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.

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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, anticleastic 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 × 55 × 2 mm²; the bending radius is 13.33 m and the bending angle is about 150 rad.

A silicon microstrip telescope is used to measure particle 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 × 3.8 cm². The telescope layout is shown in 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...
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 $\theta_{\text{in}}$ (incoming angle) and $\theta_{\text{out}}$ (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 $(\Delta \theta = \theta_{\text{in}} - \theta_{\text{out}})$ when the crystal is not present. The measured resolution is 5.2 $\mu$rad 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 $\Delta \theta = \theta_{\text{in}} - \theta_{\text{out}}$ 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 $\mu$rad in $x$ and 7.66 $\mu$rad in $y$. The measured resolution is 5.7 $\mu$rad 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.

### 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, $x_{\text{CR}}$ and $y_{\text{CR}}$ dimensions represent the active area of the crystal.

| Crystal  | Bending Radius R [m] | Dimension $x_{\text{CR}} \times y_{\text{CR}}$ [mm$^2$] |
|----------|----------------------|-----------------------------------------------------|
| STF38    | 9.00                 | $1.00 \times 55.0 \times 1.89$                      |
| STF45    | 13.33                | $0.30 \times 55.0 \times 2.00$                      |
| STF47    | 68.89                | $2.00 \times 55.0 \times 3.10$                      |
| STF48    | 11.75                | $1.00 \times 55.0 \times 2.00$                      |
| STF49    | 2.96                 | $0.50 \times 55.0 \times 0.80$                      |
| STF50    | 11.75                | $1.00 \times 55.0 \times 2.00$                      |
| STF51    | 66.67                | $2.00 \times 55.0 \times 3.00$                      |
| QMP27    | 15.26                | $20.0 \times 40.0 \times 1.77$                      |
| QMP29    | 120.00               | $20.0 \times 40.0 \times 6.00$                      |
| QMP32    | 5.48                 | $20.0 \times 40.0 \times 0.96$                      |

### 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.)

### 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 $(\Delta \theta_x, \Delta \theta_y)$ as a function of the impact...
The steps $\delta z = 0.06 \, \text{mm}$ and $\delta \Theta_y = 1 \, \text{mrad}$ are given by the apparatus resolution. From Fig. 4, Left a measurement of the torsion can be made, as well as a definition of the $x$ impact angle relative to the crystalline planes. The mean $x$ impact angle as a function of the $d_y$ is calculated and the plot is shown in Fig. 4, Right. A linear fit of these data (Fig. 4, Right) gives the torsion value and the offset angle with respect to crystalline planes. In this example $t = 7.36 \, \mu \text{rad/mm}$, with an offset of $-9.92 \, \mu \text{rad}$.}

Correcting the impact angle as in Eq. (3) the impact angle relative the crystalline planes for all the particles that hit the crystal is obtained:

$$\Theta^\text{corr}_x = \Theta^\text{rel}_x - (t \cdot d_y + \Theta^\text{off}_x).$$

After geometrical cuts and the torsion correction, a 2D plot with $x$ deflection as a function of $x$ impact angle is produced as shown in Fig. 5.

After this correction, one can perform the angular cuts to select only the particles impacting on the crystal with an impact angle equal or smaller than the critical channeling angle. This solution is applied in order to define the channeling efficiency as a function of the particles undergoing channeling. The critical angle for 400 GeV protons in a silicon crystal is $\sim 10 \, \mu \text{rad}$, hence the angular cuts are $\pm 5.0 \, \mu \text{rad}$ and $\pm 10.0 \, \mu \text{rad}$. The gaussian fit on the channeling peak gives the bending angle of the crystal.
3.2.1. Channeling efficiency

The channeling efficiency is calculated as the ratio between the number of channeled particle and the total number of particles impinging on the crystal within a given angular range. Typically two different cuts of ±5.0 μrad and of ±10.0 μrad are considered. The particles in channeling are calculated as the ones within ±3σ of the channeling peak, as shown in Fig. 6. In this example a channeling efficiency of 0.69 is measured. An efficiency of 0.53 is calculated for particles when ±10.0 μrad cut is used.

3.2.2. Nuclear dechanneling length

Nuclear dechanneling length is an effect that is predominant in short bent crystal, and is described in [17]. The relative dechanneling length ($l_d$) is also calculated for two angular cuts of ±5.0 μrad and ±10.0 μrad. An exponential fit is performed between ±3σ from the mean value of the amorphous peak and ±5σ from the mean value of the channeling peak, as shown in Fig. 7. The dechanneling length is measured to be 1.41 ± 0.14mm and 1.28 ± 0.09mm for the angular cut of ±5.0 μrad and ±10.0 μrad, respectively.

3.2.3. Population analysis

An analysis on the channeling, dechanneling and transition region (from amorphous to volume reflection) and is performed as a function of the x impact angle. The analysis is performed using...
3.2.4. Volume reflection analysis

The calculation of volume reflection efficiency is performed as shown in Fig. 8. The channeled efficiency has a maximum value for \( \theta_x = 0 \).

Table 3

| Crystal | Channeling \( \eta_{ch}^2 \) [%] | Efficiency \( \eta_{ch} \) [%] | Dechanneling \( L_{ch}^0 \) [mm] | Length \( L_{ch} \) [mm] |
|---------|-----------------|--------------|-----------------|----------|
| STF38   | 48.7 ± 0.5      | 32.9 ± 0.3   | 1.11 ± 0.08     | 0.84 ± 0.04 |
| STF45   | 68.9 ± 0.5      | 54.0 ± 0.3   | 1.41 ± 0.14     | 1.28 ± 0.09 |
| STF47   | 52.8 ± 0.2      | 45.1 ± 0.2   | 1.71 ± 0.14     | 1.47 ± 0.08 |
| STF48   | 52.9 ± 0.1      | 41.0 ± 0.1   | 1.71 ± 0.14     | 1.47 ± 0.08 |
| STF49   | 46.0 ± 0.4      | 34.6 ± 0.3   | 0.19 ± 0.01     | 0.18 ± 0.01 |
| STF50   | 54.7 ± 0.1      | 45.2 ± 0.1   | 1.52 ± 0.07     | 1.29 ± 0.08 |
| STF51   | 48.7 ± 0.1      | 44.1 ± 0.1   | 1.52 ± 0.07     | 1.29 ± 0.08 |
| QMP27   | 58.6 ± 0.2      | 50.4 ± 0.2   | 1.48 ± 0.12     | 1.35 ± 0.08 |
| QMP29   | 64.5 ± 0.1      | 56.2 ± 0.1   | 1.48 ± 0.12     | 1.35 ± 0.08 |
| QMP32   | 50.7 ± 0.8      | 40.9 ± 0.5   | 0.46 ± 0.05     | 0.37 ± 0.04 |

5. Conclusions

The crystal characterization with extracted proton beams is useful to check the crystal and to compare the results with crystal simulation routines. For the first time all the data collected from 2010 to 2012 have been processed consistently; this allowed to identify 10 crystals of interest for which different analysis routines were developed.

The performed analysis has produced the following results: channeling efficiency for single proton pass (with coherent angular cut), nuclear dechanneling length, population of particles in the different effect regions, mean gaussian value in the channeling and transition region.

The main result is the statically complete analysis on the different effects of the interaction of protons with bent silicon crystals. This represents a starting point for the comparison between the different crystal simulation routines. Other measurements, such as the dechanneling population and the volume capture length, are new results and would be the subject of a future publication. The validation of the simulation routines is ongoing. It represents a crucial step for a predictive analysis of crystal collimation in high intensity operation of hadron colliders, such as the HL-LHC.

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