Record Deflection Efficiencies measured for High Energy Protons in a Bent Germanium Crystal

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Abstract

New experimental results on the deflection of high energy protons in a bent germanium crystal are presented. At 450 GeV/c, the 50 mm long crystal gave record deflection efficiencies up to 60% for small angles (1 mrad), while at angles as large as 12 mrad, the efficiency is about 25 times larger than for a silicon crystal of the same size. The experimental results are in good agreement with a model for channeling and deflection developed by Ellison and give - together with a similar comparison for a 200 GeV/c beam - confidence in extrapolations to higher energies (e.g. to LHC), other crystal materials or different deflection angles.

1 INTRODUCTION

Proton deflection experiments using bent crystals have been performed at CERN and elsewhere since many years (reviewed in [1], [2]), and silicon crystals are being applied routinely as beam splitters [3] and for proton beam extraction [4]. Up to 50% of a parallel proton beam has been deflected by 1.5 mrad in a bent silicon crystal [5]. The experimental results are generally in good agreement with the deflection efficiencies expected from classical models [6]. A crucial test for these models, however, is to change to a different crystalline material. Besides silicon, germanium is the only crystal with a sufficiently good crystalline quality for a very high energy channeling experiment, available at a reasonable cost.

The deflection efficiency for a given incident beam / crystal configuration is influenced by four important factors: (1) the beam divergence, (2) the critical angle for channeling [7], which scales with $\sqrt{(Z_2)}$, (3) the dechanneling losses due to multiple scattering and (4) the bending dechanneling. The ‘acceptance’ of the crystal, the so-called surface transmission, is determined by (1) and (2), as well as by the planar distance in the crystal and the lattice vibration amplitude. The higher charge of the atoms in a Ge crystal (Z_2=32 compared to Z_2=14 for Si) should lead to higher deflection efficiencies than obtained with Si, (a) due to the fact that the surface transmission is larger, (b) because the channeling potential ’trap’ is deeper and thus the bending dechanneling less severe at the larger deflection angles. In order to test these hypotheses, we have conducted proton deflection experiments with a bent germanium crystal, over a large range of deflection angles, and compared the results with calculations.

2 EXPERIMENT

The present experiment continues the series of proton deflection experiments performed with bent crystals at the CERN-SPS. Information on the earlier experiments can be found in [1], [5] and [8], and further details on the recent tests with a germanium crystal (using 450 and 200 GeV/c beams) are described in [9]. In the following, a description of the H8 ’micro-beam’ option is given, together with a brief discussion of the experimental arrangement used for the 450 GeV/c proton experiment on a bent germanium crystal.

2.1 The H8 micro-beam

The micro-beam (H8 beam line) in the North Hall at the CERN-SPS has been designed in 1983 to serve the NA34 experiment. The requirement on this 450 GeV/c proton beam was to achieve an extremely small spot size (about 10 μm rms.) at the target. The conceptual design of this beam is schematically shown in Fig. 1. The beam has a large intermediate magnification in both planes ($\times 2$ horiz.(x), $\times 4$ vert.(y)) as a first stage, followed by two stages with strong demagnification (overall $\times 0.2$ horiz., $\times 0.1$ vert.). The 450 GeV/c protons from the SPS are attenuated and scattered in the T4 target (30 cm beryllium) and in an additional 80 cm beryllium attenuator, in order to reach acceptable beam intensities at the experiment. The angular space is first cut to about 100 μrad by a 2 mm diameter tungsten lined aperture

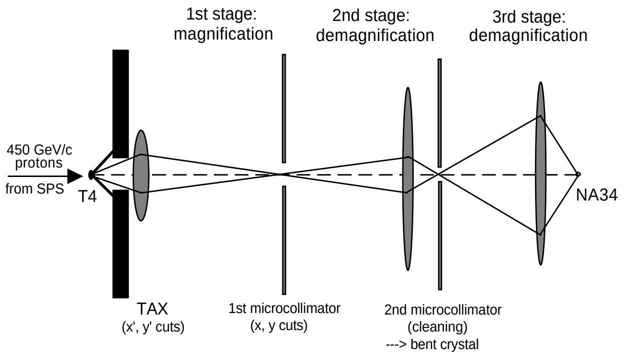

Figure 1: Conceptual layout of the H8 micro-beam (horizontal projection). For the present experiment, the cleaning collimator was removed, the bent crystal installed at its place and the beam tuned to be parallel at the crystal. For details, see text.

in a 160 cm long beam-dump collimator (TAX). The (x,y) space is then cut by precision 'micro-collimators', usually closed to $\pm 100\ \mu$m, in the place of largest magnification. In order to correct for possible alignment errors in the installation or in beam steering, these collimators can be aligned with the beam for maximum transmission in angular steps of 0.05^o. A second set of such micro-collimators is installed at an intermediate focus and serves beam-cleaning purposes. Note that this scheme reduces the beam intensity drastically, from some 10^{12} protons per spill on target T4 to a few 10^6 at the experiment. In order to minimize the contribution of momentum dispersion terms to the spot sizes, focii (or waists) were placed in all bending magnets. (Note that the 450 GeV/c beam from the SPS has an intrinsic 0.1% momentum bite as defined by the accelerator.)

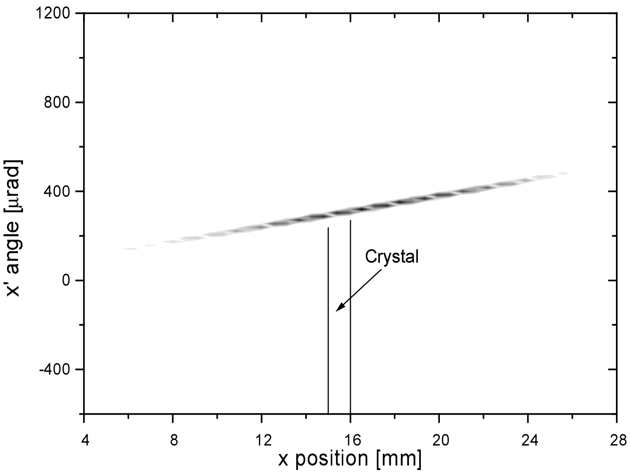

Figure 2: Horizontal phase space of the 450 GeV/c protons incident on the germanium crystal. This measurement stems from two drift chambers located 36.9 and 0.5 m upstream of the crystal (see Fig. 4). The horizontal width of the bent crystal is indicated to illustrate the relevant phase space for this experiment.

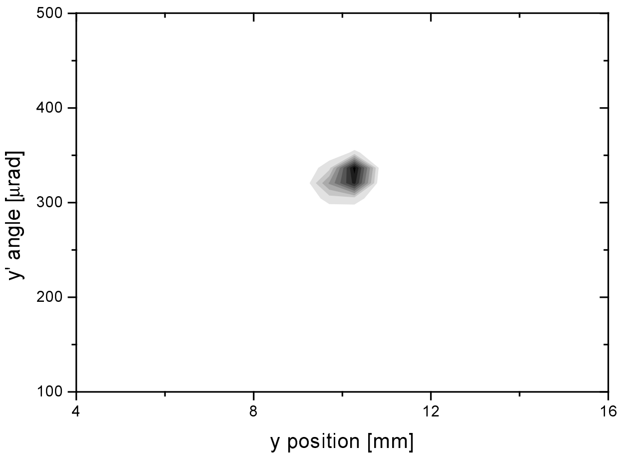

Figure 3: As Fig. 2, but for the vertical phase space (y,y'). (Note that the scale is different from the one in Fig. 2).

For the application of the bent crystal experiments in H8, the second set of micro-collimators was removed and the goniometer with the crystal installed in its place. For channeling experiments, it is important to achieve as parallel a beam as possible - in the case of planar channeling and bending, discussed here, the beam was therefore set-up to be parallel in the horizontal (channeling and deflection) plane, and focussed onto the crystal in the vertical plane. Finally, the last quadrupole upstream of the crystal was used to further increase the horizontal beam-size at the crystal position (i.e. to rotate the phase space ellipse), thus reducing the angular spread of protons inside the 1 mm wide 'slice' hitting the crystal, even if the overall divergence of the beam is increased. The resulting beam phase space as measured in the experiment is shown in Figs. 2 and 3. Note that due to the limited angular resolution in the experiment, the horizontal angular spread appears to be 6μrad (rms.). Angular scans with the goniometer (see below) indicate, however, that it is indeed much smaller, i.e. 2 to 3 μrad and thus inside the critical angle for channeling, which amounts to $\pm 7\ \mu$rad in this case.

2.2 Crystal and Detectors

The experimental arrangement is shown schematically in Fig. 4. The germanium crystal, $1 \times 10 \times 50$ mm^3, was mounted in a 'classical' three-point bending device (see [9]) and was bent over 30 mm of its length. The curvature was thus normal to the (110) plane which lay along the 50×10 mm^2 face. The newly designed bending device was optimised for stability with respect to temperature variations (titanium block). The push-pin for the crystal bending includes a micrometre read-out. The device was placed on a goniometer with 1.7 μrad step-size.

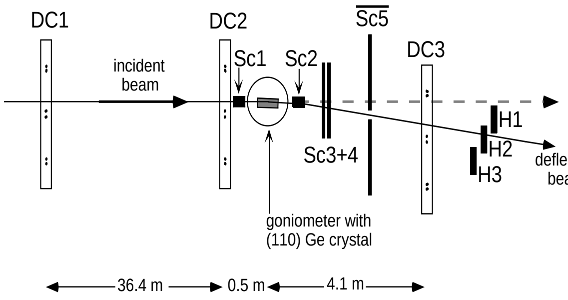

Figure 4: Schematic view of the experimental arrangement. Protons are deflected horizontally by the bent germanium crystal. Scintillators Sc1-4 are trigger counters for incident beam particles, H1, H2 and H3 for deflected particles. SC5 is a veto counter used during crystal alignment. Driftchambers DC1, DC2 and DC3 define the incoming and exiting beams, respectively.

To align the crystal, an array of scintillators, H1, H2, H3, (each $10 \times 10 \times 5$ 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, $\mathrm{H2 \cdot Sc1 \cdot Sc3 \cdot Sc4 \cdot \overline{Sc5}}$. However, the micrometre 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.

Driftchambers (DC) are used to track the incident and exiting protons in the beamline with a position resolution of about 100 μm (rms). The incident angles can be measured with DC1 and DC2, with an accuracy of about 6 μrad, which is larger than the horizontal beam divergence of the 450 GeV/c proton micro-beam, but was useful to cut the tails of the angular distribution in the 200 GeV/c experiment [9]. The experimentally determined deflection efficiency is defined as the ratio of the number of fully deflected particles (detected in DC3) originating from a specific area on the 1 x 10 mm^2 entrance-face of the crystal and the number of particles incident on this area. For each deflection angle, off-line cuts using the driftchambers were applied to determine the area with the highest deflection efficiency, thus avoiding edge and surface effects.

3 RESULTS

Deflection efficiencies for 450 GeV/c protons were measured between 0.5 and 19 mrad deflection angle. The results are shown in Fig. 5. Statistical errors are shown in the figure. The systematic errors, which can stem from mechanical instabilities of the goniometer or bending device as well as from beam instabilities, can be estimated from the fluctuation of the data points. A new record deflection efficiency, 60%, for bent crystal proton deflection was found for the small deflection angles. The beam being very parallel, this can be attributed to the larger 'acceptance' - the so-called surface transmission - of the (110) Ge crystal when compared to the (111) Si used in earlier experiments [5].

The experimental results are compared in Fig. 5 to a model calculation along the lines described by Ellison [6]. In this model, the surface transmission, straight crystal dechanneling and bending dechanneling are parametrised (for more details, see [9]). The agreement with the data is found to be very good.

4 CONCLUSION

New experimental results on proton deflection with a bent germanium crystal have been obtained, and a record deflection efficiency of 60% has been obtained for the 450 GeV/c proton beam. The H8 microbeam of 450 GeV/c protons, originally designed to give a small spot size for an experiment, is here being used to provide as parallel a beam as possible at the crystal. Together with the good crystal quality, this makes record deflection efficiencies possible. The results shown here, together with the 200 GeV/c data reported elsewhere [9], provide a crucial test for models which had previously only been compared to data obtained with silicon crystals. The agreement between data and model for germanium is now found to be excellent, too. Therefore, one can conclude that reliable predictions are indeed possible, both for a different crystal material as well as for a large energy range, and that extrapolations to much higher energies, as will be available e.g. at the LHC, are trustworthy. For silicon, the radiation resistance of the crystals to large proton fluxes has been shown in a recent experiment [10]. In summary, bent crystals are thus a very useful tool to split, deflect or extract very high energy proton beams.

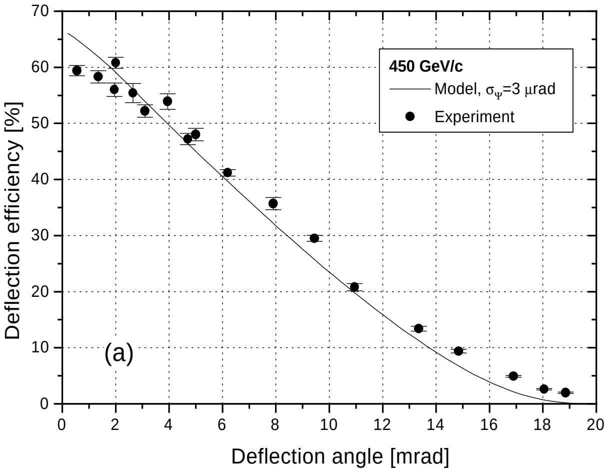

Figure 5: Deflection efficiencies measured for 450 GeV/c protons incident on a bent germanium crystal (dots) compared to calculations following the model of [6]. For details, see text.

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