Simulation of an LHC Beam Crystal Extraction

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Abstract

The extraction of protons from the halo of the LHC beam by means of a bent crystal has been simulated by computer, following the project [1] and making use of the simulation code [2] tested earlier in the CERN-SPS crystal extraction experiment [3]. The extraction efficiency has been studied as a function of the crystal length. The background produced with the aligned crystal was computed. We investigated also the influence of the crystal edge imperfection on efficiency, and discuss a co-existence of the crystal extraction with the other systems (such as beam cleaning) of accelerator.

Channeling of a beam of charged particles in a bent monocrystal has recently shown an impressive progress in efficient steering of a high energy beam [4]. The CERN experiments on the crystal-assisted beam extraction from the SPS accelerator [3] are of particular interest. These studies have in view possible application of the channeling for a beam extraction from a multi-TeV machine [1], where an extracted beam would open up very interesting possibilities for beauty physics [1].

The extraction process includes multiple passes through the crystal, and turns in the accelerator, of the beam particles. Therefore, no easy way to extrapolate the SPS experimental results onto a higher energy is possible. On the other hand, computer simulation [5] of the SPS experiments gave the results being in a good agreement with the measurements [3]. Making use of the same simulation code [2] which was tested at the SPS, here we model the crystal extraction of protons from the Large Hadron Collider beam halo, with parameters matching the project [1].

Beam bending by a crystal is due to the trapping of some particles in the potential well formed by the field of atomic planes, where the particles then follow the direction of (are *channeling* in) the atomic planes. The channeling effect survives in a bent crystal until the ratio of the beam momentum p to the bending radius R becomes as high as the maximal field gradient, which equals to 6 GeV/cm in silicon. However, the crystal bend reduces the phase space available for channeling, thus decreasing the fraction of particles channeled. This picture is disturbed by the scattering processes which could cause the trapped particle to come to a free state (dechanneling).

In the present simulation we have tracked some thousand protons through the curved crystal lattices with small, $\sim$5 μm, steps applying the Monte Carlo code CATCH [2]. This code uses the Lindhard's continuous-potential approach to the field of atomic planes, and takes the processes of both single and multiple scattering on electrons and nuclei into account. Further detail on this code may be found in [2]. We assumed the crystal to have a perfect lattice, and to be bent with a constant longitudinal curvature.

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The distribution of particles in the LHC beam halo was studied earlier [6] for the purpose of design of the LHC beam cleaning collimators. The halo is continously being fed with scattered protons from the beam core. Various "natural" scattering processes supply $\sim 4 \cdot 10^9$ protons per second [6] to the halo, which should be compared to the experiment needs of $\sim 10^8$/sec [1]. When the accelerator operates in a collider mode, the strong non-linear effects make the halo particles to diffuse further onto periphery. Any collimator (or crystal) placed at a beam periphery would intercept the diffusing protons. The impact parameters and divergence of the intercepted particles depend mainly on the transverse diffusion speed. In the studies [6] of an LHC beam cleaning insertion it was found that protons hit a collimator very close to its edge, with impact parameter having flat distribution between 0 and $b_{max} \simeq$ 1 μm, and the rms divergence being $\sigma_\psi \simeq 1.5$ μrad. (The above values correspond to the collimator (crystal) edge position X of 6-times the beam rms size σ_x, and are a function of X.) Such a low value of b_{max} calls for a good perfection of the crystal edge.

The feasibility of crystal extraction at the LHC depends on how the crystal is incorporated into the accelerator lattice. The bending angle required for a proton extraction from the LHC is equal to 0.7 mrad [1]. First we investigate the crystal transmission, simulating a single pass of the 7.7 TeV proton beam (with $\sigma_\psi = 1.5\mu$rad) through the aligned bent crystal. The Fig. 1 shows the computed angular distribution of these protons downstream the silicon (110) crystal of 5 cm length.

The fraction $\approx$ 40 % of all incident protons is bent the full angle of 0.7 mrad. This fraction (crystal "efficiency") is plotted in the Fig. 2 as a function of the crystal length L. This dependence saturates for $L \geq 5$ cm, as the p/R ratio becomes essentially lower than the critical value (of order of 6 GeV/cm). For comparison, we have also simulated the beam bending with (111) planes of silicon. The ratio of efficiency, Si(110) to Si(111), was found to be 1.21$\pm$0.03 for the case considered. The Fig. 2 shows one example for Ge(110). In the simulation we have found the critical angle ψ_c (maximal angle of the channeled particle w.r.t. atomic plane) to be equal to 2.3 μrad for Si(110) planes with small bend (pc/R=0.1 GeV/cm). The ψ_c value has decreased

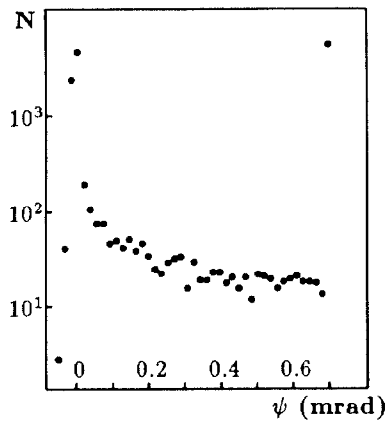

Figure 1: Angular distribution of the 7.7 TeV protons downstream the aligned bent crystal of Si (110).

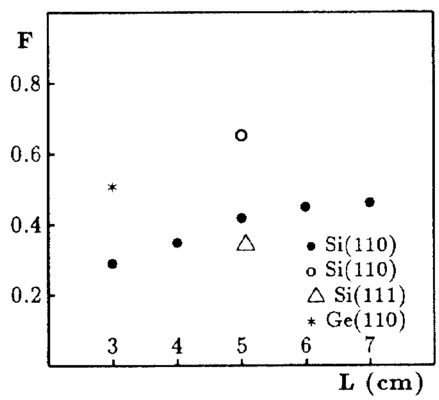

Figure 2: The fraction of protons bent the full angle of 0.7 mrad, as a function of L. The incident beam divergence is σ_ψ=1.5 μrad for (•, ∗, △) and zero for (o).

down to 1.8 μrad for the stronger bend of 1.1 GeV/cm. In our simulation performed with σ_ψ=0 the bending efficiency has increased to 65±2 % (Fig. 2).

Fig. 1 shows that considerable fraction of the protons is scattered in a broad angular range, 0 to 0.7 mrad. This background is mainly due to dechanneling of the protons captured initially. The fraction between the bent and unbent peaks contains about 10 % of the incident protons, or 25 % of the bent-peak. This means a very small local dechanneling length of the order of 5 cm/0.25 = 20 cm. Near the unbent peak the elastic scattering of the nonchanneled protons contributes to the background.

About 24 % of the incident protons leave crystal in the angular range of $\pm\psi_c$. These particles should stay in the acceptance of accelerator, and one may hope to catch a fraction of them at their secondary passes. Because of the absorption and substantial scattering in the crystal, any particle may traverse it only a few times before the eventual loss. This corresponds typically to some dozen turns in the accelerator. For such a short period we may assume linear dynamics of the protons in accelerator described by transfer matrices.

We have performed the crystal extraction simulation, which included multiple passes in the crystal, and turns in the accelerator, of the beam particles. The following relevant parameters of the machine have been used: β_x=250 m, horizontal tune 0.28+integer, crystal edge position X=2 mm ($6\sigma_x$) from the beam axis. The incident protons were distributed over the horizontal coordinate x uniformly from 0 to b_{max} = 1 μm w.r.t. the crystal edge X; the angular distribution was Gaussian with rms value σ_ψ = 1.5 μrad. The parameters roughly matched those proposed for the LHC beam cleaning system [6]. The crystal was 3 by 3 by 50 mm size, with a perfect surface, and perfectly aligned w.r.t. the incident beam.

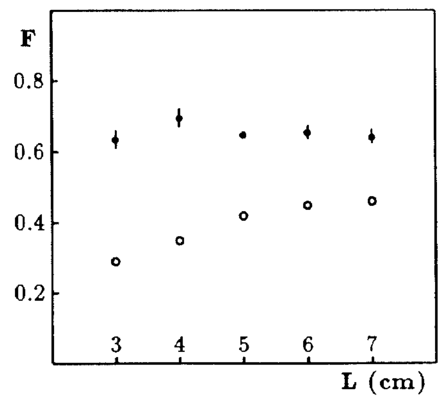

Figure 3: The multiturn extraction efficiency (•) as a function of the Si(110) crystal length. The open dots are for the first-pass efficiency.

The multiturn extraction efficiency is plotted in Fig. 3 as a function of the crystal length L. This function is a rough plateau in the studied range of L. Taking into account the saturation of the first-pass contribution at $L \geq 5$ cm, we suggest the value of 5 cm as the crystal optimal length for the case considered.

Another essential quantity is the distribution of the extracted particles over the transverse coordinate x at the crystal face (Fig. 4). It is important for understanding both the crystal co-work with the other accelerator elements (collimators), and the requirements for the crystal face perfection. From Fig. 4 we find that the extracted protons have penetrated, with secondary passes, into the crystal depth by ~1–2 σ_x. The lesson of this simulation is that, in order to have a multiturn extraction feasible, –

(a) the cleaning collimators should be positioned at least ~1–2 σ_x far w.r.t. the crystal edge, in order to make a minor effect on the extraction with *multiple* passes;

(b) the scattered protons (with amplitudes of 6–8 σ_x) should survive in the accelerator for ~20 turns.

In some sense, cleaning is "complementary" to a crystal extraction: crystal traps protons with small amplitudes (angles), while collimators have to trap the particles with big amplitudes (dangerous to machine).

For a crystal with a perfect surface the first-pass contri-

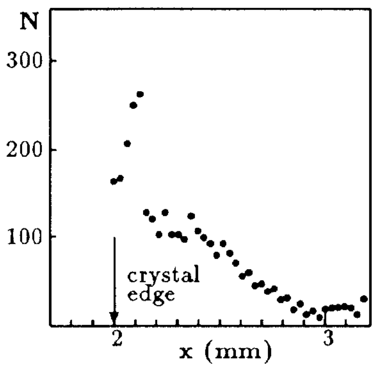

Figure 4: The distribution of the extracted protons over the transverse coordinate at the crystal face. For a perfect crystal one should add a narrow ($\sim$1 μm) first-pass peak at the edge (x=2 mm).

bution is sufficient, therefore the multipass questions are of no concern. The realistic crystal has a non-vanishing irregularity of the surface. This defines some range of inefficient impact parameters at the edge ("septum width" t), where channeling is disrupted. For b_{max} comparable to t, the multiple passes are essential. In any inefficient pass the proton is scattered by some angle ψ_s, having increased the amplitude of the betatron oscillations. At some later turn this proton hits the crystal with the impact parameter b increased by

$$\Delta b \simeq \beta_x^2 \psi_s^2 / 2X. \tag{1}$$

The ψ_s value depends on the "effective length" $\int \rho ds$ of the material traversed in one or many passes:

$$\psi_s^2 \simeq \frac{\epsilon^2}{p^2} \cdot \frac{\int \rho ds}{L_R} \tag{2}$$

Here ϵ=14 MeV/c, L_R radiation length. In order to study the influence of edge imperfection on the extraction, we have repeated the above simulation for the crystal with a nonflat surface. The amplitude of the surface "bumps" was 1 μm. We have tried the b_{max} values of 0.1 μm and 10 Å. The distribution of extraction efficiency over the pass and turn number has substantially changed. Nonetheless the overall efficiency value was about constant and equal, within the accuracy of simulation, to the efficiency of the perfect crystal (the top dots of Fig. 3). This encouraging result is owing to the fact that the change of beam divergence caused by scattering in crystal is minor (in particular near the very edge of a bent crystal), as compared to the crystal acceptance $2\psi_c$.

Due to both nonflatness and bend of the crystal surface, the Δb and ψ_s may be rather small for small b. In our case Δb has order of 0.1 mm. This means that a septum width of up to $\sim$10 μm should not be dangerous for the multiple passes. And vice versa, with t $\sim$1 μm the requirement imposed on the beta function would be as follows: $\beta_x \gg \sqrt{2tX}/\psi_s \approx 25$ m. This constraint is very weak in fact, thus leaving us much freedom in designing the extraction optics.

In the case of "infinitesimal" b or a big t, a proton may have to pass through the dead layer several times. The probability that the proton will never miss the inefficient layer of impact parameters in the subsequent passes (and thus will interact in this layer) can be estimated. The probability of interaction is

$$w_i = \frac{\int \rho ds}{L_N} \tag{3}$$

where the integral is the same as the above one, and L_N is the length of interaction. Although the quantities (1-3) depend in some sophisticated way on the particle "history" (via $\int \rho ds$), their ratio is a function of general parameters only. Therefore one can estimate the probability w of the loss in imperfect layer as follows:

$$w \simeq \frac{2tX}{\beta_x^2} \cdot \frac{L_R}{L_N} \cdot \frac{p^2}{\epsilon^2} = 0.004 \cdot t(\mu m) \tag{4}$$

Actual probability may differ from the above estimate by some factor of the order of unit. However $w \ll 1$. Note that any extra diffusion in the betatron phase space (i.e. any deviation from linearity) would only help, increasing b and reducing w. The same is true regarding the scattering in crystal: any extra contribution (from coherent acts) would reduce w.

We may conclude that the extraction scheme proposed [1] for the LHC, together with the beam parameters expected at this machine [6], favor an application of the crystal channeling for an LHC beam steering. The efficiency of crystal extraction of more than 60 % is predicted. This value is much the same even with the crystal edge imperfection and extremely low impact parameters of incident protons, thanks to the multi-pass mode of extraction. In order not to disturb this multi-pass mode, the other elements of accelerator should be positioned horizontally $\sim$1–2 σ_x farther from the crystal edge. Having understood the basics of the crystal extraction physics, further work on the extraction system design for the LHC may be started.

1 REFERENCES

[1] B.N.Jensen et al., DRDC/P29, CERN (1991).

[2] V. Biryukov, CERN SL/Note 93-74 (AP), 1993.

[3] H.Akbari et al., Phys. Lett. B313, 491 (1993).

[4] S.P. Møller et al., Phys. Lett. B256, 91 (1991).

[5] V. Biryukov, CERN SL/Note 93-78 (AP), 1993.

[6] The LHC Design Report, CERN 91-03, May 1991.