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CRYSTAL COLLIMATION FOR THE HL-LHC UPGRADE USING MERLIN++ ACCELERATOR PHYSICS LIBRARY*

Raiza Babu†, Roger Barlow, Thomas Edgecock
University of Huddersfield, Huddersfield, UK

Abstract

This paper details the implementation and bench marking of crystal collimation within MERLIN++ accelerator physics library and demonstrates its application in simulating crystal collimation process for the High Luminosity (HL) upgrade of Large Hadron Collider (LHC) at CERN. Crystal collimation is one of the key technologies suggested to enhance the current collimation system according to the requirements of HL-LHC upgrade due to its increased beam energy and luminosity. This paper outlines the proposed methodology for this study which includes implementing the demonstrated physics of particle crystal interaction in MERLIN++, bench marking it with the existing experimental data for simulating the HL-LHC operational scenarios with the crystals as primary collimators. MERLIN++ has already been efficiently used for multiple LHC collimation studies which highlights its importance, making it an essential simulation tool for comparative analysis with other simulation tools, as relying on a single tool for concluding the HL-LHC collimation system is often insufficient. As collimation systems are fundamental for machine protection, accurately predicting the crystal collimation performance is of utmost importance to know how they will perform in HL-LHC to guarantee that the HL-LHC meets its intended objectives with crystal collimators.

INTRODUCTION

The collimation system is crucial in the operation of high energy particle accelerator as it is responsible for absorbing the halo particles and thus ensuring machine protection and safe operation. Although the efficiency of current collimation system surpasses the requirements for safe operation of the LHC, the future high luminosity upgrade of the large hadron collider foreseeing a stored beam energy of 700 MJ and an increase in luminosity by a factor of 10 from the current system inevitably requires improved cleaning performance along with a significant reduction of the collimator impedance.

The new crystal collimators were proposed for HL-LHC as they offer better cleaning and reduced impedance in principle [1, 2]. In the proposed crystal collimation system a bent crystal will be used to deflect the beam halos in high energy particle beams towards a single absorber(which is a secondary collimator) thus reducing the number of stages and the impedance offered by the present multistage collimation system.The UA9 experiment set up in 2008 investigated the advantages of using bent crystal for collimation in high energy particle accelerators [3].

However, a crystal collimator also has its demerits, which include the requirement of a single passive absorber capable of extracting the halo particle power deposited in a small spot from crystal channelling, and orienting the crystal optimally for channelling as it requires angular accuracy of 2.5 μrad.

MODELLING IN MERLIN

The accurate simulation of complex beam dynamics in LHC is the corner stone for future research and other scientific developments of the LHC systems.The existing sixtrack [4] simulation tool while effective uses an outdated fortran code and struggles with the computational speed. In response to these challenges and to provide an alternative simulation technique Merlin++ was developed. This is a multi functional C++ library which integrates different physics processes required for common accelerator design studies including collimation systems. More about Merlin++ can be referenced from [5–7].

This paper outlines the addition of new crystal simulation routines into Merlin++ . Different coherent processes in crystal detailed in the next section are introduced into Merlin.The process flow diagram for crystal processes inside Merlin is shown in Fig. 1.

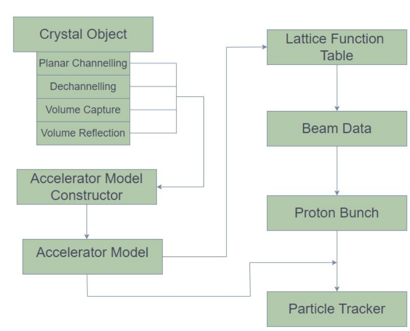

Figure 1: Flow chart representation of crystal processes added in Merlin.

IMPLEMENTED CRYSTAL PROCESSES

Charged Particles can experience different coherent interactions when hitting any block of material. However when hitting a uniformly aligned crystalline lattice particle beams undergo different processes like planar channelling, dechanneling, volume capture and volume reflection. Given the high deflection achieved by planar channelling it can be

* Work supported by STFC UK
† raiza.babu@hud.ac.uk

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used for beam collimation. A crystal few millimeter long is sufficient to steer the beam halos by tens of μrad which is equivalent to a deflection achieved by hundreds of Tesla magnetic field [8]. These four different processes are modelled in Merlin as an initiative to implement crystal simulation routine.

Planar Channeling

Explanation for planar channelling begins with the potentials developed by the crystalline planes.When the potential U_x developed by each crystalline plane are superimposed they form a potential well. The particles with transverse momentum less than the height of potential well, get trapped in between the crystalline planes and they will be channelled through the length of the crystal if they are inside the crystalline potential well. The maximum impact angle for a particle to undergo channelling is given by $\theta_{critical}$ [8].

$$\theta_{critical} = \sqrt{\frac{2U_{max}}{pv}} \tag{1}$$

where U_{max} is the maximum height of potential well and pv is the momentum. The LHC will use a bent crystal for collimation. Crystals are bent in such a way that the curvature of radius R is much larger than the thickness w, to maintain the internal structure of crystal intact. So, the channelled particle will receive a kick equivalent to the bending angle of the crystal used.

Dechanneling

Dechanneling happens when a channeled particle interacts with crystal lattice and loses its channelling property. In bent crystals, dechanneled particles escape the potential well before travelling the full length of the crystal thus resulting in a deflection lower than the bending angle. If the channelled particle oscillations inside the potential well are wide enough to bring the particle near to the edge of the potential barrier, nuclear interactions can happen and as a result the transverse momentum of the particle will get altered making it possible to escape the channelling condition. Using diffusion theory the electronic dechanneling length [8] can be calculated as

$$L_D^e = \frac{256}{9\pi^2} \frac{pv}{ln(2m e_c^2 \gamma / I) - 1} \frac{a_{TF}}{Z_i r_e m_e c^2} \tag{2}$$

where γ is the Lorentz factor,z_i is the electric charge of channelled particle I is the ionization potential, a_{TF} is the Thomas Fermi screening length while m_e and r_e are the rest mass and classical radius of electron respectively. The dechanneling length of a bent crystal can then be defined as a function of electronic dechanneling length, the critical radius and the bending radius of the crystal.

Volume Capture

If the impact of the particle in the crystal is larger than that of the critical angle mentioned in Eq. 1, the transverse momentum of the particle will be higher than the potential and channelling will not occur. This non channelled particles interacts with the crystalline lattice and as a result of this elastic interaction, particles fall back into the channelling conditions and receives a particle deflection similar to the channelling deflection. The probability for this can be modelled by Eq. 3 which is a function particle energy and bending radius R and critical radius R_c of crystal [8].

$$P_{VC} = k_{VC} \left(\frac{R}{R_c}\right) E^{0.2} \tag{3}$$

$k_{VC} = 0.0007$ a tuned experimental data constant.

Volume Reflection

If a particle enters the crystal with an impact angle greater than the critical angle but less than the bending angle of the crystal, channelling by first layer will not take place as the traverse energy will be too large. As moving towards the centre in a bent crystal, the atomic density will increase which increases the potential barrier generated by the inner crystalline planes. When the non channelled particle traversing through the crystal encounters a high potential barrier compared to its transverse momentum the motion of the particle will be reversed by the elastic interaction with the barrier and particles will escape the crystal with a deviation [8].

$$\theta_{VR} = k_{VR} \sqrt{\frac{2U_{rt}}{pv}} \tag{4}$$

where U_{rt} is the potential at which crystalline plane is tangent to the particle trajectory and $k_{VR} = 1.6$ is constant tuned to experimental data. More about crystal collimation process can be referenced from [9, 10].

VALIDATION

To validate the different crystal processes implemented in Merlin++ the simulation results are bench-marked against the experimental data of single pass crystal experiment H8RD22 [11] by creating a similar accelerator model and proton bunch in Merlin++.

Simulation Results in Merlin++

The result of H8RD22 experiment is shown in Fig. 2. We show separately the deflections for particles undergoing different processes. The relative probabilities for each process subject to crystal tilt and the particle angle have not yet been evaluated and applied.

Figure 3 shows the planar channeling, the particles receive a full channelling kick of 160 μrad in first place which is equivalent to the bending angle of the crystal used. As the crystal is rotated the deflection shifts but with the same amount.

Dechanneled particles exiting the channelling mode before traversing the full length of the crystal is shown in Fig. 4. These particles can be seen with deflections up to, but less than, the deflection for channeling in Fig. 3.

Volume reflection occurs if the particle impact angle is more than the critical angle of the crystal. The beam will

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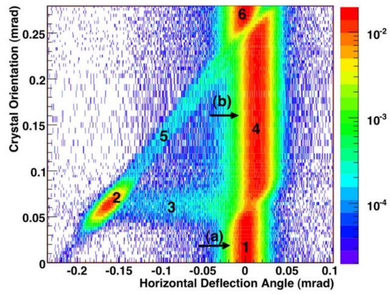

Figure 2: Beam intensity recorded by Si microstrip detectors as a function of the horizontal deflection angle (x axis) and the crystal orientation (y axis). Six regions are distinguished (1,6)nonchanneling mode, (2)channelling(channelling peak where particles received the full channelling kick, (3)dechanneling, (4)volume reflection and (5)volume capture [11].

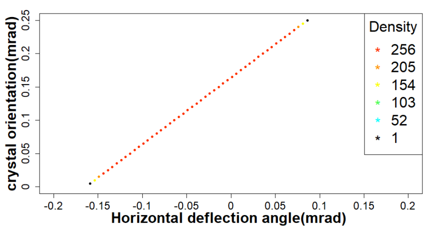

Figure 3: Crystal channelling in Merlin++.

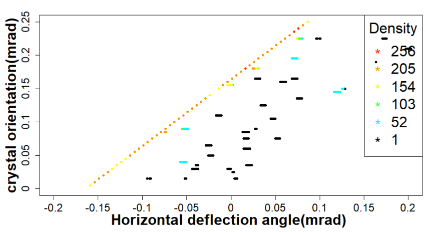

Figure 4: Crystal dechanneling in Merlin++.

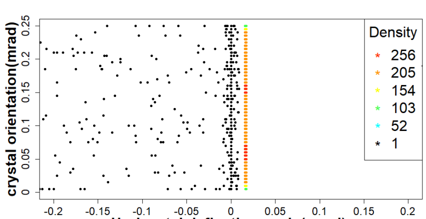

Figure 5: Volume reflection in Merlin++.

not be aligned for channelling but receives a positive kick equivalent to $1.5{*}\theta_{critical}$ shown in Fig 5.

The volume capture process allows non channelled particle to fall under the channelling conditions and these particles receive a smaller kick in the direction of channelling (Fig.6). The kick depends on the beam orientation with

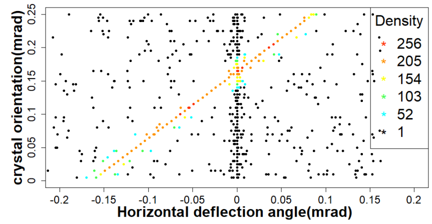

Figure 6: Volume capture in Merlin++.

crystal, if there is a misalignment of the beam at an angle $0<\Delta\theta<\theta_b$ according to the crystalline planes, the deflection associated will be the volume capture region. Particles under channeling condition in volume capture can undergo dechanneling but with a very small deflection. Fig. 7 represents the dechanneling of volume captured beam.

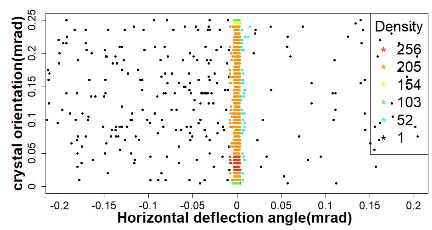

Figure 7: Dechanneled beam in volume capture process.

CONCLUSION

We have implemented the separate processes required for crystal collimation in the Merlin++ library. Moving forward, these will enable the application of Merlin++ for simulating crystal collimation in the HL-LHC. We are optimistic that further development in this simulation routine will yield substantial results aligning with our goals of predicting crystal collimator applications in HL-LHC.

REFERENCES

[1] S. Redaelli, "Beam cleaning and collimation systems", CERN, Geneva, Switzerland, Rep. CERN-2016-002, Jan. 2016.

[2] M.D'Andrea *et al.*, "Operational performance of crystal collimation with 6.37 Z Tev pb ion beams at the LHC", *Phys. Rev. Accel. Beams*, vol. 27, p. 011002, Jan. 2024. doi:10.1103/PhysRevAccelBeams.27.011002

[3] UA9, https://ua9.web.cern.ch/.

[4] SixTrack-6D Tracking Code, https://sixtrack.web.cern.ch/SixTrack/.

[5] The Merlin++ accelerator simulation program library, http://merlinpp.org/.

[6] H. Rafique, "MERLIN for High Luminosity Large Hadron Collider Colliamtion", Ph.D thesis, S.C.E Dept., University of Huddersfield, Huddersfield, UK, 2017.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPS41

[7] R. Appleby *et al.*, “Merlin++, a flexible and feature-rich accelerator physics and particle tracking library”, *Comput. Phys. Commun.*, vol. 271, p. 108204, Oct. 2021. doi:10.1016/j.cpc.2021.108204

[8] M. D’Andrea, “Application of crystal collimation to the CERN Large hadron Collider (LHC) and its high luminosity upgrade project (HLLHC)”, Dipartimento Di Fisica E Astronomia, Universita Delgi Study Di Padova, Italy, 2021.

[9] D. Mirarchi, “Crystal collimation for LHC”, Ph.D. thesis, High Energy Phys. Dept., Imperial College, London, UK, 2015.

[10] D. Mirarchi, S. Redaelli, and W. Scandale, “Crystal implementation in SixTrack for proton beams”, CERN, Geneva, pp. 91-108, CERN Yellow Reports: Conference Proceedings, Dec. 2018. doi:10.23732/CYRCP-2018-002.91

[11] V. Previtali, “Performance evaluation of a crystal-enhanced collimation system for LHC”, Ph.D. thesis, la Section de Physique de la Faculte des Sciences de Base , Ecole Polytechnique federale de Lausanne, Switzerland, 2010.