Deflection of 200 GeV/c and 450 GeV/c Positively Charged Particles in a Bent Germanium Crystal

C. Biino^a, M. Clément^a, N. Doble^a, K. Elsener^a,
A. Freund^c, L. Gatignon^a, P. Grafström^a, K. Kirsebom^b,
U. Mikkelsen^{a,b}, S.P. Møller^b, E. Uggerhøj^b, T. Worm^b

^a*CERN, Geneva, Switzerland*

^b*Institute for Storage Ring Facilities, Aarhus, Denmark*

^c*ESRF, Grenoble, France*

Abstract

Experimental results on high-energy beam deflection by means of a bent germanium crystal are presented. Record deflection efficiencies of 60% have been found for 450 GeV/c protons at small angles. The results obtained with 200 and 450 GeV/c positively charged particles are well described by a classical model, giving confidence in predictions for other crystals and different beam momenta.

Submitted to Physics Letters B

Geneva, Switzerland

February 19, 1997

1 Introduction

Deflection of charged particle beams in bent silicon crystals has been investigated since many years and is now an established technique used to extract/steer beams for experiments at CERN, Fermilab and IHEP [1], [2], [3], [4]. Theoretically, this technique would also allow a 7 TeV beam to be extracted from the halo of the future Large Hadron Collider at CERN, thereby opening a way to fixed target experiments at these high energies. Furthermore, crystals can be envisioned as elements for beam diagnostics in future high-energy storage rings.

Recent experiments have shown that the deflection efficiency in an irradiated silicon crystal is reduced by $6 \pm 2\%$ per 10^{20} protons/cm² owing to the radiation damage created by a high energy proton beam [5], [6]. Therefore, a crystalline extraction/deflection device can operate for many years even in intense beams without having to be replaced.

Due to the required crystal quality (purity, mosaic spread), mechanical properties and size along given planar directions, crystals for deflection experiments have hitherto been limited to silicon and germanium. In silicon, a solid state detector can be operated at room temperature, whereby one can distinguish between channeled and non-channeled particles through their energy-loss (see eg. [7], [8]). High quality silicon crystals are readily available from industry, and therefore most investigations have used Si-crystals.

Good agreement has been found between the measured and expected deflection efficiencies according to the model shown below for deflection of 450 GeV/c protons in silicon [7]. However, to gain confidence in the model, it is necessary to test it for at least one different energy and material. Moreover, since germanium has a higher nuclear charge and therefore a deeper continuum potential than silicon, it should be able to deflect more effectively. For a review of channeling at high energies and in bent crystals, see e.g. [9], [10].

2 Experiment

The experiment was performed in the H8 'microbeam' at the CERN SPS where a beam with very small divergence can be provided. Three drift chambers (DC1, DC2, DC3), as shown in Fig. 1, were used to measure particle tracks, two in front of the crystal placed 36.4 m apart with DC2 0.5 m upstream of the crystal, and DC3 4.1 m downstream of the crystal. A number of scintillation counters, Sc1 ($1 \times 5 \times 7$ mm³), Sc2 ($2 \times 5 \times 7$ mm³), Sc3 and Sc4 ($100 \times 100 \times 5$ mm³) were used to define the incident beam and to provide the trigger for the data acquisition system. A veto counter, $\overline{\text{Sc5}}$ ($300 \times 150 \times 5$ mm³ with a 5×15 mm² hole) was used to reduce background during crystal alignment runs (see below). The arrangement was optimised to be sensitive to the low beam deflection efficiencies expected at large bending angles. During data-taking, the motorized Sc1 was

removed from the beam to reduce the divergence resulting from multiple Coulomb scattering in the material upstream of the crystal, and the trigger was thus given by Sc2·Sc3·Sc4.

The germanium crystal, $1 \times 10 \times 50 \text{ mm}^3$, was mounted in a 'classical' three-point bending device (see Fig. 2) and was bent over 30 mm of its length. The curvature was thus normal to the (110) plane which lay along the $50 \times 10 \text{ mm}^2$ face. The newly designed bending device was optimised for stability with respect to temperature variations (titanium block) and the push-pin included a micrometre read-out. The device was placed on a goniometer with $1.7 \text{ } \mu\text{rad}$ step-size. To align the crystal, a scintillator array, H1, H2, H3, each $10 \times 10 \times 5 \text{ mm}^3$ in size, was used to detect the deflected beam and the goniometer was rotated until a maximum rate of deflected particles was observed. At large bending angles (above 15 mrad) for the 450 GeV/c beam, the low deflection efficiency resulted in a small signal to noise ratio in the five-fold hodoscope coincidence used for alignment, H2·Sc1·Sc3·Sc4·Sc5. However, the micrometer read-out on the bending device enabled a fairly accurate prediction of the new bend-angle after each change and thus a relatively fast re-alignment of the crystal was possible.

The drift chambers with cell width 25 mm and a sensitive area of $15 \times 15 \text{ cm}^2$ in the vertical plane provided information on the incident and exiting beam which was stored for later analysis. Each event was stored as a set of positions in DC1, DC2 and DC3 and the beam profiles of the exiting straight and deflected beams were obtained (see fig. 3). The resolution of the drift chambers was roughly $100 \text{ } \mu\text{m}$ (σ). Due to a non-uniform velocity of the drift-electrons in the chambers which affects the determination of the position of a particular hit, the precise deflection angle was better determined by use of the goniometer angle once the crystal was aligned. This was done by a linear fit to the goniometer readout angle as a function of the deflection angle determined by the drift chambers, where the entire chamber is used and thus the non-uniform drift velocity to a large extent cancels out. The difference in the two procedures amounted to as much as 0.4 mrad. Estimates of the divergence of the incident beam, based on the shape of angular scans and measured beam profiles, gave $\approx 3 \text{ } \mu\text{rad}$ for the 450 GeV/c primary proton beam and $\approx 7 \text{ } \mu\text{rad}$ (σ) for the 200 GeV/c secondary beam (composed mainly of about 60% protons and about 40 % pions).

In case a drift chamber cell is hit by two or more simultaneous particles (mainly δ -electrons or nuclear fragments from the crystal or the bending device) only the event closest to the anode wire will be registered. These events are visible as an excess of counts near the wires in fig. 3. Note that this figure shows the raw data: the contribution from multi-hit events is reduced to a negligible level when a severe cut on the incident beam-size is made.

The experimentally-determined deflection efficiency is defined as the number of fully deflected particles originating from a specific area on the $1 \times 10 \text{ mm}^2$ entrance-face of the crystal, divided by the number of particles incident on this area. For each deflection angle, off-line cuts using the driftchambers were used

to determine the area with the highest deflection efficiency. For the 200 GeV/c beam, off-line angular cuts were used in addition to reduce the beam divergence, within the resolution allowed by the drift chambers, to $\approx 6 \mu\text{rad}$ (σ).

3 Results

The experimental results are compared to a model calculation based on the dechanneling fraction as a function of curvature, $F(\kappa)$, the surface transmission, ε_S , and the dechanneling length, L_D . The dechanneling fraction was calculated for a perfectly parallel beam following the theory of Ellison [11], [12] and the dechanneling length used was that according to Biryukov et al. [13] - a theoretical estimate which agrees well with data for silicon. The surface transmission was found as outlined in [10]. The model calculation determines the efficiency as a function of curvature, $\varepsilon(\kappa)$, according to

$$\varepsilon(\kappa) = \varepsilon_S \cdot \exp(-L_s/L_D) \cdot \exp(-L_b/(1 - F(\kappa))^2 L_D)(1 - F(\kappa)) \quad (1)$$

where L_s is the length of the upstream unbent part of the crystal and L_b is half the length of the bent part of the crystal, since in the three-point bender the curvature dechanneling takes place upstream of the middle point, due to the almost linearly rising curvature. This procedure takes into account the increase of multiple scattering dechanneling with rising curvatures and the decrease of the depth of the potential well due to the centrifugal force on the particle in the crystal (see [8]). In the calculation, the curvature of small segments of the crystal is determined according to an ideal three-point bender and the corresponding efficiency is derived. The overall efficiency is then obtained as the product of these contributions.

Experimentally, the surface transmission can be found by extrapolating the fraction of non-channeled (ie. non-deflected) particles as a function of deflection angle to zero angle and subtracting this number from one. The numbers found by this procedure for the two beams agree within the experimental uncertainty of a few percent with the calculated values.

Figure 4 shows the experimental values (filled dots with error bars indicating statistical uncertainties). Systematic errors due to mechanical instabilities, variations in beam incident angle, etc., can be estimated from the scattering of the data points. The expected values for the deflection efficiency as a function of deflection angle determined from eq. (1) are shown as a solid line. For the 450 GeV/c beam the agreement is very good, although at small and large angles there is a slight discrepancy (fig. 4a). Note that, according to the model, the surface transmission varies less than 1% between a completely parallel beam and a beam of $3 \mu\text{rad}$ divergence at 450 GeV/c.

For the 200 GeV/c case, the centrifugal force becomes less dominant whereas the dechanneling length (which increases linearly with momentum) lowers the

efficiency at small angles (fig. 4b). Again the agreement is good although the model overestimates the overall efficiency slightly for a divergence of $6\ \mu\text{rad}$. This is not surprising since in the model the overall efficiency is fairly sensitive to the exact value of the divergence for values around $6\ \mu\text{rad}$.

4 Conclusion

After the first series of deflection experiments with 450 GeV/c protons in silicon and the demonstration that model calculations agree well with the observed efficiencies, it might still have been argued that this agreement was due to a fortuitous cancellation of different contributions. However, as the present experiment has shown, the agreement persists for a different energy and a different crystalline material, giving confidence that one can extrapolate the model rather safely to new materials and beam energies. Supported by the extreme radiation hardness of the deflection phenomenon in silicon crystals shown earlier, the use of crystals as beam splitters and extraction devices at future high energy accelerators is an attractive option. Furthermore, it seems feasible to use model calculations as described, to predict the deflection efficiencies in such devices.

References

- [1] N. Doble, P. Grafström and L. Gatignon, Nucl Instr. Meth. **B119**, 181 (1996)
- [2] R.A. Carrigan, Jr *et al.*, Nucl. Phys. **B163**, 1 (1980)
- [3] V.M. Biryukov *et al.*, Physics-Uspekhi **37**, 937 (1994)
- [4] K. Elsener *et al.*, Nucl Instr. Meth. **B119**, 215 (1996)
- [5] C. Biino *et al.*, contr. to 5th EPAC, eds. S. Myers, A. Pacheco, R. Pascual, Ch. Petit-Jean-Genaz and J. Poole, Vol. 3 (1996), 2385
- [6] A. Baurichter *et al.*, Nucl Instr. Meth. **B119**, 172 (1996)
- [7] S.P. Møller *et al.*, Phys. Lett. **B256**, 91 (1991)
- [8] S.P. Møller *et al.*, Nucl Instr. Meth. **B84**, 434 (1994)
- [9] H.H. Andersen, R.E. Carrigan and E. Uggerhøj, Nucl. Instr. Meth. **B119**, (1996), topical issue
- [10] S.P. Møller, Nucl Instr. Meth. **A361**, 403 (1995)
- [11] J.A. Ellison and S.T. Picraux, Phys. Lett. **A83**, 271 (1981)
- [12] J.A. Ellison, Nucl. Phys. **B206**, 205 (1982)
- [13] V.M. Biryukov *et al.*, Nucl Instr. Meth. **B86**, 245 (1994)

5 Figure captions

Fig. 1 Schematic drawing of the experimental setup, showing the drift chambers (DCs), the goniometer with the Ge (110) crystal mounted, the scintillator hodoscope, H1, H2, H3, the scintillator trigger counters, Sc1, Sc2, Sc3, Sc4 and the veto-counter $\overline{\text{Sc5}}$.

Fig. 2 Schematic drawing of the new "3-point" bending device: the push-pin in the centre, which is used to bend the crystal, is equipped with a digital micrometre readout.

Fig. 3 The beam profile (raw data) as reconstructed from the six cells of drift chamber DC3 for a bending angle of 14.9 mrad. The fully deflected, the dechanneled and the undeflected beam are indicated. The excess of counts around the anode wires due to multi-hits is clearly visible at 25, 75 and 125 mm. The lack of efficiency near the field wires can be observed in the dechanneling tail around 50 mm. For more details, see text.

Fig. 4 Deflection efficiency as a function of angle for (a) 450 GeV/c protons and (b) 200 GeV/c positively charged hadrons. The full-drawn curves are the model calculations on the basis of eq. (1) and the points are the experimental results with error bars indicating the statistical uncertainty.

Figure 1:

Figure 2:

Figure 3: