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Optimization of crystal parameters for effective extraction and collimation in ring accelerators

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Summary. — The efficiency of both extraction and collimation systems in ring accelerators by means of channeling in a bent crystal is defined. The dependences of extraction efficiency on geometrical parameters of a crystal such as length, width and bend angle, and also on both azimuth position of system elements and offset of the septum or collimator are investigated. The influence of crystal imperfection on the efficiency of systems is considered, and the guidelines on their tolerances are given. It is shown that in a wide range of energies from 2 GeV up to 7 TeV at optimal parameters of both the crystal and the elements positions, an extraction efficiency of more than 95% can be achieved.

PACS 29.27.-a – Beams in particle accelerators.
PACS 42.79.Ag – Apertures, collimators.
PACS 61.85.+p – Channeling phenomena (blocking, energy loss, etc.).

1. – Introduction

Ideas of using the particle channeling in bent crystals to steer the beams have been checked up and advanced in many experiments [1,2]. This method has found the largest practical application at the U-70 proton synchrotron at IHEP where crystals are used in regular runs for beam extraction and forming. The creation of effectively intercepting beam cleaning systems [3-6] is an urgent task nowadays due to increase of beam intensity at the working accelerators (IHEP, FNAL) and construction of new ones at high energies (CERN, Darmstadt, JINR). Usage of superconducting magnets in modern accelerators imposes growing requirements for quality and stability of system operation. It is shown in this paper that the application of channeling effect in bent short crystals considerably increases the efficiency of extraction and collimation systems.

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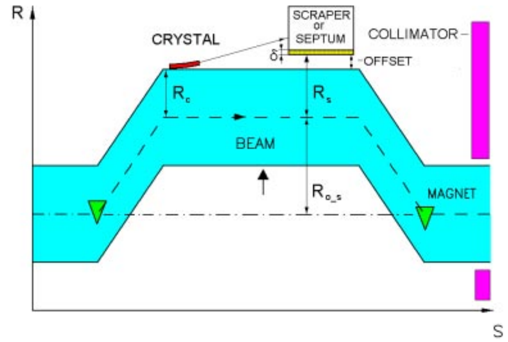

Fig. 1. – Layout of the extraction system.

2. – The principle of operation of beam extraction and cleaning systems

The typical scheme of beam extraction with usage of scattering targets is shown in fig. 1. The location of the beam and the system components in the extraction phase plane at the crystal site is presented in fig. 2. The target can be both amorphous and crystalline. In this paper we consider the usage of a short crystal curved at a small angle necessary for increasing the amplitude of particles betatron oscillations sufficient for them to be placed in the front face of the scraper or in the septum gap. At the U-70 the scraper and the crystal target are installed in 86 and 84 spaces on a negative radial coordinate (closer to the centre of the accelerator) from the equilibrium orbit. The beam is slowly directed to them in the radial plane by two wave bumps by changing of the magnets fields (76, 88, and 82, 94).

The extraction efficiency I_{out} is defined by the relative value of extracted protons hitting in the gap of the septum magnet. That is, knowing the losses of protons in the crystal I_{cry} defined by their nuclear interactions with the nucleus of the crystal, the losses in the septum partition I_{sep} and the amount of protons scattered at the big amplitudes I_{a}, it is possible to define

$$I_{\mathrm{out}} = 1 - I_{\mathrm{cry}} - I_{\mathrm{sep}} - I_{\mathrm{a}}. \tag{1}$$

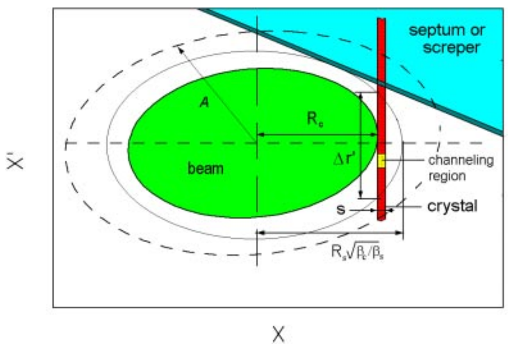

Fig. 2. – Phase plane in the crystal place.

The efficiency of the collimation system is defined by the scattered protons gone out from the system and lost in the vacuum chamber of the accelerator. The relative value of such protons to all intercepted ones can be defined as global losses I_{g}. In our case there are two main sources of losses, namely, the crystal and the scraper:

$$I_{\mathrm{g}} = I_{\mathrm{g\_cry}} + I_{\mathrm{g\_scr}}. \tag{2}$$

Knowing the value of nuclear losses for protons in a crystal, the first term can be estimated as $I_{\mathrm{g\_cry}} = I_{\mathrm{cry}} \cdot \kappa_1$, where the coefficient κ_1 is defined by both scraper and collimators positions. The value of losses from a scraper is defined by the density of particles $D(1/\mathrm{mm})$ at the scraper edge: $I_{\mathrm{g\_scr}} = D \cdot \kappa_2$. The computer simulation of the beam collimation process has shown that for the U-70 collimation system we have $\kappa_1 \approx 0.05$, $\kappa_2 \approx 0.08$. Thus, the extraction efficiency and interception halo of a beam will be as higher as fewer the losses in the crystal as well as the density of protons at the edge of the scraper or the septum.

The extraction efficiency and beam collimation depend on crystal geometrical sizes, surface and position, as well as on the position of the septum (scraper) in the accelerator. The necessary value of beam deflection by a crystal is defined by its azimuth position, and offset of the septum, which is defined as the gap between the septum and the circulating beam (fig. 1):

$$D_s = R_s - R_c\sqrt{\beta_s/\beta_c} = |R_s| - R_{s0}, \tag{3}$$

where R_s, R_c are the position of the septum and the crystal from the equilibrium orbit, β_s, β_c are the appropriate amplitude functions, R_{s0} is the beam half-size in the place of septum position. The minimum necessary bending angle of a crystal for throwing of the beam over the septum partition is defined by the equation of motion

$$\Delta x' = \vartheta + [(R_s + \delta) - R_c \cdot m_{11}]/m_{12}, \tag{4}$$

where $m_{11} = \sqrt{\beta_s/\beta_c}\cos\Delta\psi, m_{12} = \sqrt{\beta_s\beta_c}\sin\Delta\psi$ are the elements of transfer matrix, $\Delta\psi = \psi_s - \psi_c$ is the phase shift of betatron oscillations, ϑ is the angular half-size of a beam gone out from the crystal, which corresponds to a critical angle for an ideal crystal. Knowing the angular density of particles $\rho_0(\Delta x'_0)$ scattered by the crystal, it is possible to define the density in the septum partition: $\rho_s(R_s) = \rho_0(\Delta x'_0)/m_{12}$. Due to these dependences it follows that for the decrease of both crystal length, which results in the decrease of losses in it, and losses in the septum the phase shift should lie in the area $\pi/3 + \pi n < \Delta\psi < \pi/2 + \pi n$. In U-70 the system elements are located through two magnets, which corresponds to the phase shift $\Delta\psi \approx \pi/3$ that means the layout is close to the optimal.

3. – Simulation of collimation system in accelerator U-70

Let us study the influence of the offset value on the efficiency of beam extraction. For this purpose we have performed computer simulations of the beam scraper process for 50 GeV protons. All the simulations of beam extraction and collimation were made by the code "SCRAPER" [7]. The intensity of the extracted beam, or the efficiency of extraction, has been evaluated as a fraction of protons at the edge of the scraper with thickness $\delta = 1\,\mathrm{mm}$ (fig. 1). The dependences of extraction efficiency on the angular

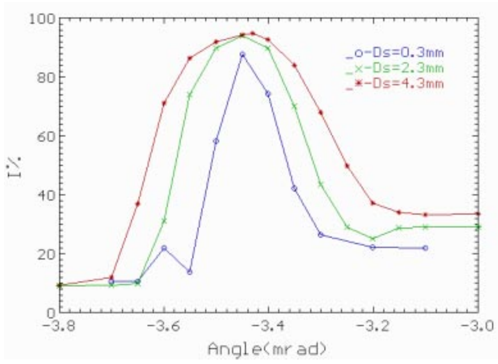

Fig. 3. – Orientation curves of extraction efficiency for various offsets.

position of the crystal (orientation curves) are shown in fig. 3 for various offsets. The value of extraction efficiency and losses in the scraper *versus* offset at the optimal crystal position (orientation angle $= -3.43$ mrad with respect to the chamber axis) are presented in fig. 4. It is visible that the efficiency does not increase at the offsets larger than 2 mm, but the width of the alignment region with high efficiency becomes broader. At small offsets the considerable part of scattered particles which have not come in the channeling mode hits on the scraper edge increasing the losses.

The increase of high efficiency region with the offset growth is explained by the increase of the capture area width for crystal angular alignment; the beam, before or after scattering, can hit that area at the channeling regime. Hence, that increase in the scraper can be derived as follows (fig. 2):

$$\Delta r' = 2\sqrt{R_s^2/\beta_s\beta_c - R_c^2/\beta_c^2} = 2\sqrt{(D^2 + 2DR_{s0})/\beta_s\beta_c}. \tag{5}$$

During the beam guidance the offset value and effective region width depend on the size of the circulating beam, which varies from maximal $R_c = 4$ mm up to 0. In the case of beam halo collimation in the colliders these parameters remain stationary. For further simulations the offset of $D = 4$ mm was selected for the amplitude of protons at a scraper $R_{s0} = 4$ mm that corresponds to the angular region $\Delta r' = 0.6$ mrad (see fig. 3).

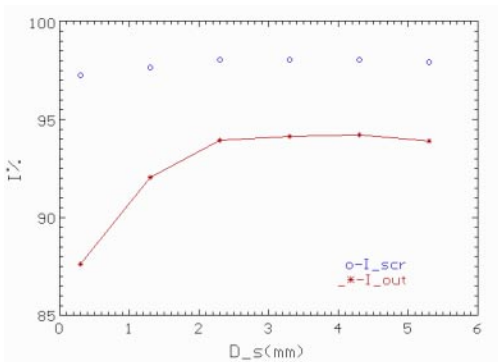

Fig. 4. – Extraction efficiency (curve) and losses in the scraper (dots) *vs.* offset.

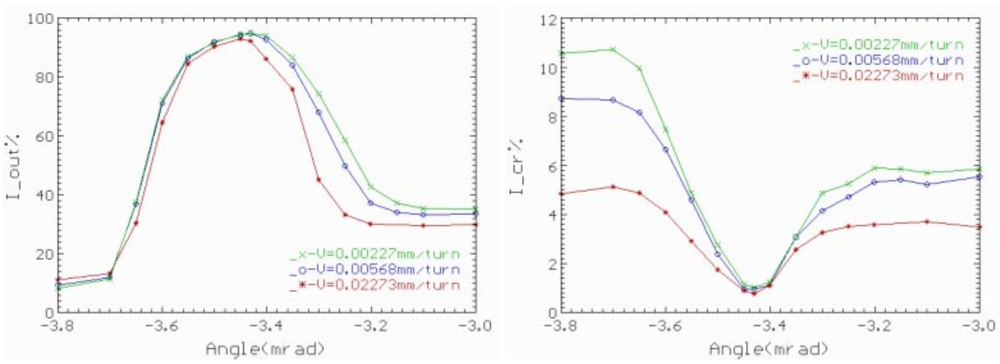

Fig. 5. – Orientation curves of extraction efficiency (a) and losses on the crystal (b) at different velocities of beam guidance.

At large offset it becomes necessary to increase the beam deflection that corresponds to the crystal length increase, which, in turn, increases the losses.

The extraction efficiency also depends on the velocity V of beam guidance towards the crystal. The calculated orientation curves of efficiency and appropriate losses in the crystal at various velocities are presented in figs. 5, 6. At major velocities of guidance the extraction efficiency and area of good efficiency are diminished, that is explained by the fast passage of a beam through the crystal, and, hence, the essential part of protons has no time to be captured in the channeling regime. The losses in the crystal are diminished due to the decrease of the intersection protons multiplicity (fig. 5, b). At optimal crystal position the efficiency starts to decrease at velocities greater than 0.01 mm/turn, from 95% up to 92% at $V = 0.02$ mm/turn.

Further calculations were carried out at velocities of beam guidance of 0.005 mm/turn. It corresponds to the beam collimation during 1000 turns. The extraction efficiency also depends on the bending angle of the crystal (fig. 6).

To deliver protons to the scraper edge the beam should be deflected by an angle of 0.22 mrad. At small bending angles a part of the beam hits on the scraper edge. At large

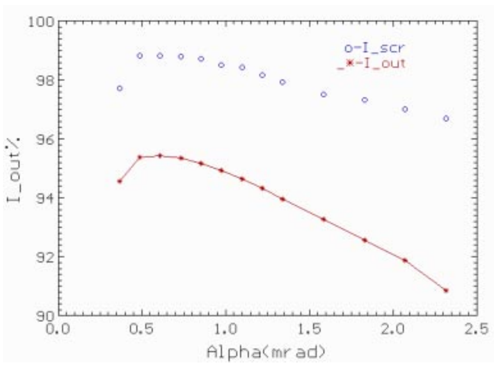

Fig. 6. – Extraction efficiency (curve) and losses in the scraper (dots) *vs.* the bending angle of the crystal with constant bending radius R = 0.82 m.

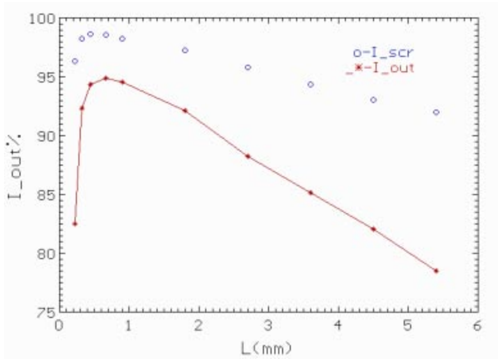

Fig. 7. – Extraction efficiency and losses in the scraper *vs.* crystal length with a constant bend angle 1.1 mrad.

bending angles the length of the crystal has to be increased that, in turn, results in the extraction efficiency drop due to strong Coulomb scattering in the crystal. As seen from the dependence the optimal region of bending angles is 0.5–0.8 mrad. The size of the extracted beam is incremented because of crystal imperfections. It is necessary to take into account that with the increase of the bending angle the area of the crystal alignment is incremented. Therefore, for the collimation and extraction systems of 50 GeV beam the optimum deflection angle will be 0.8 mrad with efficiency of $\sim 95\%$.

At the following step we shall define the influence of the bending radius on the extraction efficiency. The dependences of extraction efficiency and losses in the scraper *versus* the length of a Si crystal (size along the beam) at constant bending angle are shown in fig. 7. For very short crystals the radius of curvature is small $R = L/\alpha$, and the losses are increased because of greater dechanneling. As mentioned above, at large lengths these parameters are growing. The maximal efficiency will be at the crystal length $L = 0.7$–0.8 mm that corresponds to a bending radius $R = 0.6$–0.7 m. The calculations show that for other energies on cyclic accelerators the optimal value of bending radius makes 7–9 critical radii R_{crit}.

The extraction efficiency grows with the increase of crystal thickness (fig. 8). For very thin crystals initially scattered particles in the second turn hit in the area of channeling

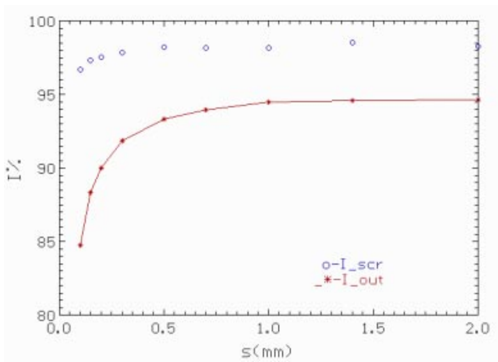

Fig. 8. – Extraction efficiency and losses in the scraper *vs.* crystal thickness (size across the beam).

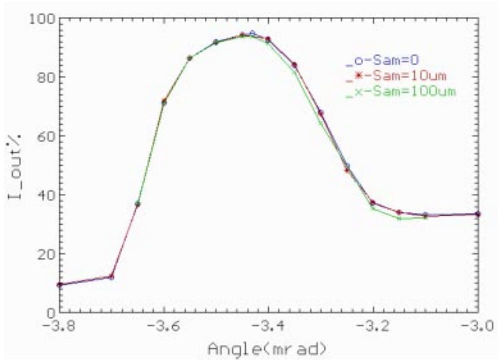

Fig. 9. – The extraction efficiency *vs.* the thickness of the crystal amorphous layer (max crystal thickness equals 1 mm).

capture with smaller probability (fig. 2). At crystal thickness larger than 1 mm the extraction efficiency practically does not vary anymore and reaches $\sim 95\%$.

For such thin crystals the extraction efficiency negligibly increases with the thickness of the amorphous layer of the crystal because of the increasing number of intersections of protons with the crystal (fig. 9). At large thickness of the layer $S_{am} \sim 100\,\mu$m the protons originally interact with the crystal as with a usual amorphous target and increase the amplitude of betatron oscillations. At the following intersections the protons hit mainly in the area of the pure crystal. That is, the average number of intersections N increase at $\Delta N = 1$–2 times and losses in the crystal grow at the value $\Delta I_{\rm cry} = \Delta NL/L_n =$ 0.2–0.4%, because of nuclear interactions. Here L_n is the nuclear length of silicon. The extraction efficiency decreases approximately at this value.

In the presence of torsion in the crystal there is a dependence of the angular position of the crystal on the vertical coordinate $z : \Delta\theta = z \cdot T$. At a vertical beam size of 4 mm and at a rather large torsion parameter $T = 0.02$ mm/mrad the maximal deviation will make $\Delta\theta_{\max} = \pm 0.08$ mrad, that will negligibly reduce the beam efficiency and increase the radial beam size in the scraper. For comparison in fig. 10 the orientation curves of efficiency for ideal and with torsion crystals are shown. The small extension of the alignment area because of the presence of torsion is visible.

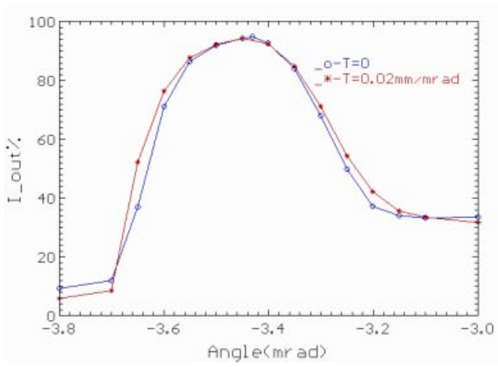

Fig. 10. – Dependence of extraction efficiency on torsion parameter.

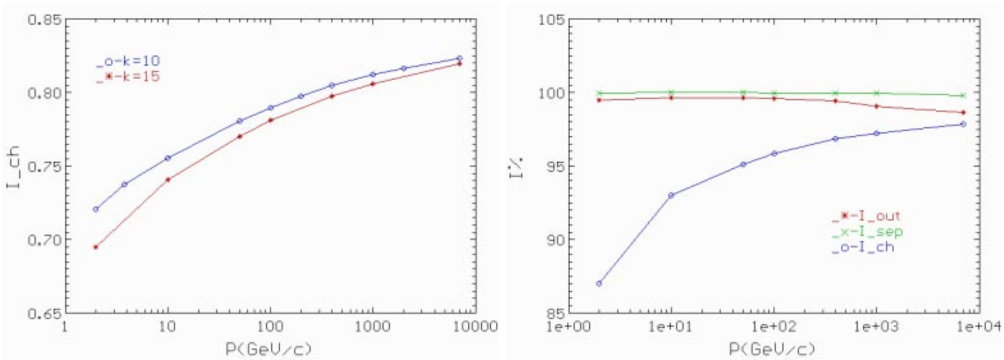

Fig. 11. – The intensity of channeling fraction *vs.* proton momentum at single passage (a) and at slow extraction due to multiturns (b).

Influence of other imperfections of the crystal, such as miscut angle and twist parameter, on the extraction efficiency in U-70 also are negligible, because the value of step size at the beam guidance reaches $\sim 50\,\mu\text{m}$, that is significantly more than the area where these effects work.

4. – Influence of beam energy on the extraction efficiency

Calculations and experiments of beam collimation in cyclic accelerators having different proton beam energy and distinguished by magnetic structure in an installation site of system elements were recently produced [2-6]. Let us consider the problem of influence of main beam parameters (energy and sizes) on the extraction efficiency. For sufficient step size of the beam in the scraper or in the septum the necessary deflection angle of protons by the crystal (see (2)) is

$$\alpha = k\sigma/\beta = k\sqrt{\varepsilon_0/PV\beta}, \tag{6}$$

where the parameter $k = 10$–15, ε_0 is the normalized beam emittance at rms level, P and V are the momentum and velocity of protons. Optimal crystal radius, as was shown earlier, can be expressed through the interplanar distance d and potential: $R_{\text{opt}} = 1.5dPV/eU_{\max} \approx 8R_{\text{crit}}$. For a silicon crystal with the planar orientation (110) the potential energy is equal to $eU_{\max} = 21.4\,\text{eV}$, then the optimal radius and length of a crystal will be defined as

$$R_{\text{opt}} = 0.0135PV, \quad L = \alpha R_{\text{opt}} = 1.16\sqrt{\varepsilon_0 PV/\beta}. \tag{7}$$

The dependences of the intensity of the channeling fraction on the proton momentum at parameters $k = 10$–15 in the case of a single passage are presented in fig. 11(a). In calculations the characteristic emittance $\varepsilon_0 = 3\,\text{mm}\cdot\text{mrad}$ and beta function $\beta = 100\,\text{m}$ were taken.

At multiple interaction with the crystal a considerable part of the originally scattered beam hits in the channeling mode. Then the extraction efficiency can be presented as $I = I_1 + (1 - I_1)\cdot\eta$, where the parameter $\eta = 0.7$–0.9 is the probability of the secondary capture in the channeling regime and it increases with the growth of energy. As a result of slow extraction the intensity of the channeling fraction (fig. 11 a, b; $I_{\rm ch}$) will increase up to 87% for low energies ($P = 2\,{\rm GeV}$) and up to 98% for maximal energy of protons (LHC). Except for the channeling fraction, other fractions (mainly the dechanneling one) also hit in the gap of the septum magnet. In the total the extraction efficiency $I_{\rm out}$ can reach 99%. All the protons $I_{\rm sep}$ practically hit in the septum except the nuclear interacted ones with the crystal ($I_{\rm cry} = 0.05$–0.25%). The quantity of losses on the septum partition (in calculations $\delta = 1\,{\rm mm}$ can be found from the difference of two values $I_{\rm d} = I_{\rm sep} - I_{\rm out}$ which gives $\sim 0.3\%$ at low and average proton energies and $\sim 1\%$ at high ones. Thus, with the use of channeling in beam collimation systems the density of protons at the edge of collimator equals $D = 0.003$–$0.01\,{\rm p/mm}$, which is two orders less than in traditional systems with an amorphous scattering target [8]. So, the crystals enable increasing the efficiency of particles interception by 20–50 times.

As follows from dependence (7) the optimal length of a crystal increases with the increase of particle energy as $\sqrt{\gamma}$. At small energies the optimal crystals are very short. Even for 400 GeV protons (SPS) the length of the optimal crystal is equal to 0.8 mm, and for energy 1 TeV (FNAL) it becomes equal to 1.3 mm. From dependence (7) it also follows that for large beta function and small beam emittance a shorter crystal is necessary, resulting finally in more extraction efficiency. For the ideal optimal crystal the extraction efficiency will reach $\sim 99\%$ at the energy 10–1000 GeV and 98% at 7000 GeV. The decrease of efficiency at higher energies is explained by the increase of nuclear losses because of growing length of the crystal.

Finally, basing on the presented simulations we can conclude that geometrical parameters of bent crystals (length, width and bend angle) affect the extraction/collimation process more essentially than crystal production details, like the amorphous layer and the miscut. The above-mentioned recommendations open new possibilities to improve the crystal extraction/collimation schemes.

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