ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOTK060

SIMULATIONS OF MISCUT EFFECTS ON THE EFFICIENCY OF A CRYSTAL COLLIMATION SYSTEM*

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Abstract

The concept of crystal collimation relies on the use of bent crystals which can coherently deflect high-energy halo particles at angles orders of magnitude larger than what is obtained from scattering with conventional materials. Crystal collimation is studied to further improve the collimation efficiency at the High Luminosity Large Hadron Collider (HL-LHC). In order to reproduce the main experimental results of crystal collimation tests and to predict the performance of such a system, a simulation routine capable of modeling interactions of beam particles with crystal collimators was developed and recently integrated into the latest release of the single-particle tracking code SixTrack. A new treatment of the miscut angle, i.e. the angle between crystalline planes and crystal edges, was implemented to study the effects of this manufacturing imperfection on the efficiency of a crystal collimation system. In this paper, the updated miscut angle model is described and simulation results on the cleaning efficiency are presented, using configurations tested during Run 2 of the LHC as a case study.

INTRODUCTION

Crystal collimation is an advanced collimation technique that exploits the peculiar properties of materials with highly ordered atomic structure. Depending on their impact angle, charged particles can get trapped in the potential well generated by neighboring crystalline planes, oscillating in relatively empty space and traversing the crystal for its full length with reduced probability of inelastic interactions. This process, called *crystal channeling*, allows a bent crystal to steer charged particles with necessary impact conditions [1, 2].

This concept has been studied at CERN as a way to improve the collimation performance of the LHC by steering beam halo particles onto a single absorber [3–5]. Since 2016, a complete test stand composed of four single-sided crystal collimators (two per each circulating beam, one on the horizontal plane and one on the vertical plane) has been installed in the LHC betatron collimation system [6–8]. A standard secondary collimator with jaws made of carbon fiber composite (CFC) can be used to safely intercept and dispose of channeled halo particles for heavy ion beams with a total stored energy up to 20 MJ, while only low-intensity proton beams are sustainable with the current setup [9]. An extensive test campaign conducted during Run 2 of the LHC (2015-2018) demonstrated the improved cleaning provided by crystal collimation of 6.37 Z TeV Pb ion beams [4, 5], leading to the integration of this technology in the HL-LHC baseline. Crystal collimation is planned to be used in operation with Pb ion beams already in Run 3 (2022-2025) [10, 11].

To reproduce key experimental results and predict the performance of a crystal collimation system, a dedicated simulation routine was developed and recently integrated in the latest version of SixTrack [12–15], a single-particle tracking code widely used at CERN for simulating beam dynamics in circular accelerators. This code performs a symplectic and fully chromatic tracking of protons and ions [16–18] through a magnetic lattice which includes all machine elements affecting the beam dynamics (such as magnets, RF cavities, etc.). A specific version of SixTrack, which can treat interactions of beam particles with the constituting material of machine elements [19, 20], is used for collimation studies to predict the distribution of losses in the accelerator ring. A dedicated routine models coherent interactions between charged particles and bent crystal collimators via a Monte-Carlo simulation [21–24], which was extensively benchmarked against experimental data [3, 4, 24–27]. Only simulations with proton beams are supported by this routine.

DEFINITION OF MISCUT ANGLE AND UPDATED GEOMETRICAL MODEL

Crystal collimation simulations for LHC consider perfectly cut crystals, with planes aligned to the lateral surface facing the beam. In reality however, a non-zero angle, called *miscut angle*, is unavoidable and causes a series of edge effects that can hinder the performance of a crystal collimation system. In particular, channeled particles travel inside the crystal for different lengths depending on their impact parameter, i.e. the distance between the impact point and the lateral side (x_{cry} in Fig. 1, while s_{cry} is the longitudinal direction tangent to the curvature of the crystal), and acquire different deflections. This is particularly relevant for the

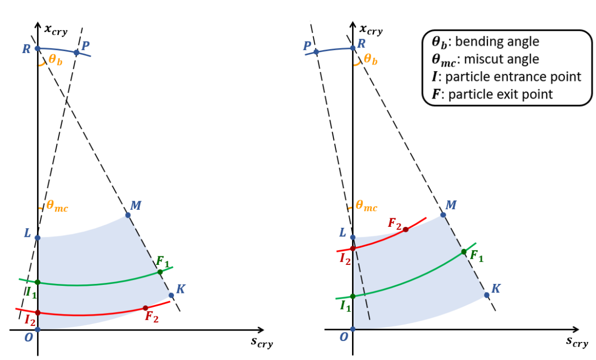

Figure 1: Geometrical model for negative (left) and positive (right) miscut in the reference frame of the bent crystal.

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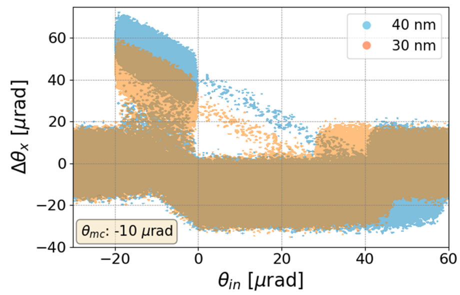

Figure 2: Simulated deflection resulting from a single passage of 450 GeV protons through a silicon crystal (4 mm length, 50 μrad bending) with impact parameters of 30 and 40 nm, as a function of the impact angle.

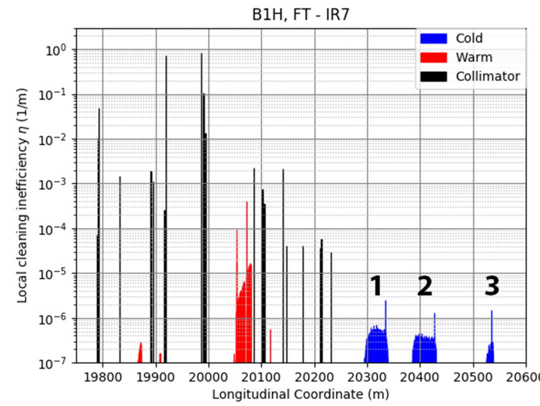

Figure 3: Simulated loss pattern in IR7 with protons for crystal collimation in operational configuration with no miscut on the horizontal plane of Beam 1 at 6.5 TeV.

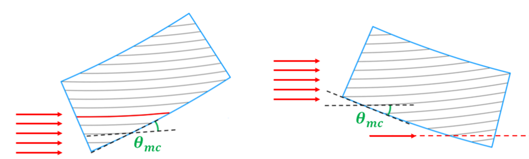

Figure 4: Impact conditions at a crystal collimator with negative (left) and positive (right) miscut angle.

LHC, as impact parameters between tens of nm and a few μm are expected on collimators [28]. For this reason, these effects need to be properly evaluated in simulation. With the integration of the crystal routine in the latest version of SixTrack [29], the treatment of the miscut angle was revised.

Rather than using a straight crystal approximation as was originally done [21], the updated miscut angle model is based on a geometrical description of the bent crystal. The model is schematically depicted in Fig. 1, where the crystal is represented as a blue box and the relevant geometrical points are shown. Using the crystal dimensions and bending radius as input parameters, the exit point of a channeled particle is calculated as the intersection of the tilted crystalline plane passing through the impact point with either the exit face of the crystal or one of the lateral faces, depending on the impact parameter. The effective path length inside the crystal and total deflection are computed and used in the calculations related to the interactions of the particle with the crystal.

The consistency of the new treatment was verified by simulating the single passage of a 450 GeV proton beam through a silicon crystal with a bending angle of 50 μrad and a miscut angle θ_{mc} of -10 μrad. As shown in Fig. 2, the miscut angle shifts the angular range for which channeling is possible, while the impact parameter, which is fixed for all particles, changes the deflection. Regions corresponding to other types of coherent interactions also shift as expected, maintaining the pattern observed in single-pass measurements and confirming the consistency of the treatment.

SIMULATED PERFORMANCE IN PRESENCE OF A MISCUT ANGLE

The effects of a miscut angle on the performance of a crystal collimation system at the LHC are evaluated by loss pattern simulations, taking into account the complex multiturn dynamics of a circular accelerator and using the collimator settings explored in 2018 tests for potential use in operation. In this configuration, the standard collimation system of the LHC is kept at nominal settings to fulfill machine protection requirements, while crystal collimators are inserted at a slightly tighter aperture than the primary stage and drive the cleaning performance by intercepting all diffusive primary beam losses [11]. The cleaning efficiency provided by this configuration was tested with Pb ion beams of up to 4 MJ stored energy, showing an improvement of up to a factor 8 with respect to the standard system. To study miscut effects, the loss pattern on the horizontal plane of Beam 1 was simulated for proton beams, considering a silicon crystal with a bending angle of 50 μrad. Particular focus is put on the limiting location of the machine, i.e. the IR7 Dispersion Suppressor (IR7-DS) located downstream of the betatron collimation insertion, since off-momentum products of the interaction of halo particles with upstream collimators are lost in this high-dispersion region. The simulated loss pattern for a perfectly cut crystal is shown in Fig. 3, with three clusters (indicated by numbers) in the region where superconducting magnets are located. These losses are typically a factor 10 lower than for the standard system [22, 30].

When considering a non-zero miscut angle, the crystal is tilted in the opposite direction to restore the alignment between crystalline planes and impacting beam at the entrance face, mimicking the operational procedure that minimizes local losses at the crystal to find the optimal channeling orientation. Negative and positive values of the miscut angle produce distinct effects which are discussed separately.

Negative Miscut Angle

In presence of a negative miscut angle, particles that hit the crystal collimator with impact parameters smaller than a few hundreds of nm can exit from the lateral side facing the beam rather than from the exit face, as shown in the left frame of Fig. 4. The signature is similar to that of the *dechanneling*

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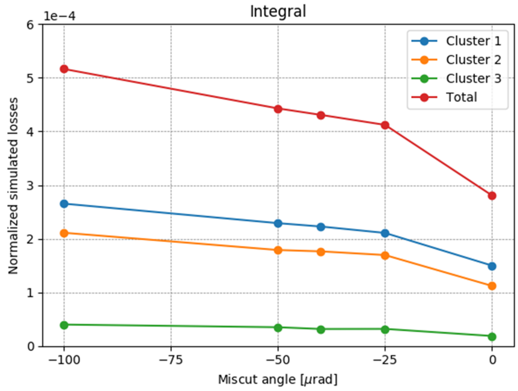

Figure 5: Integral of IR7-DS loss clusters in simulations for negative miscut angle values.

process, during which particles initially trapped between crystalline planes lose channeling conditions while traveling through the crystal, acquiring a reduced deflection.

The total losses per unit length for each cluster and the sum over the whole IR7-DS are used as an indicator of the cleaning performance of the collimation system, shown in Fig. 5 as a function of the miscut angle. An increase by a factor 1.5 is observed for θ_{mc} = -25 μrad, and by even larger factors as the absolute value of the miscut angle increases. This behavior was investigated in detail by reconstructing the history of simulated particles that are lost in the IR7-DS and their interactions with upstream collimators. Particles with impact parameters of a few tens of nm, resulting in a deflection of only a few μrad, manage to escape from the IR7 collimation insertion at the first passage without interacting with the secondary collimator used to intercept the channeled beam. These nearly on-momentum particles travel through the ring for an entire turn before impacting on a different secondary collimator (with the jaw located on the other side of the beam pipe with respect to the crystal) and getting subsequently lost in the IR7-DS. Simulations for θ_{mc} = -100 μrad show that the total losses decrease by about 23% when retracting the jaw of this collimator, as the escaping particles interact again with the crystal after a few turns. Such settings, not considered so far, could be explored at the LHC as a potential mitigation measure to improve the efficiency of the system in presence of a large miscut angle.

It is important to note that simulated particles have impact parameters of up to 10 μm due to the intrinsic halo generation in SixTrack, which needs to be further refined for these studies. In a real machine, with generally smaller impact parameters, these effects could become more significant.

Positive Miscut Angle

In presence of a positive miscut angle, the compensation tilt of the crystal brings the lateral face further towards the beam than the entrance face. Particles are then more likely to enter the crystal from the side, where the crystalline planes are not aligned to the direction of incoming particles, as shown in the right frame of Fig. 4. Thus, the probability of experiencing amorphous interactions is increased.

5000 turns in the machine were simulated for each value of the miscut angle, a number which was deemed enough to make sure that all particles entering the collimation system are absorbed. However, the analysis of the number of particles surviving until the end of each simulation showed that this setup was not sufficient to fulfill this requirement. The average deflection of particles that experience amorphous interactions with the crystal is zero, in analogy with multiple Coulomb scattering in a material without an ordered atomic structure, and only a small fraction of the crystal length behaves like an amorphous material. Thus, these particles keep traveling in the ring and interact with the crystal multiple times before finally acquiring a deflection large enough to be lost. As the probability of amorphous interactions increases for positive miscut angles, the cleaning process becomes slower and a much higher number of turns is required to lose the same amount of particles, making simulations quite heavy in terms of computational power. The possibility to exploit volunteer computing projects using internet-connected computers (such as LHC@HOME, based on BOINC [31]) will be considered to address this issue.

CONCLUSIONS AND OUTLOOK

An updated geometrical model of the miscut angle was implemented in the SixTrack simulation routine for the interaction of protons with crystal collimators. This model was used to evaluate potentially detrimental effects on the efficiency of a crystal collimation system at the LHC. The settings explored for use in operation with Pb ions during Run 3 of the LHC were chosen as a case study for simulations. For negative values of the miscut angle, an increase of the total losses in the IR7-DS is observed with respect to a perfectly cut crystal, to be considered on top of the factor ~10 reduction provided in simulations by crystal collimation with respect to standard collimation for proton beams. Based on the results showed in this paper, an absolute value of 10 μrad can be defined as the tolerance for the miscut angle for collimation applications, but simulations of Pb ion beams are needed for a definitive conclusion.

Further studies are required to verify these findings and compare them with experimental results. During Run 3, different collimator settings featuring the retraction of the secondary collimator that intercepts particles deflected by small angles in case of negative miscut can be explored to assess if the good performance of the system demonstrated in 2018 could be further improved. The case of positive miscut, on the other hand, needs to be studied further in simulations, possibly exploiting volunteer computing projects to achieve the high computational power needed for this setup.

ACKNOWLEDGEMENTS

Research on crystal collimation for the LHC is supported by the HL-LHC Project. The authors would like to thank W. Scandale for his valuable feedback.

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