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Colloquia: Channeling 2010

New approaches to the crystal collimation

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Summary. — Possibilities of application of the effects of multiple volume reflection in one crystal and of the channeling efficiency increase by the crystal cut or buried oxide layer are applied for the first time to the problem of crystal collimation. It is demonstrated that both these effects decrease the nuclear reaction rate in the crystal scraper and increase the average impact parameter of collisions of deflected protons with an absorber. However the crystal cut is efficient at precise crystal orientation corresponding to the channeling conditions while the MVROC effect can be applied at relatively rough crystal alignment.

PACS 29.27.-a – Beams in particle accelerators.
PACS 61.85.+p – Channeling phenomena (blocking, energy loss, etc.).
PACS 41.75.-i – Charged-particle beams.

1. – Introduction

Particle deflection in bent crystals can greatly enhance the collimation efficiency at the LHC and other modern accelerators. The UA9 experiment dedicated to the study of crystal collimation of a stored beam has been started at CERN [1]. Though both the channeling and volume reflection effects are already used in crystal collimators, further possibilities to increase the efficiency of both these effects exist.

First, either the microscopic crystal cut [2] or the buried oxide layer [3] can be applied to increase the probability of proton capture into the channeling regime up to 99%. In this paper we present the results of the first simulations of the SPS stored beam collimation by the crystal with cut demonstrating a tenfold decrease of the nuclear reaction rate in the collimator. A technique of fabrication of the necessary micrometer-size cuts is being developed by the Sensor and Semiconductor Laboratory of Ferrara University.

The largest increase in collimation efficiency is reached at the cost of a very precise crystal-beam alignment. It is commonly accepted that, for safety reasons, high-efficiency

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crystal collimators which need a precise alignment should be used in parallel with amorphous ones which do not need it. However the crystal collimators based on the volume reflection (VR) effect also need much less precise alignment than that using channeling. The recently predicted effect of multiple VR from different planes of one crystal [4], observed at the SPS [5] and studied in further detail in [6], allows to increase the VR angle about five times. Therefore the crystal collimators using the effect [4-6] are also good candidates for the use in parallel with channeling-based collimators for safety and reliability reasons. The results of first simulations of collimators using the multiple VR in one crystal are also discussed in this paper for the first time.

2. – Increase of the probability of particle capture into the channeling regime

The channeling phenomenon in bent crystals has been long studied to steer charged-particle beams. The fraction of particles being deflected by the crystal over the total flux of the particles traversing the latter is restricted by an incomplete beam capture into the regime of stable channeling motion occurring at the entry face of the crystal. The maximal observed value for the probability of positively charged particle capture is close to 85% [7] being limited by the strong nuclear and electron scattering in the regions $|x| < x_c$, where $x_c = 0.15 \sim 0.20\,\text{Å}$ is the critical approach distance measured from the crystal plane position.

The channeling phenomenon is effectively treated in terms of the averaged potential concept. The averaged planar potential $V(x)$ (potential energy, rigorously speaking) is obtained by an atomic potential averaging along the plane (and also over the thermal vibrations) and depends only on the transverse coordinate x measured along the normal to the planes. The $V(x)$ translational invariance ensures the conservation of the transverse energy $\varepsilon_\perp = \varepsilon v_x^2/2 + V(x)$, where ε and $v_x = v_x(x)$ are the total particle energy and velocity (measured in c units) at point x, respectively. The planar channeling is a limited transverse motion which occurs if $\varepsilon_\perp \leq V_{\max}$, where $V_{\max}$ is the maximal value of the averaged potential.

The $\varepsilon_\perp$ conservation, however, is violated by the difference of the real intracrystal potential from the averaged one. This difference is most pronounced in the regions of maximal nuclear and electron number densities like the region $|x| < x_c$ near the plane situated at $x = 0$. If a particle has sufficiently large transverse energy $\varepsilon_\perp \geq 0.5V_{\max}$ it regularly reaches such a region and experiences a strong incoherent scattering on both nuclei and electrons causing a fast $\varepsilon_\perp$ increase leading to the particle dechanneling. However the particles with $\varepsilon_\perp \leq 0.5V_{\max}$, unable to reach the regions with high nuclear and electron number densities, experience a continuous stable channeling motion.

Unfortunately, the initial transverse energy $\varepsilon_\perp = \varepsilon v_{x0}^2/2 + V(x_0)$, which a particle acquires entering the crystal, cannot be considerably less than $V_{\max}$ in the incidence regions $|x_0| \leq x_c$ even if the initial transverse velocity v_{x0} is minimal. Such particles inevitably dechannel leading to the limitation of the probability of particle capture into the regime of stable channeling motion by the mentioned value of 85%. However a fast $\varepsilon_\perp$ reduction caused by the special type violation of the planar potential translational invariance could improve the situation.

A corresponding method of increase of the particle capture probability into the regime of stable channeling motion was recently suggested [2]. It consists in placing a very thin "focusing" crystalline plate parallel to the entry face of the crystal that channels the particles. The plate must have the same inter-planar periodicity as the crystal and be perfectly aligned with it. Intuitively, such a combination may be realized by performing

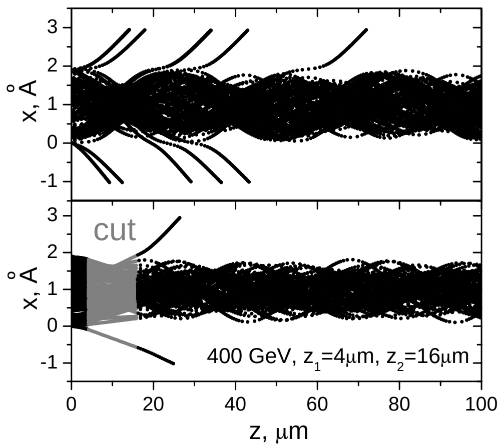

Fig. 1. – The facilitation of 400 GeV proton capture into the channeling regime by the cut, situated between 4 and 16 μm, or by a buried 400 nm amorphous layer applied under the conditions of an oblique incidence at $\alpha \simeq 0.033$ rad.

a cut parallel to the entry surface of a crystal, *i.e.*, by removing the atoms between $z = z_1$ and $z = z_2$. Thereby, a common crystalline structure is realized at $0 \le z \le z_1$ and $z \ge z_2$. The dynamics of the particles entering the crystal near the maxima of the planar potential is such that a decrease in the transverse kinetic energy $\varepsilon_\perp$ occurs.

The mechanism of transverse energy compaction can be explained as follows [2]. Let us consider a "ready to dechannel" particle with $V(x_0) \simeq V_{\max}$ and $|v_{x0}| < 0.25\sqrt{2V_{\max}/\varepsilon}$. As the particle crosses the thin crystalline plate $[0, z_1]$, it experiences a force directed towards a $V(x)$ minimum. However, the interaction time in this region is so short that the particle does not reach the potential minimum and acquires only a transverse velocity $v(x_1)$ which satisfies the condition $|v(x_0)| < v(x_1) < 0.5\sqrt{2V_{\max}/\varepsilon}$. As the particle exits the plate at $z = z_1$, both the potential energy $V(x)$ and local crystal field vanish and the transverse velocity component $v(x_2) = v(x_1)$ remains unchanged until the crystal bulk is reached at $z = z_2$. The width $z_2 - z_1$ should be chosen in such a way that the particle re-enters the crystal at $z = z_2$ close to the potential minimum, acquiring a potential energy $V(x_2) < 0.25V_{\max}$. Since the particle approaches the re-entrance point (x_2, z_2) with the reduced kinetic energy $0.5\varepsilon v^2(x_2) < 0.25V_{\max}$, the total transverse energy $\varepsilon_\perp(z_2) = 0.5\varepsilon v^2(x_2) + V(x_2)$ decreases at least down to $0.5V_{\max}$ ensuring, thus, a further stable channeling motion at $z > z_2$.

The described proton motion within $0 \le z \le z_2$ resembles that on a quarter of the channeling oscillation length λ. The method assumes the width of the empty space $z_2 - z_1$ to range between $z_2/2$ and $2z_2/3$ (depending considerably on the inevitable incident beam angular divergence), and the plate thickness z_1 between $z_2/3$ and $z_2/2$, namely $z_2 - z_1 \in [\lambda/8, \lambda/6]$ and $z_1 \in [\lambda/12, \lambda/8]$, which correspond to tens of micrometers at the LHC energy of $\varepsilon = 7$ TeV and to $z_1 = 4\,\mu$m and $z_2 = 16\,\mu$m at the SPS energy—see fig. 1. At such high energy the fabrication of a crystal with an empty space between z_1 and z_2 can be accomplished through photolithography. However the width of the empty space scales with λ nearly proportionally to $\sqrt{\varepsilon}$ and at lower energies the photolithography becomes inefficient. To circumvent this problem, the placing of a thin amorphous layer between z_1 and z_2 to play the same role as the empty space was suggested [6]. The layer can be reliably fabricated through the Separation by IMplanted OXygen (SIMOX) technique [8]. The influence of the particle scattering in the buried amorphous Si layer on its focusing effect becomes negligible starting from hundreds of MeV [6]. Note that an oblique particle incidence at an angle $\alpha < \pi/2$ on the entrance crystal plane and the buried amorphous Si layer, parallel to the latter, allows to effectively increase the plate and layer thicknesses proportionally to $\csc\alpha$, making it possible to use the most readily available SIMOX wafers with $z_2 - z_1 \simeq 400\,\mathrm{nm}$ in a wider interval of particle energies, including that of the SPS at $\alpha \simeq 0.033\,\mathrm{rad}$—see fig. 1. Another, even more important advantage of an oblique particle incidence, allowing to effectively increase the thicknesses of the thin plate and either the cut or buried amorphous layer, is the possibility to use the same crystal in a wide energy region, including the whole interval 450 GeV–7 TeV of proton acceleration at the LHC.

The main idea of this paper is to apply the possibility of increase of the probability of capture into the channeling regime by the cut or buried amorphous layer as well as by the effect of multiple volume reflection from planes of one bent crystal (MVROC) to the problem of beam collimation. Remind that VR occurs as a particle trajectory becomes tangential to a bent crystalline plane [9]. Since a crystalline axis is parallel to the line of intersection of various crystal planes, a reflection from most of them becomes possible as a proton moves at a small angle with respect to such an axis [4]. This MVROC effect increases the total particle deflection angle about five times [5,6] and is described in more detail in these proceedings [10].

3. – Performance of the new types of crystal collimators

Modern accelerators use the two-stage collimator scheme, the primary scraper of which deflects the halo particles to an absorber. If a bent crystal is used as the scraper, both the channeling and VR effects can be applied to facilitate the particle deflection to the absorber. Namely the nuclear reaction rate in the scraper decreases while the average particle impact parameter to the absorber increases. The first crystal collimation experiment [1] has recently demonstrated the former effect.

To widen the benefits of the crystal scraping we suggest to apply both the crystal cut and MVROC. To make a comparison with the "normal" crystal scraper we undertook the simulation for both the layout of the experiment [1] and 1 mm crystal length along the beam. The crystal bending radius R was chosen equal to 6.67 m both for the normal crystal and the crystal with cut and to 2 m for the crystal with the MVROC orientation. The channeling plane (110) was chosen to be normal to the bending plane of both the normal crystal and crystal with cut.

To choose the optimal orientation of the MVROC scraper we proceed from the fact that the optimal conditions for the 120 GeV proton MVROC in a crystal with $l = 1\,\mathrm{mm}$ and $R = 2\,\mathrm{m}$ arise at the incidence angles $\Theta_{X0} \simeq 275\,\mu\mathrm{rad}$ and $\Theta_{Y0} \simeq 100\,\mu\mathrm{rad}$ with respect to the $\langle 111\rangle$ axis. To make the MVROC efficient in all the experimental VR angular interval we chose the mentioned optimal MVROC orientation to correspond to the normal crystal scraper rotation angle $\theta_{\mathrm{cr}} = -70\,\mu\mathrm{rad}$. Thus, the angle of MVROC scraper rotation in the bending plane, measured from the direction of its vertical $(1\bar{1}0)$ plane at the entrance surface, will be equal to $\theta_{\mathrm{cr}} = -205\,\mu\mathrm{rad}$. The positive rotation direction coincides with that of crystal bending in all the cases.

The simulated dependences of the fraction of particles lost in inelastic reactions in the crystal scraper *versus* the crystal rotation angle are shown in figs. 2 and 3 for the normal crystal, crystal with cut and crystal in MVROC orientation. The normal crystal curve demonstrates the same behavior as that in ref. [1] with the dip corresponding to the most

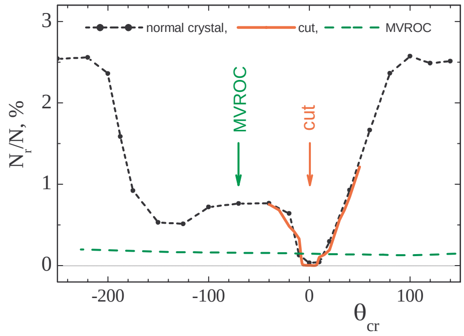

Fig. 2. – Inelastic loss fraction as a function of the angle $\theta_{\rm cr}$ of crystal rotation in the horizontal plane in a normal crystal with $R = 6.67\,{\rm m}$ (short dash), a crystal with the cut between 2 and $8\,\mu{\rm m}$ and $R = 6.67\,{\rm m}$ (solid) and a multiply reflecting crystal with bending radius $R = 2\,{\rm m}$ and the $\langle 111 \rangle$ axis forming the angles $-\Theta_{X0} = \theta_{\rm cr} - 205\,\mu{\rm rad}$, $-\Theta_{Y0} = -100\,\mu{\rm rad}$ with the channeling beam direction (long dash).

efficient deflection of channeled protons, the plateau in the region $-180 < \theta_{\rm cr} < -20\,\mu{\rm rad}$, corresponding to the VR manifestation, and that at the level of 2.5% corresponding to practically amorphous-type scattering. The "crystal with cut curve" demonstrates an order of magnitude deeper "channeling dip" directly explained by the increase of probability of proton capture into the channeling regime by the cut. The "MVROC curve", on the opposite, is distinguished by its stable behavior near the inelastic loss level lying in between the channeling dip and the VR plateau of the "normal crystal" curve. Such a behavior reflects the high deflection efficiency of the MVROC effect in a wide angular region [6].

The cut, in fact, facilitates the collimation efficiency in quite a complementary way to the MVROC effects. Namely, the former needs very precise crystal fabrication and alignment and allows to improve the normal crystal collimator functioning only near the perfect channeling alignment. The MVROC effect, on the contrary, allows to improve the collimation efficiency in the angular interval comparable in width with that of the VR effect manifestation. Such a complementarity makes reasonable a simultaneous use of the collimators based on the cut and MVROC effects.

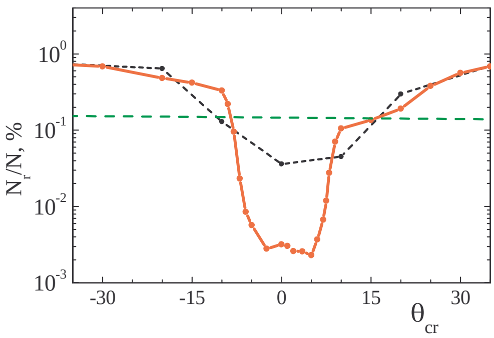

Fig. 3. – The same as fig. 2 for a narrow angular interval near the channeling crystal orientation.

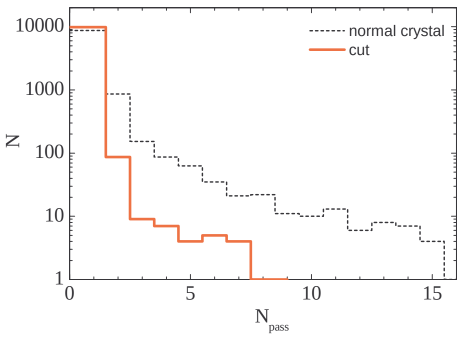

Fig. 4. – Distribution of the number of crystal crossings before hitting the absorber in normal Si crystal (dashed) and crystal with cut between 2 and 8 μm (solid), $R = 6.67$ m, $l = 1$ mm. The cut decreases the crystal crossing number.

Let us dwell on a detailed comparison of the different types of crystal collimators. Figures 4 and 5 allow to compare a normal crystal and "the cut" scrapers in the case of perfect channeling alignment. Figure 4 presents the proton distribution in a number of crystal scraper crossings before hitting the absorber. One can see that the "cut collimator" deflects about 99% of the protons to the absorber at the first crossing. The numbers of protons which experience more crossings also decreases fast with the number of the latter. Figure 5 presents the distribution of the proton impact parameters with the absorber demonstrating a great decrease in the number of protons hitting the absorber with small impact parameters by the "cut scraper".

Since the "MVROC collimator" is applicable in a wide angular region it will be natural to compare its performance with that of the normal crystal collimator at a rough alignment for the representation of which we chose the normal crystal orientation at $\theta_{\rm cr} = -70\,\mu$rad, corresponding to the proton incidence at the horizontal angle $\Theta_{X0} = 70 + 205 = 275\,\mu$rad to the $\langle 111 \rangle$ axis of the "MVROC scraper". Figure 6 demonstrates how the MVROC scraper decreases the number of scraper crossings, while fig. 7 illustrates the decrease of the number of protons hitting the absorber near its edge.

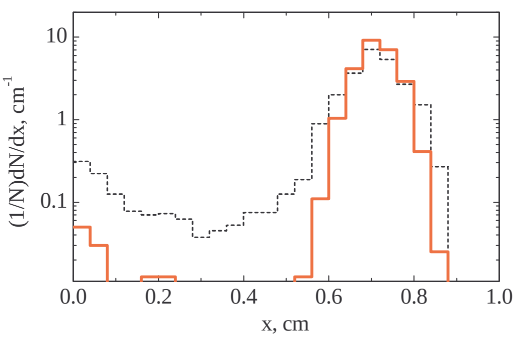

Fig. 5. – Distribution of the impact parameter of an absorber hit under the same conditions as fig. 4. The cut diminishes the number of protons hitting the absorber near its edge.

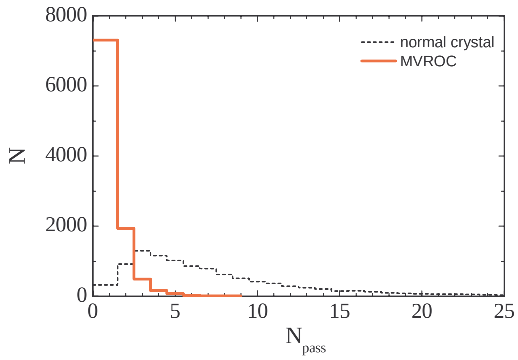

Fig. 6. – Distribution of the number of crystal crossings before hitting the absorber in usual Si crystal oriented with $\theta_{\rm cr} = -70\,\mu$rad (thin dashed), and in the multiply reflecting crystal with bending radius $R = 2$ m and the $\langle 111 \rangle$ axis forming the angles $\Theta_{X0} = -275\,\mu$rad, $\Theta_{Y0} = -100\,\mu$rad with the channeling beam direction. MVROC process decreases the crystal crossing number.

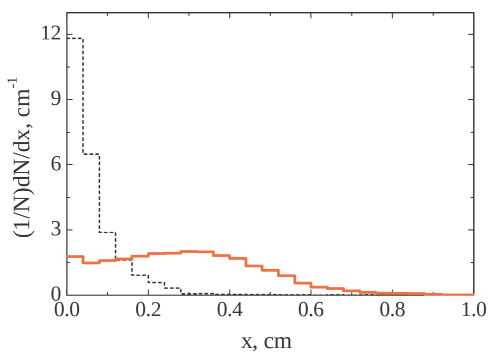

Fig. 7. – Distribution of the impact parameter of the absorber hit under the same conditions of fig. 6. MVROC process considerably increases the average impact parameter.

4. – Conclusions

In summary we have demonstrated that the increase of both the probability of proton capture into the channeling regime by either crystal cut or buried amorphous SiO_2 layer and the proton deflection angle by the multiple volume reflection in one crystal can improve the efficiency of the primary crystal scraper of the two-stage collimator system. The crystal cut should be used at precise crystal orientation corresponding to the channeling condition while the MVROC effect, on the contrary, at relatively rough crystal alignment. Both the crystal cut and MVROC scrapers can drastically reduce both the number of their proton crossings and that of protons which hit the absorber near its edge.

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