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Observation of channeling for 6500 GeV/c protons in the crystal assisted collimation setup for LHC

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ABSTRACT

Two high-accuracy goniometers equipped with two bent silicon crystals were installed in the betatron cleaning insertion of the CERN Large Hadron Collider (LHC) during its long shutdown. First beam tests were recently performed at the LHC with 450 GeV/c and 6500 GeV/c stored proton beams to investigate the feasibility of beam halo collimation assisted by bent crystals. For the first time channeling of 6500 GeV/c protons was observed in a particle accelerator. A strong reduction of beam losses due to nuclear inelastic interactions in the aligned crystal in comparison with its amorphous orientation was detected. The loss reduction value was about 24. Thus, the results show that deflection of particles by a bent crystal due to channeling is effective for this record particle energy.

1. Introduction

In the Large Hadron Collider (LHC), a multi-stage collimation system is used to absorb a growing halo of the circulating beams and to ensure a reliable operation below quench limits of superconducting magnets [1]. LHC primary collimators made from Carbon Fibre Composites (CFC) deflect halo particles by Coulomb scattering, thus increasing their impact parameters with secondary collimators. Proton interactions with the collimator material generate diffractive protons that may leak out of the collimators and be lost in cold magnets, limiting the cleaning performance of the present collimation system. A bent crystal used instead of primary amorphous collimators deflects most particles by means of channeling, directing them far from the secondary collimator edge. As a result the leakage of diffractive protons from both collimators should be strongly reduced, thus the collimation efficiency should be increased.

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Experiments on the beam halo collimation with short bent crystals have been performed at the IHEP synchrotron [2], RHIC [3] and Tevatron [4]. In the last case, the background in the CDF experiment was reduced by a factor of two by using a crystal as a primary collimator. A crystal assisted collimation scheme for LHC was under study in [5,6].

The experiment UA9 studying crystal assisted collimation at the CERN Super Proton Synchrotron (SPS) [7–11] showed strong reduction of the collimation leakage when the crystal deflector is in channeling conditions [11]. Perfect alignment of the crystal to have deflection of halo particles due to channeling was always obtained quickly by using information from the beam loss monitors (BLM) installed downstream of the crystal. Channeled particles with small oscillation amplitudes in the crystal planar channels do not have close collisions with the nuclei in the crystal, and, consequently, do not experience nuclear interactions. Therefore, the beam losses in the aligned crystal are strongly decreased in comparison with the case of its amorphous orientation.

The SPS experiments were performed with stored beams of protons and Pb ions with 120 GeV/c and 270 GeV/c momentum per charge. The collimation leakage was measured by the beam loss monitor installed in the first high dispersion (HD) area downstream of the collimator–absorber, where off-momentum particles have the first possibility to hit the beam pipe after interacting with the crystal and the absorber. With the crystal perfectly aligned, the rate of the beam loss monitors was reduced by at least an order of magnitude [11].

Two piezoelectric goniometers equipped with bent silicon crystals were recently installed in the Ring 1 of the LHC in its betatron cleaning insertion, IR7. In this letter the results of the first beam tests with bent crystals at the LHC are presented. Channeling was observed with proton beams at injection and collision energies. This observation opens new roads for high-energy beam manipulation in hadron colliders.

2. The experiment description

A particle can be captured into the channeling regime if the angle between its momentum p (velocity v) and the crystal planes is smaller than the critical angle $\theta_c = (2U_o/pv)^{1/2}$, where U_o is the well depth of the crystal potential averaged along the planes [12]. For the (110) planar channels of a silicon crystal at a room temperature, $U_o = 22.7$ eV and for 6500 GeV/c protons $\theta_c = 2.6$ μrad. The Moliere approach for the atomic potential is used here and in our simulations of the crystal assisted collimation presented below. This imposes challenging requirements to the angular control of the crystals that has to be in the sub-microradian angular resolution range.

The present setup for studying crystal assisted collimation was designed with a minimum impact on the LHC collimation system. Layout and the crystal parameters were chosen such that existing secondary collimators can be used to intercept the channeled beams [13]. Two piezo-goniometers with bent silicon crystals for horizontal and vertical collimation of the LHC beam have been installed according to the recommendations [13] in Ring 1 of the betatron cleaning insertion of the LHC during its long shutdown in 2014. Goniometers which satisfied the high requirements of sub-microradian angular resolution were developed [14]. Some relevant goniometer parameters are presented in Table 1. An important feature of the goniometer design is its complete transparency for the normal LHC operations. This is ensured by a movable segment of the beam pipe that masks the crystal and the goniometer itself. It is remotely retracted only during the special collimation tests, to allow the crystal insertion. The goniometers were mounted on standard collimation supports using the same fast plug-in technology, which ensures fast handling of the object in the tunnel.

Table 1
Relevant goniometer parameters.

Angular range (mrad)	Angular resolution (μrad)	Linear range (mm)	Linear resolution (μm)
10	0.1	40	5

Table 2
Parameters of the ST crystal after its production.

Length (mm)	Bend angle α (μrad)	Torsion (μrad/mm)	Miscut angle θ_m (μrad)
4.1	52	< 1	6

The value of the crystal bend angle was chosen for reasons of obtaining the maximal impact parameters of deflected halo particles with the collimator–absorbers while ensuring that the deflected halo should remain at a safe distance from the beam pipe [13]. The bend angle of the crystal for the LHC beam collimation was selected to be $\alpha = 50$ μrad from these considerations. This bend angle value α can be realized with different crystal length L and consequently with different bend radius R, $L = \alpha R$. However, the bend radius should be considerably larger than the critical one [15] $R_c = pv/eE_{max}$, where E_{max} is the maximal strength of the planar electric field. For protons with 6500 GeV/c momentum, $R_c = 11$ m in the (110) silicon channels. The channeling efficiency of protons for the crystal with a given bend angle α, considering the possibility of their multiple passages through the crystal, is maximal when its bend radius R is in the interval $(3\div10)R_c$. The length of the LHC crystals was chosen to be $L = 4$ mm, that is their bend radius $R = 80 \text{ m} \approx 7R_c$.

Two different methods for the crystal bending were used. A silicon strip (ST) crystal bent along the (110) planes due to anticlastic deformation [16,17] was installed for the LHC beam collimation in the horizontal direction. A QM crystal bent along the (111) planes due to the quasi-mosaic effect [18] was installed for the collimation in the vertical plane. The bending devices of both the crystals were made from titanium to reduce possible electron emission from them when the LHC proton bunches pass the azimuths of their location. Table 2 reports the main parameters for the ST crystal at the manufacturing stage. The studies described below show that the bend angle of the ST crystal increased to 65 μrad in comparison with its design value. This issue, now understood, will be discussed in a separate publication.

Fig. 1 shows the horizontal projection of the trajectory of a halo particle deflected by the strip crystal due to channeling at the bend angle $\alpha = 65$ μrad (solid line): (a) for the beam injection with 450 GeV/c, (b) for the maximum momentum 6500 GeV/c. A dashed line shows the beam envelope at $5.4\sigma_x$. This value corresponds to the operational position of the crystals in the measurements described below. Collimators of the LHC multi-stage cleaning system have horizontal, vertical and skew (45°) orientations. The vertical lines show the longitudinal positions of primary collimators (TCP) and secondary collimators made from CFC (TCSG) as well as the shower-absorber collimators made from a tungsten heavy alloy (TCLA). All horizontal and skew collimators are shown in Fig. 1. However, information is presented below only for the horizontal collimators behind the crystal, which are relevant for our experiment. Few collimators instead of a larger one are used because the beam energy absorption should be allocated between them to reduce their heating. TCSG and TCLA collimators were placed at about $7\sigma_x$ and $10\sigma_x$, respectively, in the injection case and at about $8\sigma_x$ and $14\sigma_x$, respectively, in the top momentum case. The positions of the beam loss monitors BLM_1 and BLM_2 for mea-

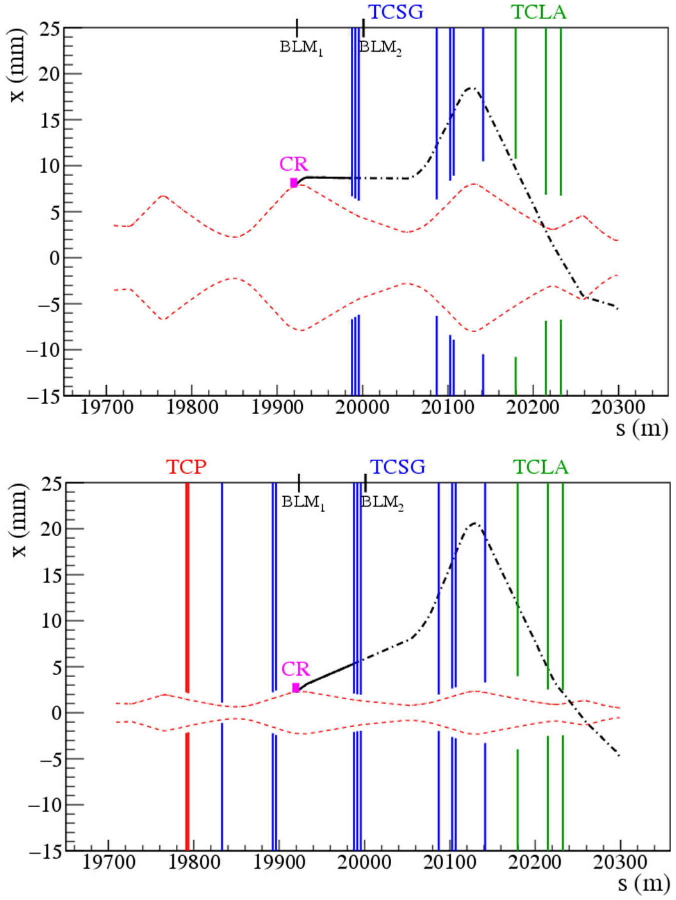

Fig. 1. (Color online.) The horizontal projection of the trajectory of a halo particle deflected by the crystal due to channeling at the bend angle $\alpha = 65$ μrad (solid line up to the first horizontal TCSG$_1$ and then by dot-dashed line to show the trajectory propagation in the case without the collimators): (a) for the beam injection with 450 GeV/c, (b) for the maximum momentum of 6500 GeV/c. Dashed lines show the beam envelope for the crystal distance from the orbit. Vertical lines show the positions of the collimators TCSG and TCLA and the primary collimators TCP (they are not visible for the injection case because they were shifted far from the orbit for the measurements). The positions of BLM$_1$ and BLM$_2$ for measuring the losses in the crystal and in the first horizontal TCSG$_1$ behind the crystal, respectively, are shown schematically.

Table 3
Relevant accelerator parameters.

Parameter	BC	TCSG$_1$	TCSG$_2$	TCLA$_1$	TCLA$_2$	TCLA$_3$
β_x (m)	342.98	141.22	338.96	161.71	66.20	64.12
σ_x (mm)	0.416	0.267	0.414	0.286	0.183	0.180
x_{im} (mm)		3.2	16	8	2.5	−0.2
$\Delta\mu_x$ from BC (2π)	0	0.0443	0.3166	0.3425	0.3979	0.4456

suring the losses in the crystal and in the first horizontal TCSG$_1$ downstream the crystal, respectively, are also shown. The relevant accelerator parameters at the azimuths of the crystal and the horizontal collimators behind the crystal are listed in Table 3, where β_x is the horizontal beta-function, σ_x is the RMS value of the horizontal beam size (for the beam of 6500 GeV/c protons with the RMS normalized emittance $\varepsilon^* = 3.5$ μm rad), x_{im} is the impact parameter with the collimators for a particle deflected by the crystal with 65 μrad, and $\Delta\mu_x$ is the horizontal phase advance between the crystal and collimators, TCSG$_1$ and TCSG$_2$ are two horizontal collimators behind the crystal.

Table 4
Collimator positions in units of RMS beam size.

	Nominal		Crystal MD	
	Injection (σ_x)	Flat top (σ_x)	Injection (σ_x)	Flat top (σ_x)
TCP	5.7	5.5	out	8.0
TCSG	6.7	8.0	6.7*	8.0
TCLA	10	14	10	14
CRY	out	out	5.4	5.4

* TCSGs upstream of the crystal are in out positions.

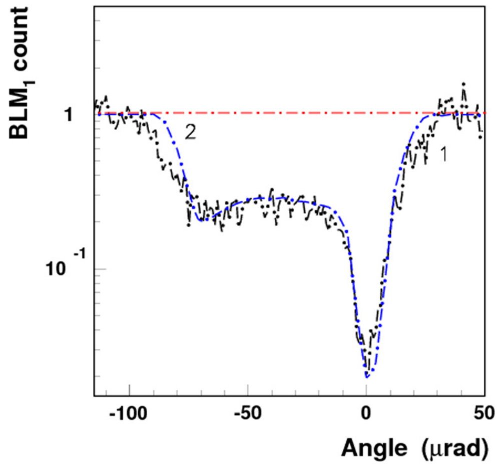

Fig. 2. (Color online.) The dependence of the beam losses observed with the BLM$_1$ downstream of the crystal (curve 1) for the injection case with 450 GeV/c protons. Curve 2 shows the dependence of the number of inelastic nuclear interactions of protons in the crystal on its orientation angle obtained by simulation.

3. Experimental results

A single bunch with 10^{11} protons was injected in our first run on the LHC collimation studies with bent crystals. At the beginning all collimators of IR7 were placed at their standard injection settings: the primary collimators (TCPs) at $5.7\sigma_x$, the secondary collimators (TCSGs) at $6.7\sigma_x$ and the absorbers (TCLAs) at $10\sigma_x$. The crystal was aligned precisely to the circulating beam and set at the TCP opening. Then the crystal was moved by 0.5 mm (about $0.3\sigma_x$) towards the beam orbit to become the primary collimator. In this position angular scans with the crystal were performed with the collimators settings listed in Table 4. As mentioned above, well-channeled particles do not experience nuclear interactions, therefore the channeling orientation of the crystal may be found through the beam loss reduction in the crystal. This loss reduction was indeed observed with the BLM downstream the crystal – BLM$_1$. Three angular scans were made and in all of them the crystal orientation for channeling was about the same. Two first scans were made with a goniometer rotation speed of 0.5 μrad/s when all collimators upstream the crystal were in their standard injection positions. One scan was performed with 1 μrad/s rotation speed when all collimators upstream of the crystal were retracted.

For the last case, curve 1 in Fig. 2 shows the observed dependence of the BLM$_1$ count on the angular position of the crystal at 450 GeV/c. The dot-dashed line shows the loss level for the crystal orientations far from alignment with the (110) planes, when it works as an amorphous substance (“amorphous” orientation). The losses are normalized to the beam flux and the loss value for the amorphous orientation. Curve 2 shows the number of inelastic nuclear interactions of protons in the crystal as a function of the crystal orientation angle obtained by simulations. They were done with the tools described in [19] by adding also the interaction with

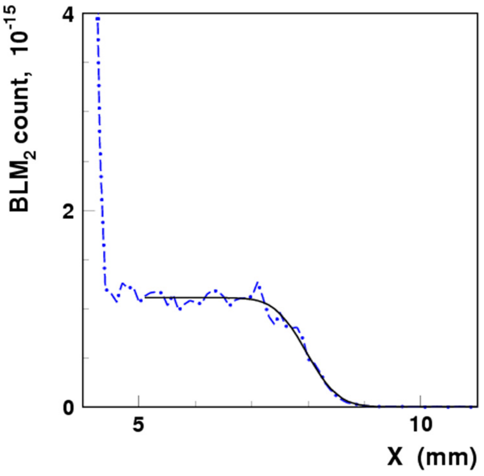

Fig. 3. (Color online.) The dependence of the BLM$_2$ signal on the horizontal position of the first TCSG$_1$ behind the crystal during its scan from the beam periphery towards the orbit ($X = 0$) is shown by dot-dashed line. The crystal angular position was fixed to be in the optimal conditions for channeling. The error function fit is shown by the solid line.

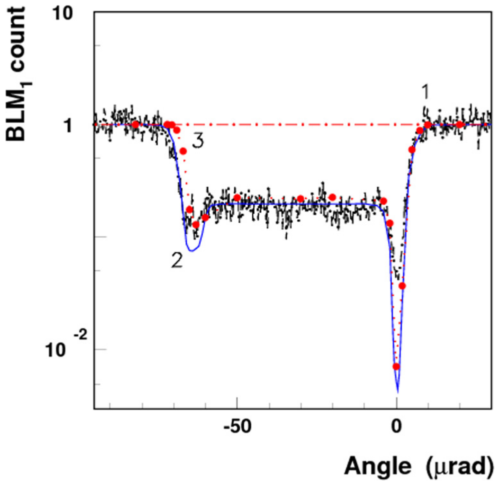

Fig. 4. (Color online.) The dependence of the beam losses observed with the BLM$_1$ downstream of the crystal (curve 1) for the LHC coasting beam of 6500 GeV/c protons. Curves 2 (solid line) and 3 (dotted line) shows the dependence of the number of inelastic nuclear interactions of protons in the crystal on its orientation angle obtained by simulation according to [19] and [13], respectively.

other collimators relevant for the experimental setup, taking into account ionization losses, multiple Coulomb scattering and nuclear interactions.

The deep minimum on the right corresponds to the optimal orientation for channeling. There is a wide area of a beam loss reduction on the left of the minimum, which is due to volume reflections (VR) of halo particles in the crystal. This reduction occurs because the particles perform a smaller number of passages through the crystal to reach the TCSG aperture than for amorphous orientations of the crystal. Agreement of the simulation with the experiment is sufficiently good. Some discrepancies near the edges of the beam loss dependence are not yet well understood and will be investigated in new measurements. The loss reduction in channeling is 47.3 and 50.7 from the experiment and simulation, respectively. The loss reduction values in the VR region are also very close.

The first horizontal collimator TCSG$_1$ behind the crystal was used to scan horizontal positions across the beam deflected by the crystal when its angular position was fixed close to the beam loss minimum detected in the angular scan. The BLM$_2$ downstream of the collimator registered secondary particles generated by inelastic nuclear interactions of protons in the collimator. Fig. 3 shows the dependence of the BLM$_2$ signal on the collimator position by a dot-dashed line. The BLM$_2$ signal increases when the collimator, moving from $X_1 = 9$ mm up to $X_2 = 7$ mm, intercepts the beam halo deflected in channeling states by the crystal. The observed profile is consistent with the presence of a well-defined channeled halo separated from the beam core by a distance that can be determined with optical transport between the two locations after the angular kick of the crystal bend angle value. The loss dependence gives the integral of the deflected beam distribution. The solid line in Fig. 3 shows a fit of the dependence with an error function. The fit center is at $x_m = 7.9$ mm. An error function is the integral of a Gaussian therefore x_m is the center of the Gaussian which fits the deflected beam distribution. The detected displacement x_m of the deflected beam halo from the beam envelope at the collimator location determines the angular kick produced by the crystal for channeled particles, $\theta_m = 65$ μrad. This deflection should be equal to the bend crystal angle if the crystal planes at its entrance were really parallel to the beam envelope for the collimator scan.

The beam test with bent crystals for 6500 GeV/c protons was performed in the next run. In this case, 16 bunches of 10^9 protons, evenly spaced around the ring, were injected and accelerated to 6500 GeV/c. The collimators were in their nominal positions for these conditions, as in Table 4, the primaries at $5.5\sigma_x$, the secondary collimators at $8\sigma_x$ and absorbers at $14\sigma_x$. The crystal was aligned with respect to the primary collimators and then was moved toward the orbit by about 0.05 mm to intercept the primary halo. The angular scan was performed with the goniometer rotation speed of 0.2 μrad/s and with collimator settings shown in Table 4. Individual bunches were excited one at a time to increase beam losses during the measurements. Curve 1 in Fig. 4 shows the dependence of the BLM$_1$ count on the angular position of the crystal. Channeling was clearly observed. It is clearly seen that the loss reduction “well” in the region of channeling and volume reflection has steeper walls than what was observed at 450 GeV/c. This may be explained by a strong reduction of multiple Coulomb scattering at higher energy; the results show that a particle cannot come to the channeling region when its incident angle with the crystal planes is larger than 10 μrad.

The channeling minimum on the right is narrower because the critical channeling angle is about 4 times smaller than at injection energy. The loss reduction in channeling is about 24. The second minimum on the left in the VR region is clearly seen here. This minimum was also observed in our studies with bent crystals at the SPS. The minimum is at an angular distance from the channeling orientation about equal to the bend angle value, 65 μrad. In this case, the whole VR region is on the same side relative to the beam envelope direction. Therefore, angular kicks due to VR always increase the oscillation amplitudes of particles and they more quickly reach the secondary collimators. Curve 2 shows the dependence of the number of inelastic nuclear interactions on the crystal orientation obtained by simulation according to [19]. The agreement with the experiment is good enough. The walls of the loss reduction dependence coincide well with the experimental ones. This means that the crystal bend angle measured by the collimator scan is right (the angular crystal position for this scan was chosen close to the perfect one for channeling). The loss reduction for VR region is the same as in the experiment. However, the loss reduction value for channeling, $R = 187$, is considerably larger than the experimental one. This difference may be explained by the residual angular instabilities of the goniometer. Multi-turn simulation with a SixTrack code, including other collimators in all ring insertions and a detailed beam aperture model [13], gives also good agreement with the angular scan data (curve 3), although the loss reduction value, $R = 140$, is also larger than the experimental one.

Similar measurements performed with the QM crystal for the LHC proton beam collimation in the vertical plane and measurements with the stored beam of Pb ions for the injection energy also showed a strong beam loss reduction in the aligned crystals. Detailed results will be reported in a future publication.

4. Conclusions

First experiments on the study of the LHC beam halo collimation assisted by bent crystals were successfully performed in machine studies during the LHC run II, at the injection energy of 450 GeV as well as at the record proton beam energy of 6500 GeV. Beam losses due to inelastic nuclear interactions of particles in the aligned crystal were strongly reduced in comparison with the amorphous crystal orientations. This proves that deflection of particles due to channeling in a bent crystal is effective at this record particle energy. It will be very important to compare leakage values for the crystal assisted and standard collimations in our future measurements at the LHC.

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