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A crystal routine for collimation studies in circular proton accelerators

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ABSTRACT

A routine has been developed to simulate interactions of protons with bent crystals in a version of SixTrack for collimation studies. This routine is optimized to produce high-statistics tracking simulations for a highly efficient collimation system, like the one of the CERN Large Hadron Collider (LHC). The routine has recently been reviewed and improved through a comparison with experimental data, benchmarked against other codes and updated by adding better models of low-probability interactions. In this paper, data taken with 400 GeV/c proton beams at the CERN-SPS North Area are used to verify the prediction of the routine, including the results of a more recent analysis.

1. Introduction

In large accelerating machines such as the Large Hadron Collider (LHC), the prediction of how particle losses are distributed around the whole ring is crucial. This is performed at CERN using a SixTrack version for collimation studies [1–5]. A routine to simulate interactions of protons with bent crystals was also added for crystal collimation studies [6]. This routine is based on a Monte-Carlo approach, and the proton interactions with crystals are randomly sampled using probability distributions, as opposed to other tools [7] that integrate the proton motion in the crystalline potential. The routine is therefore optimized for high statistics runs, without jeopardizing its performance because the known interactions with bent crystals are modeled accurately in the literature, and the few free parameters can be tuned on experimental data.

The crystal routine is composed of two main blocks with interplay between them: one contains models to describe coherent interactions in a bent crystal, and a scattering routine that describes interactions with amorphous materials. The scattering routine, recently updated to take into account LHC measurements [8], is called each time a proton is traversing crystal behaving as an amorphous scatterer. The same scattering routine is also applied to particles trapped between crystalline planes, but with cross sections rescaled by the average nuclear density seen during their path [9]. Thus, the possibility of such protons also to experience nuclear interactions [14] is now taken into account. The coherent processes in bent crystals modeled are channeling, dechanneling, volume reflection, volume capture and dechanneling after volume capture. The models used are extensively discussed in [9], and based on work reported in [10–14]. Possible crystal imperfections were also introduced, such as the presence of an amorphous layer and the miscut angle [6]. The benchmarking with respect to experimental data of such a crystal routine is discussed.

2. Single-pass measurements

The experimental measurements have been performed with 400 GeV/c proton beams at the CERN-SPS North Area, in the framework of the UA9 collaboration. A total of 26 crystals was tested in the runs between 2009 and 2012. After detailed analysis of all the data collected during those years, a subset of 10 crystals was chosen for comparative studies with simulation routines [15,16]. Among those ten crystals, a specific reference case was used to benchmark all the existing simulation codes for bent crystals developed in the framework of the UA9 collaboration, during "The 6th International Conference – Channeling 2014" [17]. The benchmarking described below refers to such a crystal, which is a silicon strip crystal 2 mm long and with 13.9 m bending radius. Besides the code discussed in this paper (CRYCOLL), other crystal routines involved in these comparisons are based on integration of an equation of motion in crystalline potential (CRYD) [7], and implementation of a crystal geometry in FLUKA [18] and GEANT4 [19]. An overview of results obtained by the different codes can

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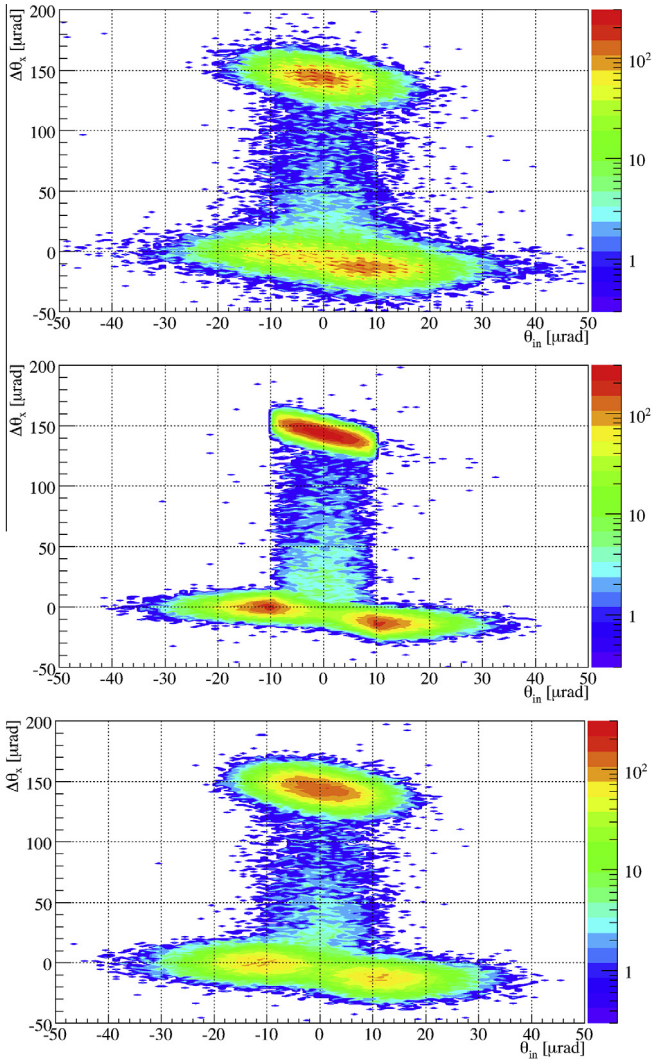

Fig. 1. Angular deflection given to each particle as a function of the incident angle with respect to crystalline planes, during a high statistics run. (top) Experimental data, (middle, bottom) simulated data without, and including, the experimental resolution, respectively.

be found in [20]. Other simulation codes are available [21] which are not included in the present comparisons.

An example of a high statistics run in optimal channeling orientation for this crystal is given in the top graph of Fig. 1, while the middle and bottom graphs of Fig. 1 refer to simulation results. From these plots the effect of the experimental resolution on the agreement between experimental and simulated data is clearly visible. The experimental resolution is taken into account by adding random gaussian noise with $\sigma \sim 5$ μrad to the simulated deflections, which corresponds to the measured resolution of the telescope used [22]. Simulation data are generated in a format that mimics the measured data format in order to apply the same analysis tools developed and used in [15,16]. This ensures a consistent treatment of simulation results and measurement data.

3. Qualitative comparison

In this section a qualitative overview of measured and simulated data, for the high statistics run in Fig. 1, is given. A ±10 μrad cut on the proton incident angle is applied, and the distributions of deflections obtained are superimposed in Fig. 2. It is possible to evaluate the agreement between:

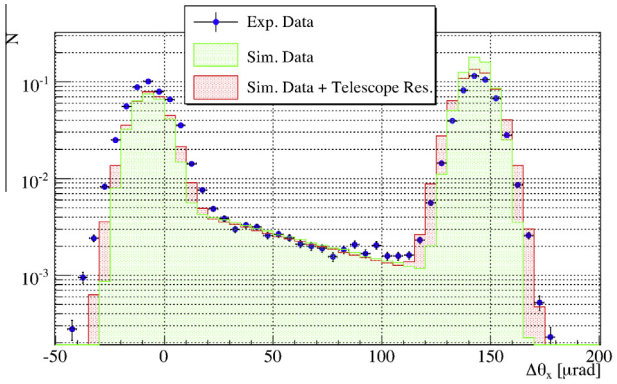

Fig. 2. Distribution of deflections given to protons with an incoming angle within ±10 μrad. Experimental data are reported in blue dots with their statistical error, simulated data are shown in green, and their convolution with the telescope resolution is given in red. The binning of 5 μrad is chosen according to the experimental resolution, and histograms are normalized to the total number of entries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

- Distribution of channeled particles, both on the mean and width when the telescope resolution is taken into account.
- Distribution of particles in the transition regions, i.e. deflections close to zero, both on the mean and width when the experimental resolution is taken into account.
- Distribution of dechanneled particles, where experimental and simulated data match very well, with and without the telescope resolution.

The relative height of these distributions shows that the assumptions used to model the coherent processes in bent crystals, are qualitatively adequate. In the selected angular range of the incoming protons the processes of channeling, dechanneling, volume reflection, and amorphous orientation occur simultaneously. A detailed analysis of these data for each of the items above follows.

4. Channeling efficiency

One of the key observables to be reproduced by crystal simulation routines is the channeling efficiency for a given bending radius. The channeling efficiency is a quantity used to define the fraction of particles undergoing channeling, normalized to the total number of particles impinging on the crystal within a given angular range. This cut on the angle of incident protons is needed to avoid any feature due to particles that cannot be channeled in any case (i.e. angles above the critical channeling value), as well

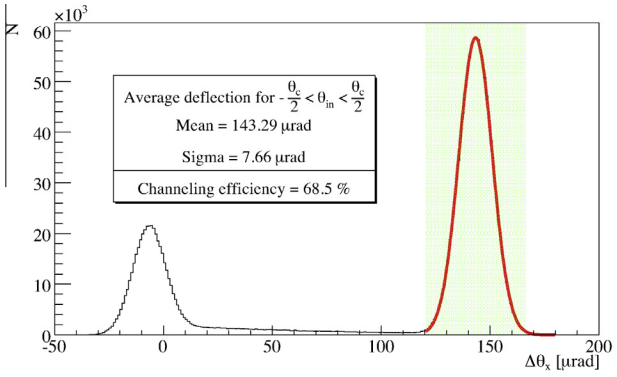

Fig. 3. Simulated distributions of angular deflections given to protons with an incoming angle within ±5 μrad. The angular range in which protons are considered as channeled is highlighted in green. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)