTRODUCTION

When a charged particle penetrates a crystal along crystalline directions it scatters coherently off the atoms along the axes or planes. In the so-called continuum approximation, introduced by Lindhard [1], the particle is 'steered' through the crystal since the transverse motion is governed by the lattice and not the single atoms. For positive particles, this channeling effect reduces the energy loss, multiple scattering and nuclear interaction probability, since the particle is excluded from regions of large electron and nuclear density. This, combined with the smaller multiple scattering angles at higher energies, makes it possible for a considerable fraction of 450 GeV/c protons to traverse crystals with lengths of several centimeters.

For the particle to be channeled, its transverse energy in the crystal must be less than the potential height of the plane. This leads to a critical angle, ψ_c, with respect to the crystalline direction for the effect to occur. For Si the critical angle is 8 μrad for a 450 GeV/c particle in the {111} planes and roughly a factor of 3 higher along an axis.

2 DEFLECTION OF HIGH ENERGY BEAMS IN BENT CRYSTALS

The channeling phenomenon persists even when the crystal is bent slightly. A useful parameter in this context is the critical bending radius, r_c, beyond which the deflection efficiency drops rapidly. Thus in Si along the {111} planes, r_c is 0.9 m which corresponds to a deflection angle of 28 mrad over 25 mm. At the critical curvature, the centrifugal force acting on the penetrating particle in the curved crystal forces it towards a plane where it is lost in a close encounter with an atom in the lattice. As the curvature approaches the critical radius, the particle suffers increased multiple scattering and nuclear interactions which leads to a reduction in the deflection efficiency.

At CERN, the use of bent crystals has been investigated for some years [2,3] and simple models of the deflection efficiency as a function of the bending angle show good agreement with experimental results. The deflection of high energy protons in bent crystals is now a well-established technique and is being used for beam-splitting eg. in the NA48 experiment at CERN [4] and at IHEP, Protvino [5]. The first tests were also initiated in view of using a crystal as an extraction device at eg. the LHC [6, 7]. For a comprehensive review, see eg. [8].

It is of considerable interest to determine the effect of irradiation of the crystal in view of its possible application in regions of intense particle flux as an extraction device or a beam-splitter. This has been investigated earlier at lower energy and dose at IHEP where a crystal irradiated with 10^{19} protons/cm^2 at 70 GeV/c showed no noticeable efficiency deterioration [9]. Baker *et al.* have observed a reduction in low energy channeling capability for a crystal exposed to $4\cdot10^{20}$ protons/cm^2 at 28 GeV/c [10]. Since the number of atoms in the crystal lattice encountered in one channeling oscillation is of the order of $1/\psi_c$ - which is proportional to $(pv)^{1/2}$ - it is, however, hard to relate the low energy behaviour to that at high energies.

Three types of crystal imperfections can affect the channeling properties: point defects (vacancies, interstitials, impurities), dislocations and mosaic spread. Point defects are not as important at high energies owing to the large number ($\approx10^5$) of atoms participating in one oscillation of a channeled particle, whereas dislocations can enforce a local curvature comparable to the critical curvature. Therefore, a large dislocation density can lead to a high dechanneling fraction and resulting deterioration of the deflection effect. For good Si crystals the mosaic spread is far smaller than the critical angle even at tens of TeV, ie. below 1 µrad, and can thus be neglected.

3 IRRADIATION OF THE CRYSTAL

For the present investigation, a silicon crystal which had earlier given 50 % deflection efficiency [3] was reused. The crystal was irradiated with 450 GeV/c protons at one of the SPS target stations, T6, during one year of operation. At T6, the beam divergence is roughly 0.2 mrad (RMS) and the crystal was not aligned during irradiation. The proton beam intensity as measured by Secondary Emission Monitors was recorded throughout the year and the beam spot size was checked regularly. It was found that the total intensity was $2.4 \cdot 10^{20}$ protons/cm^2 over an area of 0.8×0.3 mm^2 (FWHM), calculated from an equivalent square box with RMS given by the beam-profiles.

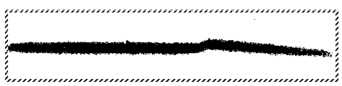

Figure 1 *Picture of the irradiated silicon crystal (broken into two pieces). Exposure: 20 s., Kodak X-Omat AR film. The contour shows the 10×50 mm^2 surface of the crystal*

The position of the irradiated spot on the crystal was verified by contact radiography, revealing the region of highest induced radioactivity. Unfortunately, during this measurement, the $50 \times 10 \times 1$ mm^3 crystal was broken in two pieces. Figure 1 shows an image of the 10×50 mm^2 crystal face with the irradiated area in black.

4 BEAM DEFLECTION EXPERIMENT

The experiment was performed in the H8 'micro-beam' at the CERN SPS where 450 GeV/c protons are available with very low divergence. The setup is shown schematically in figure 2, where the bending plane is horizontal. For the alignment of the crystal planes with respect to the beam a goniometer with 1.7 µrad step-size was used. For the bending of the crystal a 'classical' three-point bender as shown in fig. 3 was used like for the earlier measurements [3], but this time the distance between the bending points was reduced from 30 to 25 mm. This leads to a smaller radius of curvature for fixed bending angle and therefore a reduction in deflection efficiency.

The signature for alignment was the observation of the bent beam in the scintillator-hodoscope H1, H2, H3.

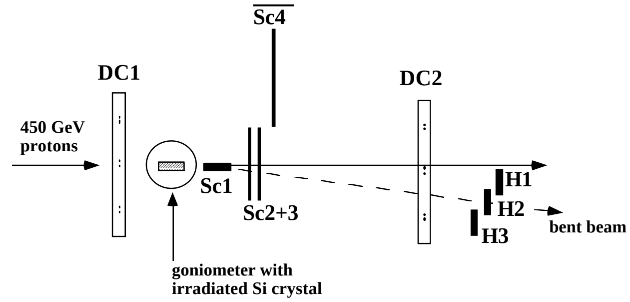

Figure 2 *Set-up for the experiment in the SPS H8 'microbeam, for details see text*

To define the beam a number of scintillator counters were used: Sc1 to reduce the effective beam-size during alignment and data acquisition, Sc2 and Sc3 to define the trigger and Sc4 as a veto-counter to reject nuclear interactions with origin in the bending device. For the off-line analysis two drift chambers (DCs) were used to identify the direct and the bent beam. From these the deflection efficiency could be determined as the ratio of the bent beam to the incident beam flux.

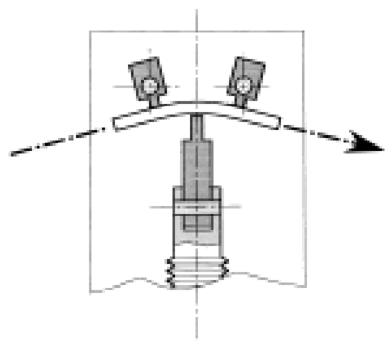

Figure 3 *The 'classical' three-point bender with a bent crystal*

5 RESULTS

Due to the short distance over which the crystal was bent, the fracture and possibly the irradiation, the crystal showed a large anticlastic bending, ie. it was also bent in the direction orthogonal to the desired bending.

To determine the influence of the radiation damage, which in the setup was a function of the vertical position on the crystal, the small beam was displaced vertically over the entry edge of the crystal. Each time the beam was displaced, the crystal was realigned to compensate for the anticlastic bending.

Two investigations were made with essentially the same result - one with the beam focussed in the vertical plane and parallel in the horizontal plane (with a beam-size of 0.7×1.5 mm^2) and one with the beam being parallel in both planes (beam-size 1.5×1.5 mm^2).

The anticlastic bending complicated the analysis and interpretation of the results since it introduced a coupling between the optimum alignment and the vertical position on the crystal, even within the small vertical beam-spot. Therefore, for each position of the beam a variation of the deflection efficiency with the vertical position was observed. Figure 4 shows the results obtained with the beam tuned to the parallel-parallel mode. The black ellipse and the curve at the top indicate the area and profile of the irradiation seen from the 1×10 mm^2

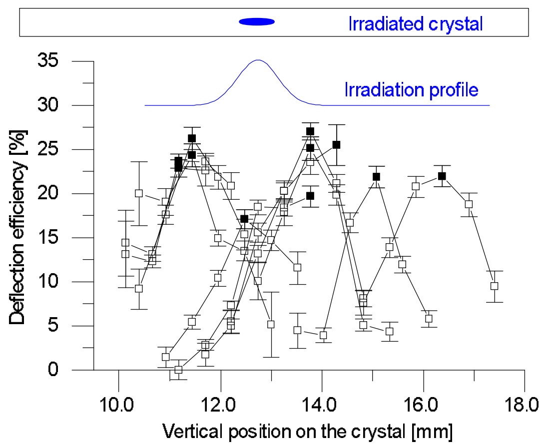

Figure 4 *Deflection efficiency for the irradiated crystal as a function of vertical position (see text).*

endface of the crystal and the connected squares are the measured points corresponding to each vertical beam position. Filled black squares show the maximum efficiency value for each beam position. For a few curves in the neighbourhood of the irradiated part this maximum lies at the edge. There can be two reasons for this: The deflection efficiency is suppressed in the irradiated area or the alignment was not correct. The second explanation can be ruled out by observation of the goniometer angle as a function of vertical position - this gives the shape expected for an anticlastic effect for the points near the middle of each scan.

The variation over one scan in fig. 4 due to the anticlastic bending can be seen as a 'bell'-shaped curve and a reduction in deflection efficiency of around 30% is seen in the irradiated region.

In fig. 5 the points measured at optimum alignment for each scan has been fitted by a Gaussian, keeping the σ and position fixed at values corresponding to the

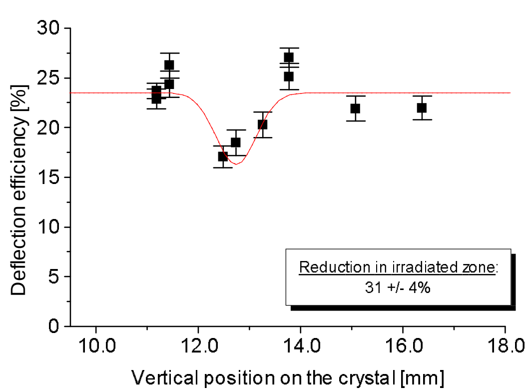

Figure 5 *A fit using the inverted irradiation profile to the measured points at expected optimum alignment*

irradiation profile. This fit gives a reduction in the irradiated zone of 31±4%. Furthermore, assuming that the damage depends linearly on the irradiation, distributed as a Gaussian for which the peak value then becomes $5.0\cdot10^{20}$ protons/cm^2, the deterioration coefficient is: 6±2% /10^{20} protons/cm^2. This number is most likely lower if the beam is incident within the critical angle, as in eg. a crystal extraction scheme.

6 SUMMARY AND CONCLUSION

We have investigated the reduction in deflection efficiency in a bent Si crystal resulting from radiation damage. The crystal was irradiated by an average $2.4\cdot10^{20}$ protons/cm^2 at 450 GeV/c which leads to a reduction of around 30% in the deflection efficiency.

This relatively large dose and small effect means that crystals can be subjected to large particle fluxes without deteriorating as deflectors. For the practical application of a Si crystal as a beam splitter in the NA48 experiment at CERN, the proton dose used in the present investigation corresponds to about 100 years of running time - it is therefore safe to assume that the crystal in NA48 will not have to be exchanged.

Concerning the use of a bent crystal as an extraction device, the degradation due to irradiation depends sensitively on the spot-size on the crystal. Realistic assumptions for this, eg. a spot-size of 100nm×1mm at the SPS and much smaller for the LHC, indicate that in the worst case up to a year and several months, respectively, of continuously extracted beam can be envisaged without having to displace the crystal.

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