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CRYSTAL COLLIMATION PERFORMANCE AT THE LHC WITH A 6.8 TEV PROTON BEAM*

M. D'Andrea†, O. Aberle, A. Abramov, R. Bruce, R. Cai[1], M. Calviani, Q. Demassieux, K. A. Dewhurst, M. Di Castro, L. S. Esposito, Y. A. Gavrikov, S. Gilardoni, P. D. Hermes, Y. M. Ivanov, B. Lindström, A. Lechner, E. Matheson, D. Mirarchi, J. B. Potoine[2], S. Redaelli, G. Ricci, R. Seidenbinder, S. Solis Paiva, CERN, Geneva, Switzerland
L. Bandiera, V. Guidi, A. Mazzolari, M. Romagnoni, M. Tamisari, INFN-Ferrara, Ferrara, Italy
[1]also at EPFL, Lausanne, Switzerland
[2]also at University of Montpellier, Montpellier, France

Abstract

Crystal collimation is studied to improve the collimation efficiency with ion beams at the High-Luminosity Large Hadron Collider (HL-LHC). Bent crystals are used instead of conventional primary collimators to deflect high-energy halo particles at angles orders of magnitude larger than what can be achieved with scattering by conventional materials. Following the promising results obtained during Run 2 (2015-2018) and the first year of Run 3 (2022), this collimation technique is planned to be used operationally already for LHC Run 3 heavy-ion operation, starting in 2023, to mitigate the risk of magnet quenches from beams of higher energy and intensity. Tests with low-intensity proton beams are extremely important to characterize the crystal collimator hardware, assess the performance and investigate other operational aspects in preparation for the ion run. This paper presents the results of tests carried out in 2022 with proton beams at the record energy of 6.8 TeV.

INTRODUCTION

The LHC [1] is designed to accelerate and collide two counter-rotating beams of protons or heavy-ion nuclei. The physics program of the ongoing Run 3 (2022-2025) will profit from the upgrades carried out in the context of the LHC Injector Upgrade (LIU) [2] and High-Luminosity LHC (HL-LHC) [3,4] projects. In the 2023 run, Pb ion beams are planned to collide at the unprecedented energy of 6.8Z TeV (to be compared with previous runs at 6.37Z TeV) and with about 50% higher beam intensity than in previous runs, aiming at more than 20 MJ of stored beam energy [5]. Such conditions require careful handling of beam losses to reduce the risk of quenches for the superconducting magnets [6–10]. For this reason, the innovative crystal collimation technique, studied at CERN over the past decade [11–13], will be deployed during regular operation with heavy-ion beams for the very first time. As opposed to standard collimation, which uses multiple collimator stages (primaries, secondaries and shower absorbers) to progressively outscatter beam halo particles, this concept is based on the peculiar properties of crystalline materials, whose atoms are organized in a series of parallel planes. Positively charged particles with suitable impact conditions can get trapped in the potential well generated by neighboring planes and can travel through the crystal (*crystal channeling*) with a greatly reduced probability of inelastic interactions [14]. A bent crystal can then be used to steer halo particles in an accelerator towards a single absorber [15]. At the top energy of the LHC, this effect is equivalent to the steering by a magnetic field of hundreds of Tesla without affecting the beam core.

Four Si crystals (one on the horizontal and one on the vertical cleaning plane of each beam) [16,17] are installed in the LHC. While a standard secondary collimator can be used to safely intercept the beam halo deflected by a crystal in operation with ion beams, the deployment with full intensity proton beams, with a factor 20 higher stored beam energy than the ions, is severely hampered by the need to design a special absorber [18]. However, beam losses are not a limitation for proton operation during Run 3. Nevertheless, tests with low-intensity proton beams (up to $3 \cdot 10^{11}$ circulating protons per beam) are extremely important to obtain preliminary feedback on the crystal devices, especially given the limited amount of time allocated for operation with heavy-ion beams (typically a month per year preceded by about a week of setup). This paper will describe the outcome of such tests carried out in 2022, focusing mainly on the two vertical crystals, which were exchanged during the Second Long Shutdown (2019-2021) with an updated assembly design. Tests with Pb ion beams performed during the 2022 ion beam test are described in another paper [19].

CRYSTAL CHARACTERIZATION MEASUREMENTS

Data for these measurements (performed at the injection energy of 450 GeV and the top energy of 6.8 TeV) are collected via the Beam Loss Monitoring (BLM) system [20]: it consists of ionization chambers placed around the accelerator ring to detect products of nuclear interactions of beam particles with machine elements. Due to the physics of the interaction processes at play, crystal collimation produces particular loss patterns that allow measuring the geometrical properties and channeling efficiency of a crystal device.

Each crystal is inserted into the beam halo using an alignment procedure similar to what is done for standard collimators [21]. Afterwards, when the crystal is the primary

* Work supported by the HL-LHC Project.
† marco.dandrea@cern.ch

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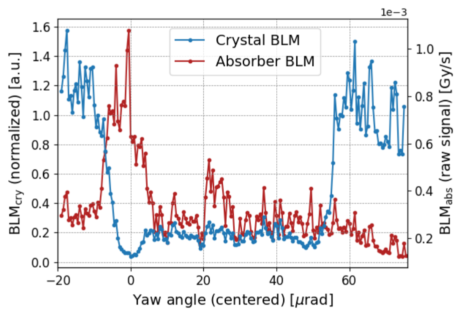

Figure 1: Normalized BLM signal at the crystal and raw BLM signal at the absorber during an angular scan (vertical crystal, Beam 1) with 6.8 TeV protons.

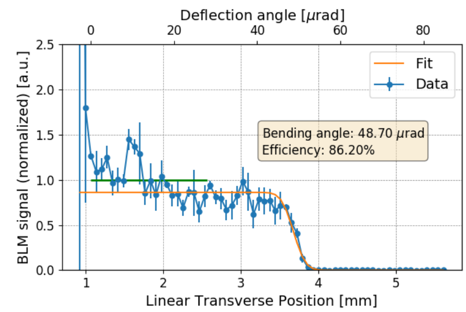

Figure 3: Normalized BLM signal at the absorber during a linear scan (vertical crystal, Beam 2) with 6.8 TeV protons.

aperture bottleneck of the ring, all collimators upstream of the crystal and all secondaries between the crystal and the corresponding absorber are retracted to give clearer signals at the crystal and the absorber. To further increase the signal, the Transverse Damper (ADT) [22] is used to induce primary beam losses on the collimation system by inducing a controlled emittance blow-up. Two types of measurements (angular and linear scans) are then performed [23, 24].

During an *angular scan*, the aligned crystal collimator is rotated at constant speed along the deflection plane, changing the probability of different interaction processes between halo particles and the crystalline lattice. This is reflected in the observed signal at the crystal and downstream absorber BLM. An example measurement is shown in Fig. 1. This procedure is essential to identify the orientation that maximizes the probability of planar channeling (which corresponds to a minimum in the BLM signal at the crystal and a maximum in the BLM signal at the absorber). The width of the channeling well is related to the acceptance angle of the channeling process. The width of the full region with reduced signal is proportional to the bending angle of the crystal, allowing to validate this geometrical parameter.

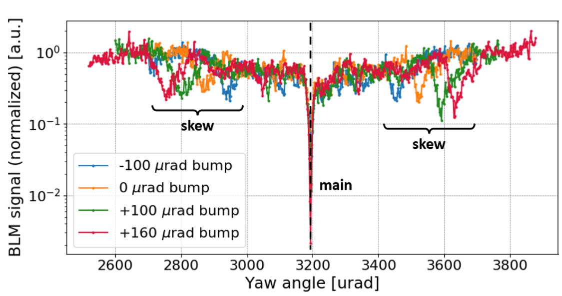

Figure 2: Normalized BLM signal at the crystal during angular scans (vertical crystal, Beam 2) with 450 GeV protons for different local orbit tilts at the entrance face.

When the alignment of a crystal with respect to the beam axis is close to its *crystalline axis*, impacting particles can experience planar channeling by planes other than the main one. These *skew planes* produce additional wells placed symmetrically around the main planar channeling. Their angular distance from the main well is smaller the closer the crystal orientation is to the axis. This condition was previously observed at the LHC [23] and is generally undesirable, as skew planes located too close to the main planar channeling peak can compromise the collimation performance by partially masking the optimal channeling orientation and by introducing a coupling effect in the deflection between different directions. The newly installed crystal on the vertical plane of Beam 2 showed this behavior in the first angular scans at 450 GeV. The signature was confirmed to originate from skew planes by using a local orbit bump to alter the direction of the halo particles hitting the crystals, i.e. mimicking a realignment of the crystal with respect to the beam axis. As expected, the symmetric wells around the main planar channeling moved closer or farther away as a function of the applied tilt, as shown in Fig. 2. A linear fit of the skew planes angular locations allowed the orientation of the crystal collimator to be determined as about 500 μrad away from the crystalline axis (normally, at least 1 mrad is advised to avoid this effect). Due to the design of the assembly, it was not possible to realign the crystal without a major intervention. However, the skew planes were found to be spaced sufficiently as not to interfere with the identification of the optimal orientation. Furthermore, tools to automatize this procedure and distinguish skew planes from main channeling are being developed and tested [25–27].

In a *linear scan*, the crystal collimator is set at the previously identified optimal channeling orientation, while the absorber is moved away from the beam. In this condition, the deflected halo is intercepted by the downstream collimators. The absorber is then progressively inserted back towards the beam. As it starts intercepting the deflected halo, the BLM signal at the absorber location starts to increase until it reaches a certain saturation level. The scan is interrupted when the absorber touches the primary beam, as signaled by a massive spike in the BLM signal. By fitting the rise of the BLM signal with an error function, it is possible to estimate the displacement of the deflected beam with respect to the primary beam envelope, and to convert it into a measurement of the bending angle via transfer functions that describe the trajectory of the circulating particles. The ratio between the signal recorded just before touching the primary beam and the saturation of the error function gives an estimate of the multiturn channeling efficiency of the crystal.

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Linear scans performed for the newly installed vertical crystals, exemplified by Fig. 3, showed in both cases a bending angle compatible with the required specifications of 50 µrad and a good channeling efficiency of more than 70%. In particular, no clear loss in performance can be observed on the Beam 2 crystal despite the skew plane effects, leading to the decision not to intervene for a realignment. Results for the horizontal crystals were in line with Run 2 observations.

CLEANING INEFFICIENCY MEASUREMENTS

The performance of the LHC collimation system is assessed by measuring the *cleaning inefficiency*, i.e. the fraction of intercepted particles that leak out of the collimation insertion and generate losses at sensitive locations. This is done by exciting the beam with the ADT to produce controlled losses that impact the collimation system. The resulting BLM signals around the entire ring are displayed in a so-called *loss map*. The area of interest for the comparison of standard and crystal collimation is the Dispersion Suppressor (DS) located downstream of the IR7 collimation insertion where particles with high momentum offset resulting from nuclear interactions with the upstream collimators are lost due to the high dispersion (Fig. 4 shows examples of the measured pattern with standard and crystal collimation).

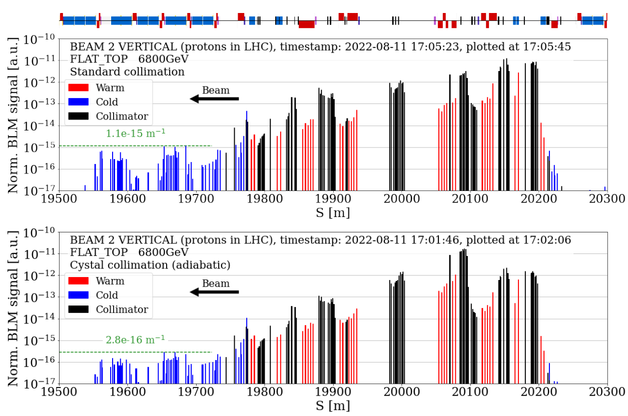

Figure 4: Loss pattern with standard (top) and crystal (bottom) collimation in the vertical plane of Beam 2.

To compare the loss pattern observed with standard and crystal collimation, the BLM signal (after the subtraction of the background recorded before the measurement) is normalized by the intensity lost over time [23,24]. The cleaning inefficiency η_c is defined as the highest normalized BLM signal recorded in the DS region (shown in green in Fig. 4). The *global leakage ratio* (*GLR*) is then calculated as:

$$GLR = \frac{\eta_c^{\mathrm{STD}}}{\eta_c^{\mathrm{CRY}}}, \tag{1}$$

where STD and CRY represent standard and crystal collimation respectively. With this definition, the use of crystal collimation improves the performance of the system if this quantity is larger than 1. The *GLR* measured in 2022 is reported in Fig. 5 for each plane. In these measurements, the crystal system was deployed with the settings proposed for regular use during ion operation (i.e. standard collimators kept at nominal settings, crystal primary collimators "adiabatically" inserted at a slightly tighter aperture than the standard primaries to drive the cleaning) [28]. The cleaning performance was compared against the standard system with nominal settings [29]. An improvement of up to a factor 4 was observed with crystal collimation, with the highest values achieved for the two newly installed vertical crystals. The lower performance of the horizontal crystals is not considered a limitation at present as they were later exchanged with new devices requiring further characterization.

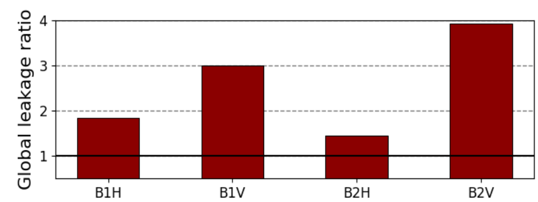

Figure 5: Global leakage ratio measured in all four planes.

Although the observed performance with proton beams cannot be easily scaled to ion beams, due to the very different particle interactions with matter, these first measurements were important to identify potential issues and unexpected behaviors of the crystal devices well ahead of the very limited time allocated to commissioning with Pb ions.

CONCLUSIONS AND OUTLOOK

During the 2022 commissioning of the LHC, an extensive campaign of crystal collimation tests with proton beams was carried out. This allowed to fully characterize the newly installed vertical crystals of both beams, and to confirm the performance gain observed in 2018 with the horizontal crystals. Despite the presence of undesired skew plane effects with the vertical crystal of Beam 2, no evidence of performance loss was observed. Loss map measurements in the operational configuration show an improvement of up to a factor 4 in the cleaning efficiency compared to standard collimation, although these results cannot be easily scaled to heavy-ion beams. Measurements performed during the 2022 Pb ion beam test are detailed in another paper [19].

A remaining point to be addressed is the capability of maintaining optimal channeling orientations during dynamical phases of the LHC cycle, notably the energy ramp during which the beam size changes. Following a first early assessment with promising results [23, 24], further dedicated tests with protons are planned before the 2023 ion run.

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