

Simulation of the channeling effect and its application for the LHC collimation system

Alexei Sytov*

Supervisor: Stefano Redaelli, CERN, Geneva, Switzerland

Supervisor in Belarus: Victor Tikhomirov,

Research Institute for Nuclear Problems,

Belarusian State University, Minsk, Belarus

Abstract

The paper is devoted to simulation studies of single passage of protons at the LHC energy through the crystal. The two different codes are compared CRYAPR and CRYSTAL-channeling. The differences of them for the simulation of channeling, dechanneling, volume reflection, volume capture, coulomb and nuclear scattering, miscut angle, ionization and diffractive energy losses are analyzed as far as the possible influence to the LHC collimation efficiency.

1 Introduction

A question of beam collimation is essential for the LHC because of problem of superconducting magnets quench. The nominal luminosity of High Luminosity LHC will increase in 5 times, so the superconducting magnets will obtain more radiation damage. The crystal-based collimation system can considerably improve the halo cleaning. That's why it is important to have state-of-the-art simulation tools to model the particle dynamics correctly.

My mission at CERN was to compare crystal routine CRYAPR [1-3] implemented in SixTrack [3-5] and CRYSTAL-channeling simulation code designed by A.Sytov, V.Tikhomirov and used in [6]. The main difference between these two routines is that CRYSTAL-channeling provides tracking of proton trajectories in crystal by solving an equation of motions with interplanar field potential. CRYAPR makes a statistical treatment of various interactions between protons and crystal, optimized for multi-turn tracking in accelerator.

2 Input for single passage simulation

During the simulations only single passage of $7TeV$ protons through the crystal was studied. Only perfect crystal was considered without amorphous layer, miscut, crystal torsion and lattice imperfections. Input beam distribution was calculated with SixTrack for $7TeV$ energy. This distribution is an assumption for the LHC.

I simulated with both routines the following cases: crystal length and bending angle were correspondingly $l_{cr} = 3, 4, 5mm$, $\theta_b = 40, 50, 60\mu rad$. For $l_{cr} = 3mm, \theta_b = 40\mu rad$ and $l_{cr} = 4mm, \theta_b = 50\mu rad$ the crystal orientation values was also $\theta_{tilt} = -100, -25, -35, 100\mu rad$. In this paper only simulation for $l_{cr} = 3mm, \theta_b = 40\mu rad$ is discussed.

*E-mail: alex_sytov@mail.ru

3 CRYSTAL-channeling and CRYAPR simulations comparison and analysis

The possible effects in crystal are shown in Fig. 1a. These effects are channeling, volume reflection from bent crystal plane, different types of scattering.

The LHC case is untypical for channeling orientation. Very high energy means very few number of channeling oscillations ~ 4 per mm. Therefore, if the angular divergence is rather low as for the present case, the correlation between different trajectories will be very high. The second peculiarity is rather large impact parameter which makes the angular distribution unsymmetrical. The third peculiarity is rather high bending requiring for collimation which means small bending radius and very unsymmetrical potential well.

The horizontal kick distribution at channeling orientation is shown in Fig. 1b-d. The difference in channeling as far as in volume reflection profiles can be explained by the reason that in CRYAPR they are estimated by Gaussian distribution. In CRYSTAL-channeling they strongly depend on both shape of potential and initial angular distribution. It is important that the correct angle value of volume reflection peak must exceed channeling critical angle [2],[7] which is about $2.1 \mu\text{rad}$ for 7 TeV energy and 75 m bending radius. This is clearly seen for CRYSTAL-channeling simulations Fig. 1d. At the same time the VR peak for CRYAPR simulation is located at a half of critical angle value. For volume reflection orientation (Fig. 2a) the same tendency is visible.

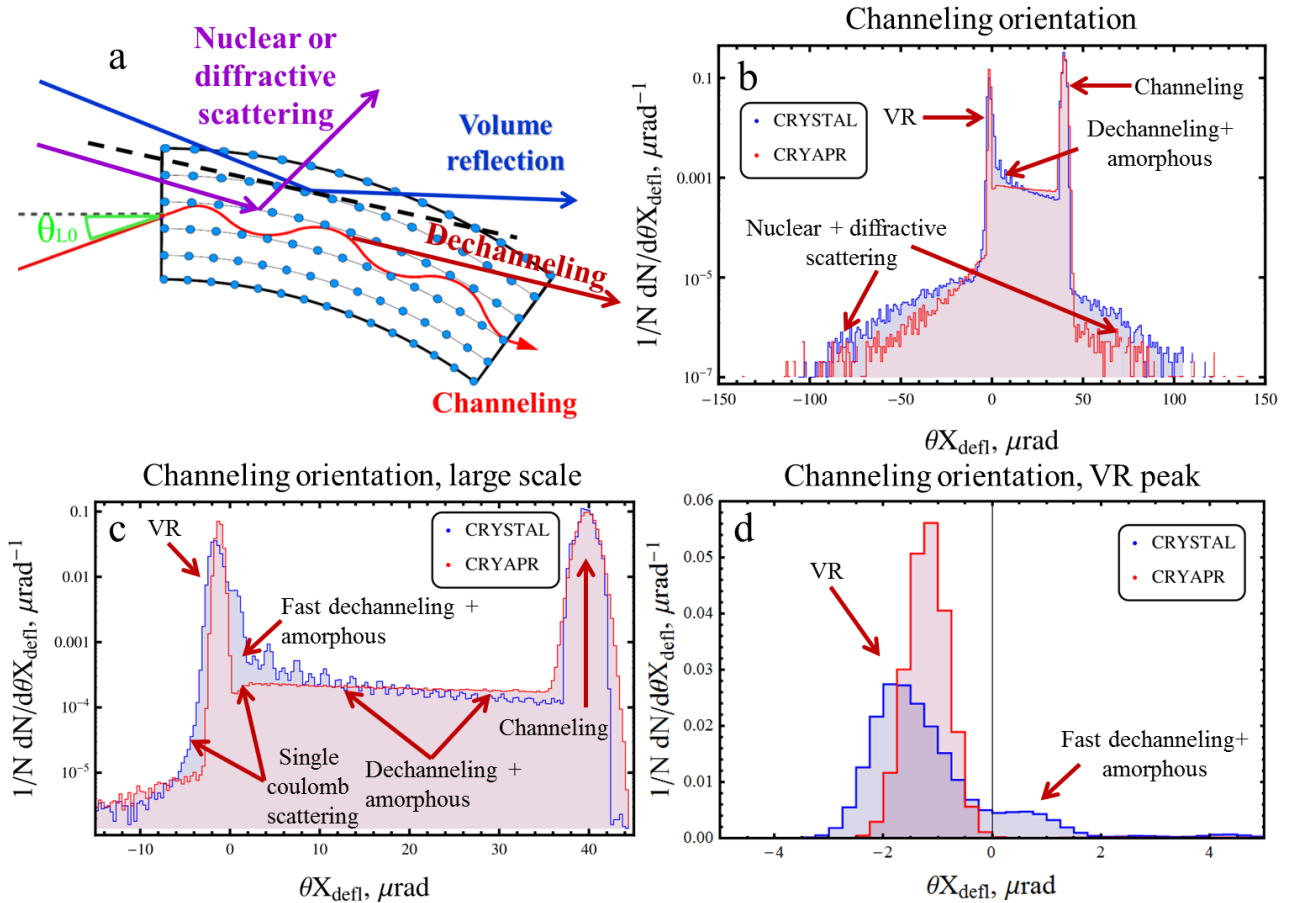


Figure 1: Schematic representation of possible effects in crystal (a); horizontal kick distribution in different scales at channeling orientation (b-d)

Very interesting picture is observed for dechanneling. For CRYSTAL-channeling simulations one can notice dechanneling peaks. They can be explained by very good correlation between different trajectories. The dechanneling probability is high only close to crystal planes. This situation corresponds to dechanneling peaks. At the center of the channel the dechanneling probability is low, this case corresponds to dechanneling deeps. The number of oscillations in 3mm crystal is 12. Taking into account both of extrema of channeling oscillations we double this number. Therefore, the estimated number of dechanneling peaks is 24. Exactly this number is observed (see Fig. 1c).

Let us understand, why a half of these peaks is much higher than another one. It can be explained by the asymmetry of both potential well shape (Fig. 2b) and angular distribution. Because of strong centrifugal force particles will dechannel much more frequently at low potential minimum. And because of asymmetry of potential well the phase correlation between dechanneling particles will be very high.

For the volume reflection orientation (see Fig. 2a) only high dechanneling peaks are visible. It can be explained by very good phase correlation between volume captured particles, even better than for channeling orientation. The reason of it is that a particle can be captured with high probability only near lower potential peak because of high asymmetry of potential well (see Fig. 2b). That's why the phase of different particles will be almost the same.

The volume capture (Fig. 2b) can occur due to scattering on nuclei or electrons. In the LHC case the scattering on electrons is very small. So, only scattering on nuclei is responsible for both dechanneling and volume capture. This is another reason of very high phase correlation of volume captured particles. Nuclei are distributed more close to crystal plane than electrons, that's why particles can be scattered only near the planes at the phase equal to 0.

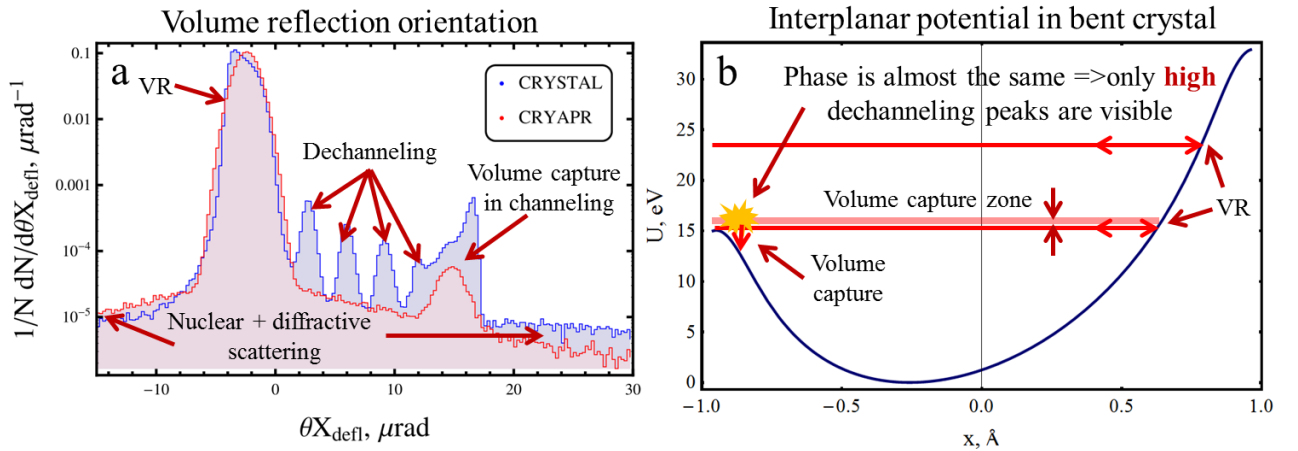


Figure 2: Horizontal kick distribution at volume reflection orientation $-25\mu rad$ (a); interplanar potential well and schematic representation of volume capture in channeling (b)

The difference in volume capture probability for CRYAPR and CRYSTAL-channeling simulations (Fig. 2a) can be also explained by importance just of nuclear scattering at $7TeV$. The estimation of this probability can be provided by approximation formula [7]:

$$\eta_{VC} = \frac{\pi R \theta_c}{2 L_D} \sim 1\%. \quad (1)$$

The obtained value is close to CRYSTAL-channeling simulation.

There are several kinds of scattering dominating in different angular regions: the coulomb multiple and single scattering, elastic and diffractive nuclear scattering. All these types are

shown in Fig. 3a. The main difference in simulation of both codes is considering of single coulomb scattering by CRYSTAL-channeling. The rate of this type of scattering is several times higher than of nuclear scattering: correspondingly 0.7% and 0.3% of particles for amorphous orientation and 0.25% and 0.08% for the channeling one. At the same time the angle is large enough to make the consequent capture in channeling regime very unlikely. That's why strong single coulomb scattering may be important for collimation no less than the nuclear one. A difference in nuclear scattering is explained by different types of models implemented in two routines. However, they are still under studies.

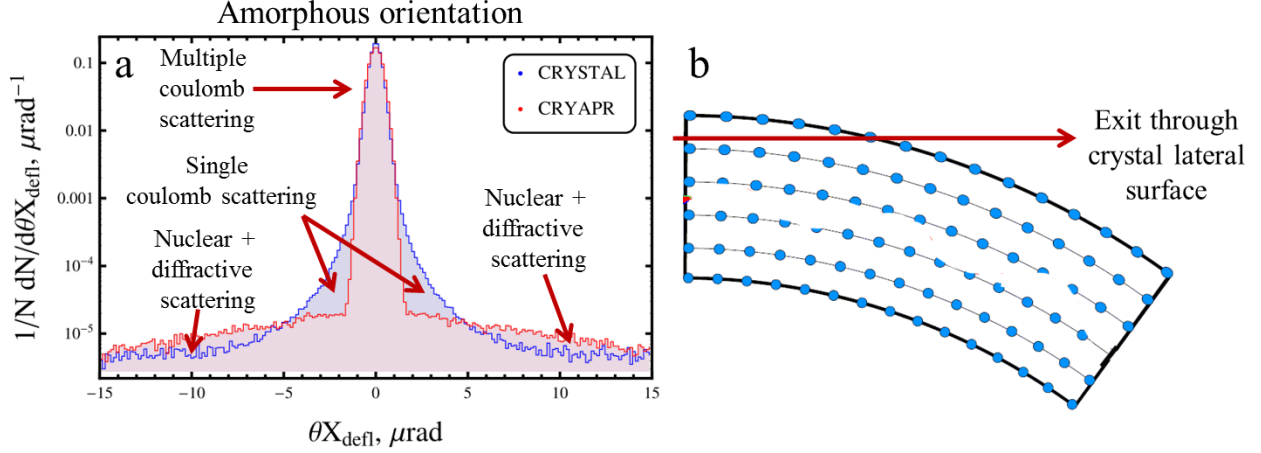


Figure 3: Horizontal kick distribution at amorphous orientation $100\mu\text{rad}$ (a); schematic representation of particle escape through the crystal lateral surface (b)

The ionization losses map at channeling orientation is shown in Fig. 4. The considerable difference between two codes is for channeling regime. In CRYAPR the energy losses of channeled particles are assumed to be zero and only if particle dechannel, it will lose the energy. However, the losses for channeling along full crystal length are not zero. For CRYSTAL-channeling the losses of both channeled and dechanneled particles are much greater than zero.

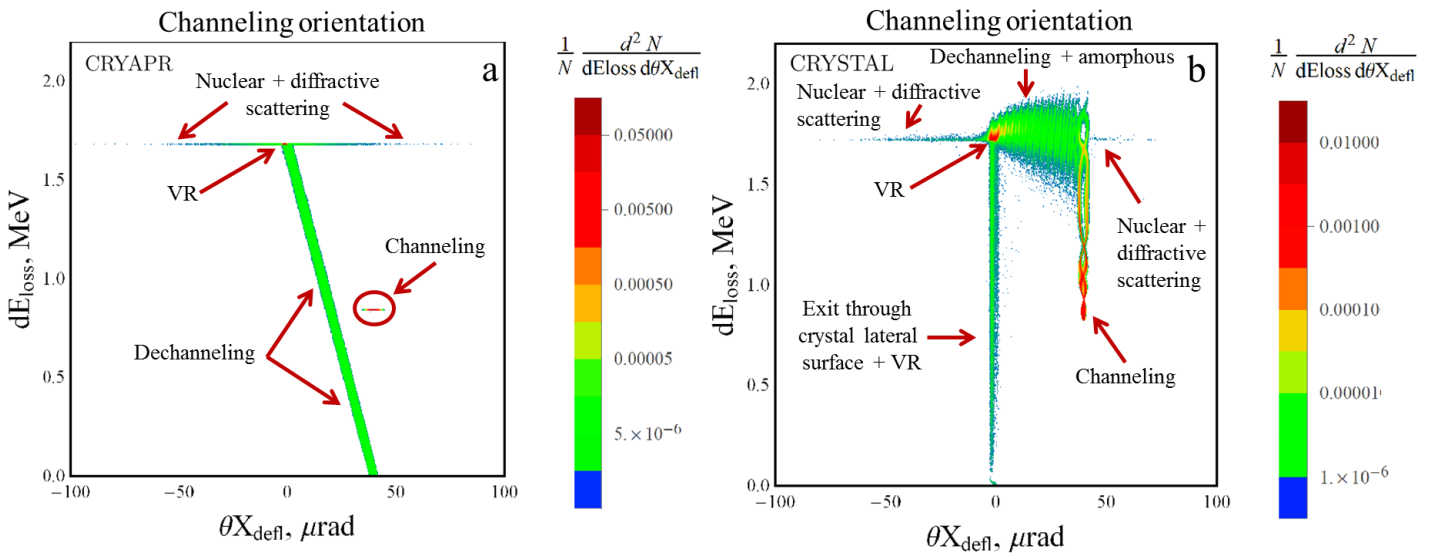


Figure 4: Ionization losses map for CRYAPR (a) and CRYSTAL-channeling (b) simulations

Another difference is simulation of particle exit through crystal lateral surface by CRYSTAL-channeling (see Fig. 3b). If particle doesn't pass full crystal length, it will lose less energy.

A little exceeding of amorphous value of energy losses can be explained by increasing of energy losses of particles with high amplitude of channeling oscillation. This is because the particles "spend a lot of time" near crystal planes where the electron density is much higher than the amorphous value of it. Usually these particles dechannel fast.

4 Conclusions

A systematic comparison of CRYSTAL-channeling with different crystal routine was performed, a detailed analysis of possible effects in crystal was provided. I found some differences related to the physics treatment of particle dynamics in crystal: dechanneling peaks well correlated with channeling oscillations, channeling and volume reflection profile, single coulomb and nuclear elastic scattering, simulation of escape through crystal lateral surface.

The obtained results were reported on both poster and oral student sessions. Also they were presented at the LHC Collimation Upgrade Meeting. Additionally, they will be published in CERN note.

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