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Measurements of coherent interactions of 400 GeV protons in silicon bent crystals

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ABSTRACT

Within UA9 Collaboration bent silicon crystals has been irradiated by 400 GeV proton beams at the H8 line of the CERN SPS North Area. Proton–crystal interactions were investigated by analyzing the particle trajectories hitting the crystal. 26 crystals were tested and 10 of them used to extract key crystal properties, such as bending angle, channeling efficiency and so on. A statistical analysis of the results is presented. The results provide experimental data to be used for an exhaustive comparison with simulation routines.

1. Introduction

Crystal channeling [1–3] can be used to develop a collimation system based on bent crystals for high intensity machines like the Large Hadron Collider (LHC). A first step towards the studies for LHC application [4] is the experimental characterization of bent crystals with high-energy proton beams. The crystals are tested at the SPS H8 extraction line to study the interaction with 400 GeV protons. The H8 tests are used to study single pass interactions, and then complemented by the tests with circulating beams at SPS, with protons and ions at the energies of 120 and 270 GeV [5–8].

In addition to the characterization of the crystals, beam tests are also providing crucial input for simulation tools. In particular, single pass data from H8 have been used to evaluate the predictivity of simulation routines [9,10]. Examples of this comparison are presented in [11–13]. The simulation code [14] had been compared with [11] giving excellent results. Other simulation codes are available [15] which are not yet compared with the results presented in this paper.

2. Experimental setup

The tested silicon bent crystals have two different structures. Strip (ST) crystals are bent through the crystalline axis (1 1 0), while the Quasi–Mosaic (QM) crystals are bent through the (1 1 1) crystalline axis. In both cases, anticlastic forces generate the crystal curvature. The difference between ST and QM is in the interplanar potential created by the distance between the planes. The strip crystals have equidistant crystalline planes, so the channels have all the same size, while QM crystals have a ratio 1:3 for subsequent planes.

Ten crystals were selected to perform a complete analysis, and a list with their manufacturing specifications is given in Table 1. The analysis of the crystal STF45 is presented as example; this crystal was tested in 2010. The dimensions of the strip, which correspond to the x, y and z coordinates are $0.3 \times 55 \times 2\ \mathrm{mm}^3$; the bending radius is 13.33 m and the bending angle is about 150 μrad.

A silicon microstrip telescope is used to measure particles trajectories upstream and downstream of the crystal. The telescope and the experimental layout are described in [16]. Five two dimensional silicon detectors with microstrip sensors are arranged to measure at five points the transverse coordinate orthogonal to the beam direction. The microstrips are coupled in pairs orthogonally, for an active area of $3.8 \times 3.8\ \mathrm{cm}^2$. The telescope layout is shown in the Fig. 1. As discussed in [16] the dominant contribution to the angular resolution is due to the multiple scattering of the particles with the sensors, while the position resolution of the impact parameter at the crystal position is influenced by the closest position of the sensor to the goniometer position. The incoming track is reconstructed from an extrapolation of the line reconstructed with the points measured by the first two planes. The outgoing tracks are reconstructed fitting the points measured

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Table 1
Crystals manufacturing specifications, provided by PNPI and Ferrara INFN. In the name of the crystal the first two letters give the information on the kind of crystal. In the QM case, x_{CR} and y_{CR} dimensions represent the active area of the crystal.

Crystal	Bending Radius R [m]	Dimension $x_{CR} \times y_{CR} \times z_{CR}$ [mm^3]
STF38	9.00	1.00 × 55.0 × 1.89
STF45	13.33	0.30 × 55.0 × 2.00
STF47	68.89	2.00 × 55.0 × 3.10
STF48	11.75	1.00 × 55.0 × 2.00
STF49	2.96	0.50 × 55.0 × 0.80
STF50	11.75	1.00 × 55.0 × 2.00
STF51	66.67	2.00 × 55.0 × 3.00
QMP27	15.26	20.0 × 40.0 × 1.77
QMP29	120.00	20.0 × 40.0 × 6.00
QMP32	5.48	20.0 × 40.0 × 0.96

with the last three planes. For a single trajectory, the two tracks upstream and downstream of the crystal, need to have the same impact point at the crystal position. This condition is used as a constraint for the fit. Hence, for each track, three free parameters for each projection on the orthogonal axis are given: the two angles θ_{in} (incoming angle) and θ_{out} (outgoing angle) and the impact point at the crystal position d_0 (impact parameter at $z = 0$). The angular resolution of the telescope is measured in a specific alignment run that is presented in the next section. The resolution is calculated as the angular deflection of the particle ($\Delta\theta = \theta_{in} - \theta_{out}$) when the crystal is not present. The measured resolution is 5.2 μrad for both x and y plane.

2.1. Alignment runs

Alignment runs are performed by measuring the trajectory with the full setup but without the crystal. The key observables are the beam divergence and its profile at the crystal entrance. The main outcome from this analysis is the telescope resolution. This is inferred from the angular distribution $\Delta\theta = \theta_{in} - \theta_{out}$ of the single-track events measured by the telescope without the crystals. In the STF45 case, the beam spot has a double gaussian shape with a transverse sigma of 0.96 mm and 0.72 mm in the horizontal and vertical planes, respectively. The divergence of the beam is found to be 10.67 μrad in x and 7.66 μrad in y. The measured resolution is 5.7 μrad as shown in Fig. 2.

2.2. High statistics runs analysis

The analysis is applied after selecting only the tracks that are impacting on the crystal impact face. Geometrical cuts are performed analyzing the x and y deflection with respect to the x and y impact point of the tracks. The crystal torsion is also corrected: it is estimated on the study of the crystal channeling efficiency as a function of the impact x angle and the vertical impact point.

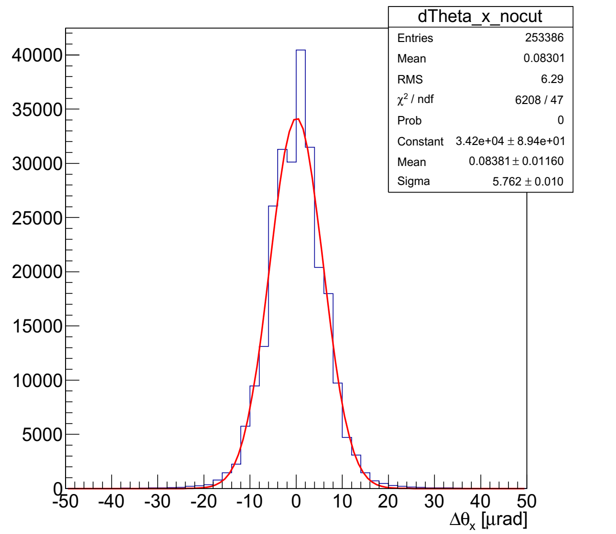

Fig. 2. Run 411: Telescope resolution from the alignment run of the STF45 crystal.

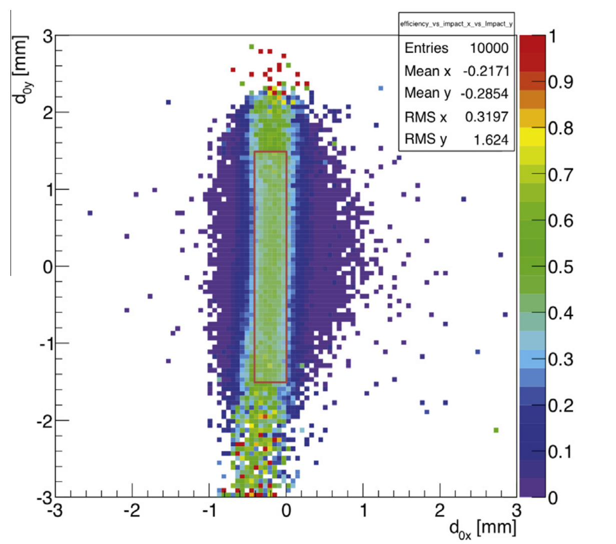

Fig. 3. Channeling efficiency as a function of the impact point on the crystal QMP27 impact face.

3. Analysis details on case study

3.1. Corrections and cuts on data

Three different corrections have to be applied before starting the analysis: geometrical cuts (different for ST and QM crystals), torsion correction, angular cuts. This selection is performed to collect only the tracks of the particles that hit the crystal. Multiple Coulomb scattering is useful to identify these particles. Studying deflection distributions ($\Delta\theta_x$ and $\Delta\theta_y$) as a function of the impact

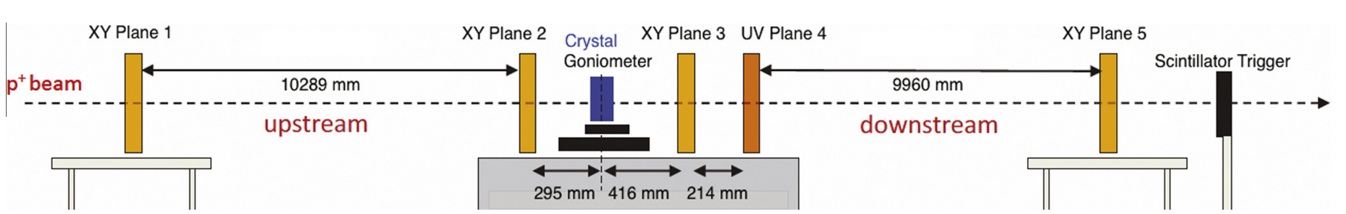

Fig. 1. H8 UA9 Telescope layout. The plane 4 in different color is rotated of 45°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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