# Computer Simulation of Crystal Extraction of Protons from a Large-Hadron-Collider Beam

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The extraction of protons from the halo of the Large-Hadron-Collider beam by means of bent crystal channeling has been simulated by computer, making use of the simulation code CATCH tested earlier in a CERN-SPS crystal extraction experiment. The multipass extraction efficiency and the background produced with the aligned crystal have been investigated.

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Recent studies [1,2] have made impressive progress in efficient steering of high energy charged-particle beams using bent crystal channeling. The CERN experiments on the crystal-assisted beam extraction from the SPS accelerator [3] are of particular interest. These studies have in view the possible application of channeling for beam extraction from a multi-TeV machine [4,5], where an extracted beam would open up very interesting possibilities for beauty physics [4–6].

The extraction process includes multiple passes through the crystal, and turns in the accelerator, of the beam particles. Therefore there is no easy way to extrapolate the SPS experimental results to a higher energy. On the other hand, computer simulation [7] of the SPS experiments gave results in good qualitative agreement with the measurements [3]. Making use of the same simulation code [8] which has been tested at the SPS, we here model the crystal extraction of protons from the Large-Hadron-Collider (LHC) beam halo, with parameters matching the project [4]. We emphasize the crystal efficiency, the background produced with the aligned crystal, and the effects of multiple passes through the crystal. We also consider the influence of a crystal edge imperfection on the multipass extraction, and discuss the coexistence of the crystal extraction with the other systems of the accelerator.

Beam bending by a bent crystal is due to the trapping of some particles in the potential well formed by the field of the bent atomic planes; the particles are then steered between two adjacent atomic planes. The channeling effect persists 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 (~6 GeV/cm in silicon). However, the crystal bend reduces the phase space available for channeling [9], thus decreasing the fraction of particles channeled. The scattering processes may cause the trapped particle to come to a free state (dechanneling).

In this simulation we have tracked protons through the curved crystal lattices with small, ~5 $\mu$m, steps applying the Monte Carlo code CATCH [8]. This code uses Lindhard's continuous-potential approach to the field of atomic planes, and takes into account the processes of both single and multiple scattering on electrons and nuclei. Further details of this code may be found in Ref. [8]. We assumed the crystal to have a perfect lattice and a constant longitudinal curvature.

The distribution of particles in the LHC beam halo was studied earlier [10] for the purpose of design of the LHC beam cleaning collimators. The halo is continuously being fed with scattered protons from the beam core. At the design luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ various natural scattering processes supply $\sim 4 \times 10^9$ protons per second [10] to the halo, which should be compared to the experimental needs of $\sim 10^8$/sec at a fixed target [6]. When the accelerator operates in a collider mode, the strong nonlinear effects cause the halo particles to diffuse further into the halo region. Any collimator (or crystal) placed at the beam periphery would intercept the diffusing protons. The impact parameters and divergence of the intercepted particles are defined by the transverse speed of the amplitude growth for the particle betatron motion in nonlinear fields. In the studies [10] of a LHC beam cleaning insertion it was found that protons hit a collimator very close to its edge, with impact parameter $b \sim 1$ $\mu$m, and a rms divergence $\sigma_\psi \sim 1$ $\mu$rad. To supply particles from the beam core into the halo, one may also apply a noise to the circulating beam [11], thus providing a controllable source of halo while keeping the beam core undisturbed; however, $b$ is still in the micron range. Such low values of $b$ call for a good perfection of the crystal edge. Alternatively to a perfect edge, one should investigate how a crystal extracts particles in the multipass mode, which involves many turns in the accelerator and several scatterings in the crystal of the circulating particles. This mode is emphasized in the present work.

The feasibility of crystal extraction depends on how the crystal is incorporated into the accelerator lattice. The bending angle required for proton extraction from the LHC is equal to 0.7 mrad [4]. 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. Figure 1 shows the computed angular distribution of the protons downstream of the silicon (110) crystal of 5 cm length. A fraction ($\approx$40%) of all incident protons is bent the full angle

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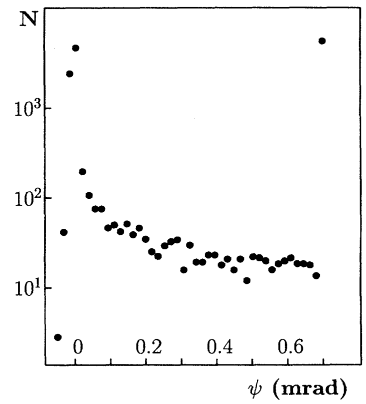


FIG. 1. Angular distribution of the primary protons downstream of the aligned bent crystal of Si(110).

of 0.7 mrad. This fraction (crystal "efficiency") is plotted in Fig. 2 as a function of the crystal length $L$. It saturates for $L \geq 5$ cm, as the $p/R$ ratio becomes essentially lower than the critical value (6 GeV/cm). This dependence agrees, within 5%, with a calculation by the continuum model of channeling [9] if the critical distance $x_c$ (maximal allowed amplitude of a channeled particle) is taken as $d_p/2 - u$, where $d_p = 1.92$ Å is the interplanar spacing of Si(110) and $u = 0.075$ Å is the amplitude of the atom thermal vibration. 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 $L = 5$ cm. Figure 2 shows one example for a crystal of germanium (110) which has a field twice as strong as that of silicon. In the simulation we have found the critical angle $\psi_c$ (maximal angle of the channeled particle with respect to the atomic plane) to be equal to 2.3 $\mu$rad for Si(110) planes with small bend

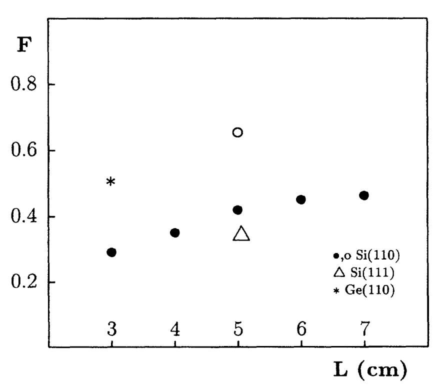


FIG. 2. The fraction of protons bent the full angle of 0.7 mrad, as a function of the crystal length. The dots • and ∘ are for the single pass through the Si(110) crystal, △ for Si(111), ∗ for Ge(110). The incident beam divergence $\sigma_\psi = 1.5$ $\mu$rad for (•, ∗, △) and zero for (∘).

($pc/R = 0.1$ GeV/cm). The $\psi_c$ value has decreased down to 1.8 $\mu$rad for the stronger bend of 1.1 GeV/cm. Clearly, the crystal efficiency depends on the incident beam divergence $\sigma_\psi$. For $\sigma_\psi > \psi_c$ efficiency decreases like $1/\sigma_\psi$. For $\sigma_\psi < \psi_c$ some increase of efficiency may be expected. In our simulation performed with $\sigma = 0$ the bending efficiency has increased to $(65 \pm 2)\%$ (Fig. 2).

Figure 1 shows that a considerable fraction of the protons is scattered in a broad angular range, from ~0 to the bend angle of 0.7 mrad. This background is due to dechanneling of the protons captured initially, caused by the multiple scattering along the crystal. The fraction between the bent and unbent peaks contains about 25% with respect to the protons in the bent peak. The dechanneling loss caused by the scattering is commonly described with a dechanneling length $L_D$ [1], along which the beam channeled fraction decreases by the factor of $1/e$. For a perfect Si(110) at 7.7 TeV, one expects $L_D \simeq 340$ cm in a straight crystal, and $L_D \simeq 140$ cm with the bending of $pv/R = 1.1$ GeV/cm [12,13]. However, dechanneling follows the law $\sim\exp(-L/L_D)$ only for $L$ comparable with $L_D$, while for $L \ll L_D$ the dechanneling rate is essentially higher (see discussion and simulations in Ref. [12]). In our case the "local" value of $L_D$ [derived from the data fit with $\exp(-L/L_D)$] is only $\sim 5$ cm/0.25 = 20 cm; this is due to rapid dechanneling of the *few* particles with highest amplitudes of channeling (of order and above $x_c$). In analytical estimates, such particles are simply considered as lost; in Monte Carlo simulations (or a real crystal) this loss is actually a gradual process developed along the crystal length [12] due to nuclear scattering (slow at very high energies). Near the unbent peak the elastic scattering of the nonchanneled protons contributes to the background.

The full divergence of the bent peak is $2\psi_c$. The angular distribution near the unbent peak is of more interest. The rms width of the unbent peak equals 2.4 $\mu$rad. With 1.5 $\mu$rad for the rms divergence of incident particles, this gives 1.9 $\mu$rad for the rms angle of scattering in the crystal. This is higher than the 1.3 $\mu$rad of the rms multiple Coulomb scattering angle over 5 cm of silicon. The rest of the contribution, also about 1.3 $\mu$rad, comes from the coherent scattering in the field of atomic planes. Notice that the mean angle of the unbent peak is not zero, but $-1.8$ $\mu$rad (about $-\psi_c$); this effect, so-called "volume reflection" [14], is the result of coherent scattering of the nonchanneled particles in a bent crystal. Most of the particles stay in the acceptance of the accelerator, and potentially can be trapped in channeling trajectories on their secondary passes. However, this is sensitive to details of the accelerator and should be the subject of a more detailed analysis.

Because of the absorption (nuclear reactions) and substantial scattering in the crystal, any particle may traverse it only a few times before eventual loss. This corresponds typically to some dozen turns in the accelerator.

For such a short period we may assume linear dynamics for the protons in the accelerator described by transfer matrices. We have performed the crystal extraction simulation including multiple passes in the crystal. The following relevant parameters of the machine have been used: $\beta_x = 250$ m, horizontal tune 0.28 + integer, crystal edge position $X = 2$ mm ($6\sigma_x$) from the beam axis. The incident protons had a flat distribution over the horizontal coordinate $x$ from $X$ to $X + b_{\max}$, with $b_{\max} = 1$ $\mu$m; the angular distribution was Gaussian with rms value $\sigma_\psi = 1.5$ $\mu$rad. The parameters roughly matched those proposed for the LHC beam cleaning system [10]. The crystal was $3 \times 3 \times 50$ mm$^3$ in size, with a perfect surface, and perfectly aligned with respect to incident beam. The overall extraction efficiency is plotted in Fig. 3 as a function of the crystal length $L$. This function is roughly constant 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 optimal crystal length for the case considered.

For understanding both the crystal interplay with the other accelerator elements (collimators) and the requirements for the crystal face perfection, the distribution of the extracted particles over the transverse coordinate $x$ at the crystal face is essential. Figure 4 shows this distribution for protons extracted with secondary passes (on pass 2 or higher), just before extraction. For a perfect crystal one should add a narrow ($\sim 1$ $\mu$m) first-pass peak at the edge. From Fig. 4 we find that the extracted protons have penetrated, with secondary passes, $\sim(1-2)\sigma_x$ into the crystal. The lesson of this simulation is that feasibility of multiturn extraction requires (a) the cleaning collimators to be positioned at least $\sim(1-2)\sigma_x$ outside the crystal edge, in order to make a minor effect on the extraction with *multiple* passes and (b) the scattered protons (with amplitudes of $(6-8)\sigma_x$) to survive in the accelerator for $\sim$20 turns.

For a crystal with a perfect surface the first-pass contribution is sufficient and therefore multipass questions are of no concern. However, a realistic crystal has a nonvanishing irregularity of the surface. This defines some range of inefficient impact parameters at the edge ("septum width"), where channeling is disrupted. With special polishing, the irregularity may be lowered down to a submicron level, or even below it. Unfortunately, the impact parameters $b_{\max}$ may also be extremely small (even down to $\sim$Å range), because of their sensitivity to the accelerator nonlinearities. The SPS experience has shown that the problem of a nonzero septum width does exist. For $b_{\max}$ comparable to (or even much lower than) the septum width, multiple passes are of primary importance. In any inefficient pass the proton is scattered by some angle $\psi_s$, which in turn increases the amplitude $x_{\max}$ of subsequent betatron oscillations. At some later turn this proton hits the crystal with the impact parameter $b$ increased by $\Delta b \approx \sqrt{x_{\max}^2 + \beta_x^2\psi_s^2} - x_{\max} \approx \beta_x^2\psi_s^2/2x_{\max} \approx \beta_x^2\psi_s^2/2X$; note that $\Delta b \ll X$. In our case $\Delta b \simeq 0.1$ mm; this explains some peaking in Fig. 4 at the depth of $\sim$0.1 mm, caused by the *second*-pass distribution. This means that a septum width of $\sim$10 $\mu$m should not be dangerous for the multiple passes. Conversely, with a septum width of $\Delta b_{\text{dead}} \sim 1$ $\mu$m the requirement imposed on the beta function is very weak: $\beta_x \gg \sqrt{2\Delta b_{\text{dead}} X}/\psi_s \approx 25$ m, thus leaving us much freedom in designing the extraction optics.

In order to study the influence of an 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 $\mu$m. We have tried the $b_{\max}$ values of 0.1 $\mu$m and 10 Å. The distribution of extraction efficiency over the pass and turn number was substantially changed. Nonetheless, the overall efficiency value was about constant and equal, within the accuracy of simulation, compared to the efficiency of the perfect crystal (the top dots of Fig. 3). This encouraging result is due to the fact that a change in beam divergence caused

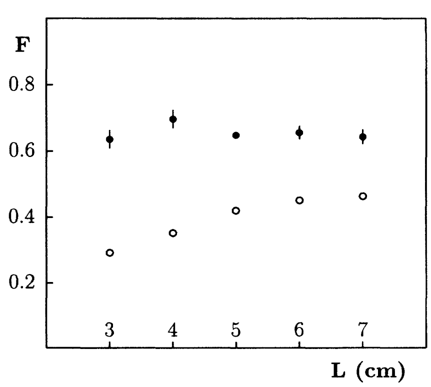


FIG. 3. Overall extraction efficiency (•) as a function of the Si(110) crystal length. The open dots are for the first-pass efficiency.

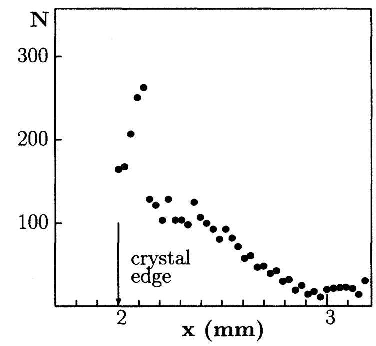


FIG. 4. The distribution of the protons extracted with multipasses, over the transverse coordinate at the crystal face. For a perfect crystal one should add a narrow ($\sim 1$ $\mu$m) first-pass peak at the edge ($x = 2$ mm).

by scattering in the crystal is minor (in particular near the very edge of a bent crystal), as compared to the crystal acceptance $2\psi_c$.

We can conclude that the extraction scheme proposed [4] for the LHC, together with the beam parameters expected at this machine [10], favor an application of the crystal channeling for a LHC beam steering. An 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, owing to the multipass mode of extraction. In order not to disturb this multipass mode, the other elements of the accelerator should be positioned horizontally $\sim(1-2)\sigma_x$ outside the crystal edge. With the basics of the crystal extraction physics understood, further work on the extraction system design for the LHC can be started. The results cannot be readily scaled to other experiments [3,5]; we refer to other simulations with CATCH [7,15]. One general trend in the results of these simulations, from SPS [7] to Tevatron [15] to LHC, is worthwhile to mention: The difference in efficiency of the ideal crystal and crystal with imperfect surface vanishes with energy $E$, because the scattering angle reduces faster ($\sim 1/E$) than $\psi_c$ does ($\sim 1/\sqrt{E}$).

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