SINGLE PARTICLE MULTI-TURN DYNAMICS DURING CRYSTAL COLLIMATION *

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Abstract

As the quest for luminosity remains a high-profile issue for current and future accelerators, protecting superconducting magnets from beam induced quenches demands using high efficiency halo cleaning devices. In CERN's LHC, a multi-stage collimation system is being set up with a predicted halo cleaning efficiency up to 99.995%. Given that LHC superconducting magnets have very low quench thresholds, silicon-based crystals may be used as a primary collimator for the halo particles in order to improve the cleaning system even further. Dedicated experiments have recently been performed in an SPS extraction line with a bent silicon crystal for single-pass particles [1]. This article compares the published results of this experiment with simulations using established tracking codes. The goal is to better describe the main physics mechanisms involved in the beam-crystal interaction. A simple algorithm is then introduced to allow for fast tracking of the effect of a bent crystal on a high energy proton beam over many turns.

SIMULATION TOOLS

Detailed studies of the effect of a specific crystal on halo particles have been performed using the CATCH program [2], which simulates the trajectory of individual particles going through the planes of a bent crystal. All crystal modes are considered: (de)channeling (CC), volume reflection (VR), volume capture and amorphous kick (AK). The energy dependence of these mechanisms, as discussed in a recent publication [3], is also included. Figure 1 shows the case of a silicon crystal bent in the horizontal plane simulated in CATCH when targeted by 400 GeV (CERN H8 experiment energy) and 980 GeV (Tevatron T980 exp. energy) protons. The kick received by each particle is determined by comparing the transverse momentum of that particle with the potential well of the crystal planes. For each energy, the relative angle $\alpha_{crystal}$ between the crystal and the incoming particles is scanned; the statistics of particles receiving a given kick XP_{out} from the crystal are then collected into 50 μrad bins.

Three areas are clearly visible in the contour plots:

- the "channeling island" (1) at $XP_{out} \simeq -180\ \mu$rad;
- the "volume reflected bar" (2) between $\alpha_{crystal} \simeq 0$ μrad and $\alpha_{crystal} \simeq 180\ \mu$rad;
- the two remaining areas (A), (B) slightly off-centered around $XP_{out} = 0$.

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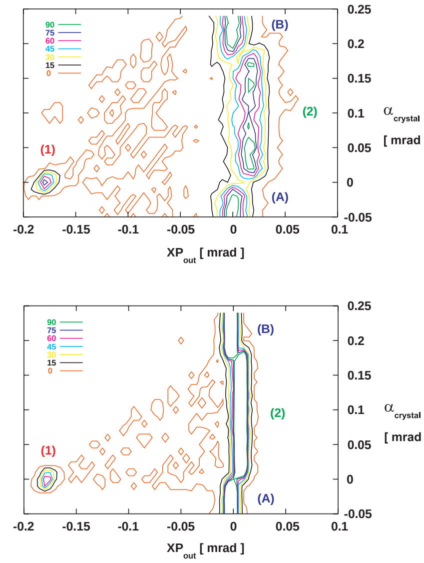

Figure 1: Change in the horizontal angle XP_{out} given by a 110 Si bent crystal to protons at 400 GeV (top) and 980 GeV (bottom) as a function of the orientation of the crystal $\alpha_{crystal}$ with respect to the incoming particles. Data obtained from CATCH simulations. The initial distribution counts 500 protons.

Table 1: RMS position and spread of channeling area (1), volume reflection area (2), and amorphous areas (A) and (B) from Figure 1 as a function of the energy of the impacting particles. The initial distribution of particles counts 500 protons.

Energy		**400 GeV**	**980 GeV**
Area (1)	position	-183.3 $\pm$ 0.4	-183.5 $\pm$ 0.2
[μrad]	spread	6.3	4.5
Area (2)	position	9.9 $\pm$ 0.2	8.2 $\pm$ 0.1
[μrad]	spread	11.0	4.2
Areas (A,B)	position	-3.1 $\pm$ 1E-4	-6.3 $\pm$ 2E-5
[μrad]	spread	10.0	4.5

Area (1) contains protons that have been channeled, i.e. captured within the crystal planes so as to follow its bent structure (CC). Area (2) contains the uncaptured particles that reflected off the surface of a crystal plane (VR). Areas A and B correspond to particles that received an amorphous kick (AK) due to multiple coulomb scattering.

Table 1 lists the main parameters of these distributions in the cases shown in Figure 1, assuming Gaussian distributions for particles in each area (1), (2), (A) and (B). The channeling angle of the crystal is independent of the energy of the incoming particles. The distributions around each kick angle get narrower as the energy increases, decreasing

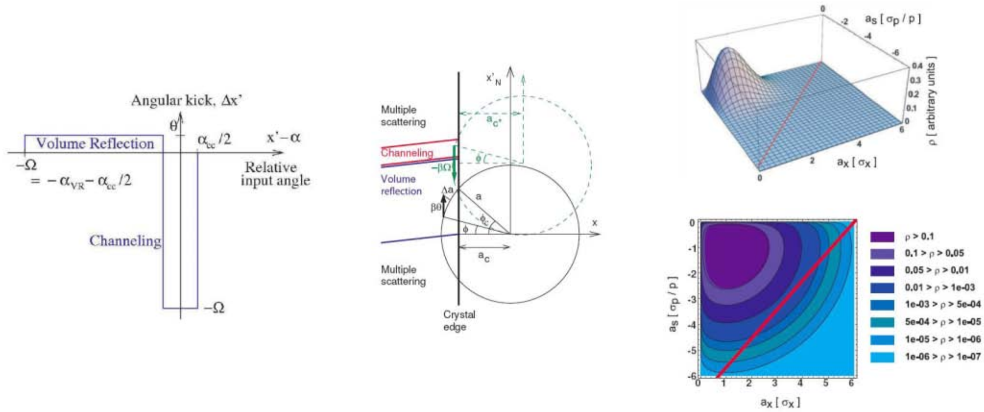

Figure 2: Left: Schematic of the physics processes involved in the motion of a single particle through a bent crystal. α is the orientation of the crystal with respect to the incoming particles. - Center: Applying SCM for a given crystal angle on the trajectory of a single particle in normalized phase space at the location of the crystal. The solid black circle is the trajectory of a particle with $\delta p/p$ = 0. The dashed green ellipse is the trajectory of a particle with $\delta p/p \neq 0$. - Right: 3D (top) and 2D projection (bottom) representation of the probability function ρ as a function of a_x and a_s in units of σ_x and σ_p/p. The solid red line is a representation of Equation (1) for $X_c = 6\sigma_x$ and D_x = -0.88 (SPS experiment case)

by almost a factor of 2 for VR and AK.

Fast codes for multi-turn simulations

One method to speed up the tracking process is to "emulate" the action of the crystal: instead of using full description codes *a la* CATCH, each process is modeled using Gaussian distributions as in Table 1. Put in another way, each process (channeling, VR and AK) is defined by a specific acceptance range of transverse angle XP between the trajectory of the particle in the horizontal plane and the crystal planes.

A Simplified Crystal Model (SCM) could be described by Figure 2. This assumes that amorphous kicks are only applied when outside of both CC and VR acceptance ranges. The description of a crystal is then reduced to three parameters: the bending angle of the crystal Ω, the channeling acceptance range α_{CC} and the kick from volume reflection θ.

SCM in the multi-turn case

SCM allows studying in a practical way the effect of a given crystal over many turns. Figure 2 (center) shows a sample representation in the horizontal phase space of the trajectory (solid black circle) of a single particle with amplitude a and $\delta p/p$ = 0. The crystal sits at a displacement a_c so that a particle with betatron amplitude a has an overall phase acceptance $2\phi_c$. The angle α of the crystal is chosen in Figure 2 so that VR is the favored mechanism giving a positive kick while CC gives a negative one.

An on-momentum particle ($\delta p/p$ = 0, solid black circle in Figure 2) arrives at the crystal with a phase ϕ in the range for volume reflection, and receives a positive normalized angular kick $\beta\theta$ which increases its normalized amplitude by Δa. This particle will come back and hit the crystal again after a number of turns that is only a function of the transverse tune of the machine. The normalized amplitude will keep increasing until the X'_N falls in the CC range (when the particle will be channeled by an angle -$\beta\Omega$), or until that particle hits an aperture restriction, e.g. a secondary collimator.

An off-momentum particle ($\delta p/p \neq 0$, dashed green ellipse in Figure 2) is shifted in both position and angle from the synchronous trajectory due to the dispersion function. The new center is located at coordinates ($D_N\frac{\delta p}{p}$,$D'_N\frac{\delta p}{p}$) in (X_N, X'_N) space. For the same betatron phase ϕ arriving on the crystal, this particle is now in the acceptance range for channeling, so that the kick received will increase its normalized amplitude. Depending on the location of the crystal in the machine, the effect of the dispersion might become significant enough to alter the data taken by a dedicated single particle multi-turns detection system.

Assuming that the studied crystal sits at a transverse position X_c in the horizontal plane, a particle will hit the edge of the crystal for:

$$D_x * a_s + a_x = X_c \quad (1)$$

where D_x is the dispersion function, and a_x is the betatron amplitude in millimeters at the crystal and a_s is the synchrotron amplitude in units of σ_p/p at the crystal. The probability ρ for a single particle to have (a_x,a_s) for coordinates in the (X,σ_p/p) reads:

$$\rho(a_x, a_s) = K * a_x * a_s * \exp\left(-\frac{a_x^2}{2\sigma_x} - \frac{a_s^2}{2\sigma_p/p}\right), \quad (2)$$

with K a constant. Figure 2 shows the combination of Equations (1) and (2), taking X_c = 6 σ_x. Following the variations of ρ along the solid red line, one can then generate a distribution of particles to be tracked around the crystal.

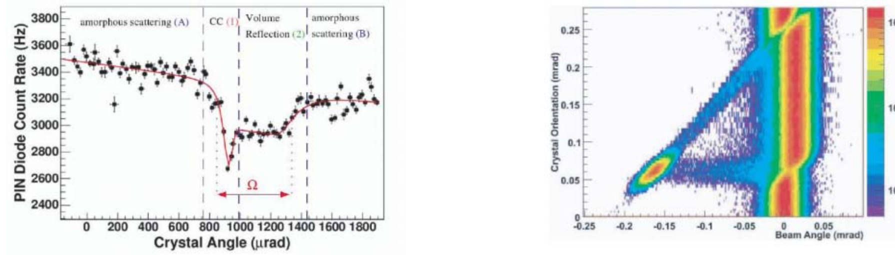

Figure 3: Left: Particle scattering rate as a function of relative beam-crystal angle as seen by beam loss monitors downstream of a 440 μrad O-shaped Si crystal during RHIC Au-store 1737 (taken from [4]). The angular resolution is approximately 25 μrad. The red solid line is from a fit to the data. - Right: Data taken during the CERN H8RDD22 experiment (taken from [1]).

DATA FROM PAST EXPERIMENTS

During the early RHIC runs (up to 2003) a bent Si-crystal was installed in one of the two RHIC rings providing first channeling data from circulating p- and Au-beams. Beam loss monitors ("Pin Diodes") a few meters downstream of the crystal vessel monitored the rate of particles scattering off the crystal. This rate starts to drop when the crystal is rotated such that particles are channeled or volume reflected rather than amorphously scattered. Figure 3 (left) presents data from a typical scan of the relative beam-crystal angle. Shown is essentially the inverse of a projection onto the vertical axis in Figure(s) 1. It depicts all three areas: AK (A+B), CC (1) and VR (2), likely for the first time in a multi-turn scenario with circulating beam. However, the focus then was on the channeling efficiency (here about 25%). The VR area was interpreted as volume capture since the angular distribution of the particles coming out of the crystal could not be measured.

Figure 3 shows a measurement of the simulations as shown in Figure 1 from an SPS run [1]. It confirms the simulation results shown above. However, it was obtained with extracted beam, i.e. single-pass particles, not applicable for a circular collider with stored beams. More effort is needed to confirm simulations quantitatively, their energy scaling and in a multi-turn environment.

LAYOUT OF EXPERIMENTS

Figure 4 shows the current proposal for a multi-turns experiment (CRYSTAL) in the SPS at CERN. Using three detection stations, one at the crystal and two Roman Pots (RP) downstream of it, the goal of the experiment is to detect individual particles once they are kicked by the crystal and reconstruct their trajectories. Identifying each particle from the raw data requires a high resolution in both time and transverse position at each station for the experiment to be successful. In the SPS, to increase the efficiency of the detection system, the RPs are placed as far downstream as possible from the crystal.

SCM can be used to produce sample datasets equivalent to the ones generated by the stations to tune the data analysis code that will be used during the experiment. The synchrotron motion has to be taken into account during the tracking, therefore the momentum deviation due to scattering processes at each detection station is also included in the tracking studies. A similar experiment (T980) is planned at the Tevatron to study the efficiency of multi-turns crystal collimation at TeV energies.

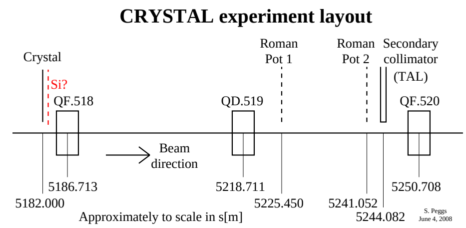

Figure 4: Schematic layout of the proposed CRYSTAL experiment at CERN's SPS. A silicon detector and two roman pots are installed at and downstream of a bent silicon crystal to study the multi-turns pattern of the single particles deflected by the crystal.

SUMMARY

Bent crystals might be a promising device for proton collimation. However, more studies with circulating beam and fast simulations are needed to determine the best mechansim to be used (CC or VR). Two more dedicated experiments are being prepared at this time, one at the SPS and one at the Tevatron.

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