STATUS OF CRYSTAL COLLIMATION STUDIES AT THE LHC*

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Abstract

Crystal collimation is a technique that relies on highly pure bent crystals to deflect coherently beam particles – through the channeling mechanisms – onto dedicated absorbers. Standard multi-stage collimation systems for hadron beams use amorphous materials as primary collimators and might be limited by nuclear interactions and ion fragmentation that are strongly suppressed in crystals. A crystal collimation setup was installed in the betatron cleaning insertion of the Large Hadron Collider (LHC) to investigate with LHC beams the feasibility of this concept and to compare its performance with that of the present system. Channeling was observed for the first time with 6.5 TeV beam and plans for further crystal collimation beam tests at the LHC are discussed. Results of these first beam tests are presented.

INTRODUCTION

High-energy particles interacting with monocrystalline materials can experience coherent interactions with the electromagnetic potential generated by atoms in the lattice. Planar channeling is achieved when charged particles impinge on the crystal at angles close to the direction of atomic planes. In channeling, bent silicon crystals can coherently deflect beam halo particles by several tens of µrad, as opposed to the multiple coulomb scattering (MCS) with RMS angle of a few µrad provided by the 60 cm long primary collimators (made of carbon). This is achieved with the additional advantage of strong suppression of diffractive interaction [1]. In principle bent crystals could be used with a single absorber as opposed to the standard multi-stage collimation where several secondary collimators and absorbers are needed to dispose of the halo particles.

Bent crystals have been installed in the betatron cleaning insertion (IR7) to address the feasibility of crystal collimation under LHC conditions and to evaluate if the expected performance improvement can be indeed reached. Two crystals for horizontal and vertical collimation were installed in 2014 in one ring and have been tested with beams in various conditions. In 2017, two new crystals with improved hardware were added on the other ring. In this paper, we present the results from the beam tests, which demonstrated for the first time crystal channeling of multi-TeV hadron beams and discuss the future plans for crystal collimation.

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Table 1: LHC Crystals Specifications

Beam	Type	Plane	Length [mm]	Bending Angle [µrad]
B1	ST	H	4	65
B1	QM	V	4	50
B2	QM	H	4	55
B2	QM	V	4	55

CRYSTAL COLLIMATION LAYOUT AT THE LHC

Betatron collimation is required both in horizontal and vertical planes, which can show a quantitative difference in cleaning. Thus, both planes were equipped with the crystals for conclusive tests. The setup has been conceived to use only existing secondary collimators as absorbers for channeled beam [2]. The goniometers were installed on the clockwise Beam 1 (B1) during the LHC long shutdown in 2014. Two crystal manufacturing technologies were tested in the B1 installation: Strip crystals (ST) [3] are based on anti-clastic forces to give the needed bending angle, Quasi-Mosaic crystals (QM) [4] rely on quasi-mosaic effects itself to achieve the same results. The main specifications of the crystals installed in the LHC are listed in Table 1. The goniometers that house the crystals use piezo-electric actuators that can achieve a resolution of 0.1 µrad and are inserted into a special tank shielded from the beam by an 'O' shaped replacement chambers during LHC standard operation [5].

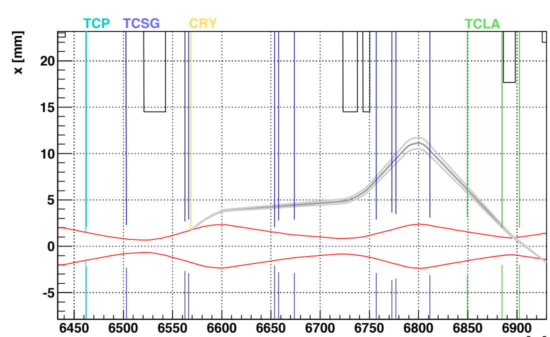

Figure 1: Projection of horizontal trajectories of channeled halo particles as a function of the B2 longitudinal coordinate in IR7. Bending angles of 50 µrad (dark gray line, with $\pm\theta_c$ in light gray lines) are applied starting from the 5.5 σ envelope (red lines). Vertical solid lines show gaps of primary (TCP, cyan) and secondary collimators (TCSG, blue), of shower absorbers (TCLAs, green) and crystals (CRY, yellow). The geometrical aperture is also shown (black lines).

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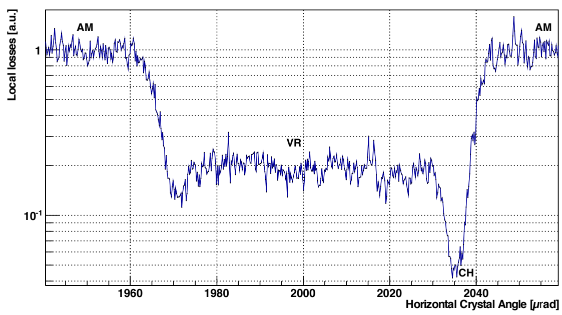

Figure 2: Beam loss downstream of the crystal as a function of rotation angle. Beam losses are normalized to the beam flux and to the losses in amorphous orientation.

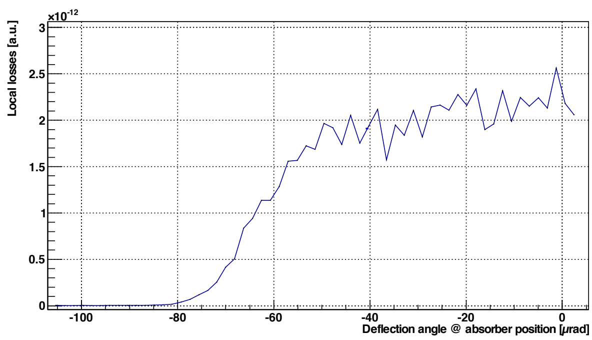

Figure 3: Beam loss downstream of the absorber collimator as a function of equivalent kick angles at collimator position with horizontal crystal in channeling orientation, at injection energy. Beam losses are normalized to the beam flux.

Low-intensity beams are adequate to achieve the initial feasibility goals. During 2015 and 2016 both crystals have been tested achieving for the first time the observation of channeling in LHC at both injection and top energy [6]. A new layout was proposed for two new goniometers on anti-clockwise Beam 2 (B2), where horizontal and vertical planes were equipped (Table 1) in positions that are functionally similar to those of B1. A simple single-turn matrix tracking of trajectories was used to optimize the positions. See an example for the horizontal plane in Fig. 1, where the effect of a crystal bent by 50 μrad on the 5.5 σ particles is shown.

HIGHLIGHT FROM BEAM TEST RESULTS

Angular scans are performed by changing the crystals' orientation angle with respect to the beam envelope while monitoring beam losses immediately downstream of the goniometers with crystal acting as primary collimator. Channeling (CH) is observed as a reduction of local beam losses, as nuclear interactions are suppressed compared to the amorphous orientation.

A complete angular scan done at 6.5 TeV with the horizontal crystal is shown in Fig. 2. The broader angular scan shows the regimes of volume reflection (VR) [7] and amorphous (AM). The loss reduction from amorphous to channeling orientations is of about a factor 26 in this case. For the vertical crystal, a reduction of 23 is found in similar conditions.

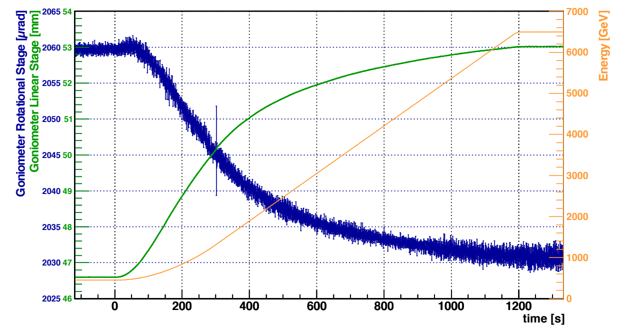

Figure 4: Linear and rotational stages points during the energy ramp. Data are averaged over a second (raw data rate 10 Hz), also RMS is calculated and shown as error bars.

To characterize the extracted beams a transverse scan with secondary collimators downstream of the crystal is performed when the crystal is oriented at its optimum angle for channeling. An example for the horizontal crystal is shown in Fig. 3. It is possible, with a simple transport matrix, to transform the linear position axis of the collimator to the angular deflection given by a device at crystal position. This allow evaluating the crystal bending angle. For the horizontal crystal the bending angle is evaluated as 65.1 μrad, and for the vertical is evaluated as 50.1 μrad. The bending angle of the horizontal crystal is 30% larger than the design value of 50 μrad [2]. The two crystals mounted in 2017 on B2 were carefully characterized before installation to stay within specifications.

In order to use crystal collimation during operation, the possibility to keep the crystal in the channeling condition during dynamics phases like the energy ramp and the betatron squeeze needs to be assessed. This is challenging because the critical angle θ_c (above which channeling regime is lost) scales as the inverse of the square root of the energy, and its value for 6.5 TeV protons for a silicon crystal is 2.5 μrad. Standard collimator ramp functions [8] were adapted to generate new functions for a single side device with a rotational stage. The crystal position, $x(t)$, follows a function of time $x(t) = x_c(t) - n(t) \times \sigma(t)$, where $n(t)$ and $\sigma(t)$ are respectively the normalised settings and the beam size in mm that depend on time during the ramp, and $x_c(t)$ is the beam position at goniometer location. These parameters are typically different at injection and flat top. We use a linear interpolation to build continuous functions from the injection value to the flat-top value that are established with beam-based techniques. For instance, for the $n(t)$ we used:

$$n(t) = n_{\mathrm{inj}} + \frac{n_{\mathrm{ft}} - n_{\mathrm{inj}}}{\gamma_{\mathrm{ft}} - \gamma_{\mathrm{inj}}} \left(\gamma(t) - \gamma_{\mathrm{inj}}\right). \qquad (1)$$

For the goniometer angle the same ideas are used, but in this case, the optimum channeling angle for injection and flat top are the first and the last point of the ramp function. Those functions were used during a dedicated test in LHC.

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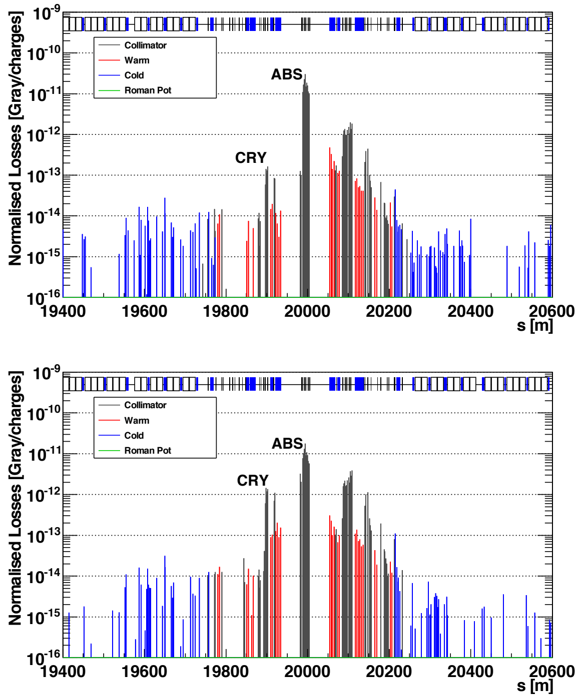

Figure 5: Loss pattern in IR7 during horizontal angular scan when the crystal is oriented in channeling (top) and in amorphous (bottom). Losses are normalized to the beam flux. Crystal (CRY) and the collimator used as absorber (ABS) are shown on the plots.

In Fig. 4 the goniometer stages movements (and the RMS over a 10 Hz acquisition) are shown. The rotational stage vibrations are well below the $\pm\theta_c(E)$ acceptance for channeling orientation. To verify whether channeling conditions were preserved, beam losses were measured continuously during the ramp. The channeling condition corresponds to very characteristic loss patterns, different from what is observed in amorphous orientation. Figure 5 (top) shows the loss pattern of IR7 when the crystal is in CH orientation, while Fig. 5 (bottom) shows the loss pattern when it is in AM orientation. The ratio of the measurements of two monitors that respond differently in the two cases is used as an empirical figure of merit to identify channeling conditions. In particular, the monitor at crystal and at absorber positions are used. The result of Fig. 6 shows that channeling was successfully maintained at all energies while ramping the beams.

FUTURE PLANS

The presently ongoing effort is focused on the comparison between the collimation cleaning from a crystal-based system and a standard multi-stage collimation. Preliminary analysis of 2016 are encouraging but not yet conclusive at this stage. Additional measurements are required to assess the performance of crystal collimation in final experimental conditions at top energy with squeezed beams at 6.5 TeV, as present tests could only be done at flat top with un-squeezed optics.

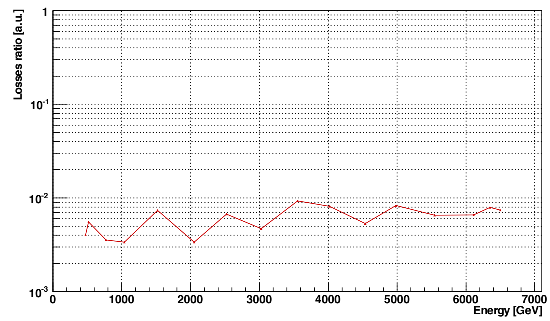

Figure 6: Ratio of losses recorded at crystal and absorber as a function of the energy during the ramp.

The new installation on B2 improves the hardware by adding crystals with bending angles closer to specification and improved goniometers. Tests will start in 2017 with proton beams and continue in 2018 with Pb ion beams. Tests with ions are particularly important because crystals might provide a way to improve significantly the collimation performance for the parameter set that is planned for the LHC Run 2 or Run 3 [9]. In the yearly stop at the end of 2017, an update of the control system is planned to make the setup compatible with the collimator beam interlock implementation. This will open the possibility to perform tests with beam intensity above the present limit of 3×10^{11} p at 6.5 TeV.

CONCLUSIONS

A unique installation in the LHC allows testing bent crystals with multi-TeV hadron beams, aimed primarily at studying crystal beam collimation for the HL-LHC upgrade. The crystal collimation setup has been successfully tested during the last two years, demonstrating the reliability of the installed devices in various machine conditions. Demonstration of channeling was achieved for the first time at the record energy of 6.5 TeV for proton and lead ion beams. Channeling has been successfully maintained during the whole LHC energy ramp, demonstrating the reliability of the goniometer devices for this kind of applications. Further tests with an improved hardware for B2 will also be performed. The new installation carried out in 2017 complete the test stand. The complete setup allows for integral collimation tests in both beams and planes and this will be exploited until the end of Run 2 with the aim to collect enough evidence on whether crystal collimation can be deployed operationally for ion beam collimation.

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