ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM120

LHC CRYSTAL COLLIMATION TESTS WITH 6.8 Z TeV PB BEAMS*

R. Cai[†1], O. Aberle, R. Bruce, M. Calviani, M. D'Andrea, Q. Demassieux, K. Dewhurst, M. Di Castro, L. S. Esposito, S. Gilardoni, P. D. Hermes, A. Lechner, E. Matheson, D. Mirarchi, S. Redaelli, G. Ricci, R. Seidenbinder, S. A. Solis Paiva, CERN, Geneva, Switzerland
M. Seidel[2], Paul Scherrer Institut (PSI), Villigen, Switzerland,
[1, 2]also at École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

Abstract

In the next heavy ion runs at the LHC, the cleaning of the beam halo will rely on crystal collimation. A test system installed in the collimation cleaning insertion is being upgraded for the operational challenges of the ion runs. Therefore, it is crucial to experimentally test the performance of the newly installed crystal primary collimators. During a dedicated short Pb ion beam test in 2022, crystal collimation was tested for the first time with 6.8 Z TeV Pb beams. These results provide very important input for the configuration of the Pb ion run at the LHC in 2023. In this paper, the results and analysis of the crystal measurements in the 2022 ion test are presented.

INTRODUCTION

At CERN, the Large Hadron Collider (LHC) [1] accelerates and collides counter-circulating proton or heavy-ion beams. The amount of energy stored in the LHC beams is enough to cause quenches of the superconducting magnets or even induce damage to machine hardware. To protect against these risks, a multi-stage collimation system [2–5] is installed in the LHC. Due to nuclear fragmentation and electromagnetic processes in the collimator material, collimation is more challenging for heavy ions than for protons [6–8]. Furthermore, the energy of the heavy-ion beams will be increased from 6.37 Z TeV to at least 6.8 Z TeV in future runs, and the stored beam energy will increase by about 50% [9] following the LIU upgrade, compared to 2018. For these reasons, collimation based on channelling in bent crystals [10, 11] was introduced for heavy-ion operation, as part of the HL-LHC upgrade baseline [12, 13]. Crystal channelling [14, 15] is a phenomenon where charged particles are trapped between planes of the periodic crystalline structure. Bent crystals can be used to guide halo particles onto an absorber while reducing the probability of inelastic interactions with the atoms of the crystal and thus limiting nuclear fragmentation.

Considering that crystal collimation is the baseline for future heavy-ion runs, it is crucial to test its performance with Pb ions at 6.8 Z TeV. This was possible during a short low-intensity Pb beam test in 2022 [16], using the machine configuration for 2022 proton operation [17]. At the time of the 2022 measurement, there were four crystals of the strip type [18, 19] available for usage in the LHC, one per plane and beam. In particular, the two vertical crystals had already been upgraded with a design that was not yet tested with heavy-ion beams. This paper reports on the crystal tests carried out during the 2022 heavy-ion test and their results.

The crystal measurements follow a standard procedure as in past tests [20–28]. It includes four main steps: transverse alignment of the crystal to the beam, followed by angular and linear scans, as well as the acquisition of loss maps for different collimator configurations to assess the cleaning performance. The procedure was performed at injection energy (450 *Z* GeV) and at top energy (6.8 *Z* TeV).

RESULTS OF ANGULAR SCANS

Once the crystal is transversely aligned, the angular scan is performed by rotating the crystal in the bending plane. It is done while exciting the beam with the transverse damper (ADT) [29] and with all collimators upstream of the absorber open, in order to increase the signal-to-noise ratio. The angular scan allows finding the best orientation for channelling by observing the signal of the beam loss monitor (BLM) [30] installed close to the crystal. The signal reaches a minimum for the optimum orientation, when the channelling efficiency is highest. Figure 1 shows one example of the BLM signal as a function of the crystal orientation. Similarly, the optimum channelling orientation was successfully found also for the other crystals. The shapes of these curves and the channelling orientation agree well with the ones found in the previous scans using proton beams [31].

The width of the channelling well, indicated by vertical dashed lines in Fig. 1, is shown in Fig. 2 for all crystals at both energies. The narrow width of the well might give rise to a need of angular re-alignments during longer physics runs, which could be done using automatic tools [32]. In Fig. 2, the reduction factor in local losses at the crystal in channelling orientation is defined as $\frac{BLM_{AM}}{BLM}$, where BLM and BLM_{AM} are the BLM signals in the channelling and amorphous orientations. Figure 2 shows a similar reduction factor also for the volume reflection (VR) orientation of the crystal, when particles are reflected off the crystalline planes (details can be found in Ref. [11]). The measured reduction factors are lower than for protons. This is consistent with similar studies performed in 2018 [25, 27]. The differences between beams and planes come from different standard system performances, optics and crystal location.

RESULTS OF LINEAR SCANS

With the crystal at the optimal channelling orientation, the downstream absorber, intercepting the channeled particles,

* Research supported by the HL–LHC project
† rongrong.cai@cern.ch

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

14th International Particle Accelerator Conference,Venice, Italy JACoW Publishing
ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM120

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

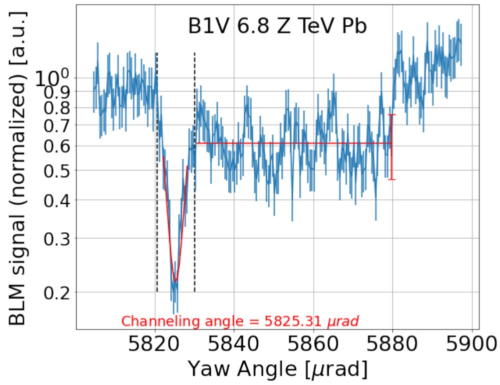

Figure 1: Normalized measurement of the BLM signal as a function of the B1V crystal orientation angle at 6.8 Z TeV.

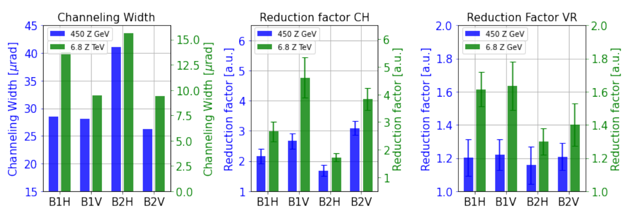

Figure 2: Channelling width and nuclear interaction reduction factors linked to crystal channelling (CH) and volume reflection at injection energy (450 Z GeV—blue) and top energy (6.8 Z TeV—green).

is slowly moved out and inserted back. This allows recording the beam profile of the channeled halo at the absorber using its nearby BLM. As for the angular scan, the collimators upstream of the absorber are opened. The BLM signals on the absorber as a function of the absorber position are used to derive an estimate of the crystal bending angle and the multi-turn channelling efficiency of the crystal. Due to time constraints, only the newly installed vertical crystals, which had not been tested with ions before, were measured with a linear scan at 6.8 Z TeV.

The results are shown in Fig. 3. The bending angles agree with those identified in the previous proton scans [31]. However, the multi-turn channelling efficiency, which was more than the 70% in the proton scans, was found with ions to be only 34% for the B1V crystal and 57% for B2V. The cause of this reduction is being investigated, but as shown in the following section, the obtained cleaning efficiency with these crystals is anyway very good. The lower multi-turn channelling efficiency is hence not expected to have a sizeable negative impact on the tolerable ion beam loss rates.

RESULTS OF LOSS MAPS

Loss maps have been gathered for various collimation configurations using crystals as well as the standard system. The reference emittance used was equivalent to 3.5 µm for protons. The configurations include crystals in channelling (CH) or amorphous orientation (AM) and different settings

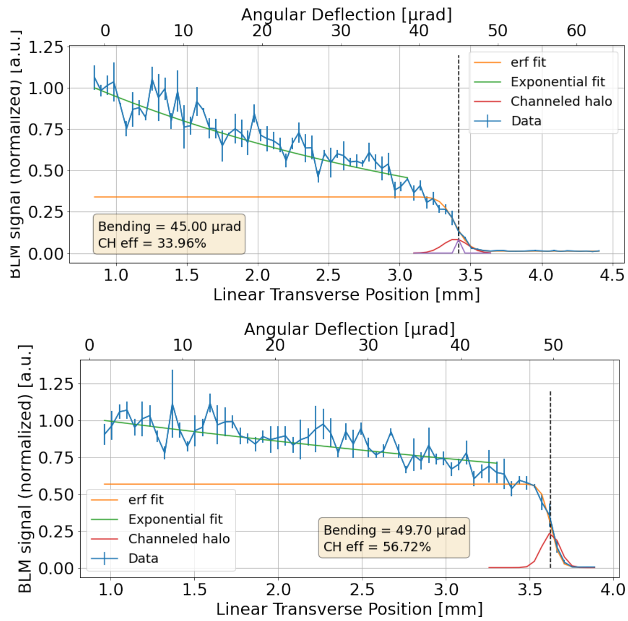

Figure 3: Linear scan of Beam 1 vertical crystal (top) and Beam 2 vertical crystal (bottom) is plotted together with exponential fit of the dechannelling range, the error function fit of the channelling range and the extrapolated Gaussian beam halo. The crystal bending angle and channelling efficiency are reported in the yellow boxes.

Table 1: Collimator openings in IR7 of the loss map configurations tested.

Setup	TCPC	TCLA	Upstream collimators
Standard	OUT	Nominal	Nominal
C1	4.75 CH	Nominal	Nominal
C2	4.75 CH	8	Nominal
C3	4.5 CH	8	Nominal
C4	4.75 CH	Nominal	OUT
C5	4.75 AM	Nominal	Nominal

of the crystal (TCPCs), the collimators upstream of the crystal in IR7 and the other collimators. The settings are reported in Table 1.

During a loss map acquisition, single bunches are excited with the ADT to create artificial losses on the collimation system. After setting up the full crystal collimation system, the residual loss pattern around the full ring is observed on BLMs. The efficiency of the beam cleaning is concluded based on the leakage of losses to cold elements.

To quantify the cleaning performance we define a cleaning inefficiency η for crystal collimation measurements:

$$\eta = \frac{\mathrm{BLM}}{\nu_{\mathrm{tot}}}, \qquad (1)$$

where BLM is the BLM signal at any position in the ring and ν_{tot} is the measured particle loss rate. As an example, the B1V loss maps with the standard and crystal collimation systems are in shown respectively in Figs. 4 and 5. In both cases the maximum losses occur in the dispersion suppressor

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM120

(DS) directly downstream of the collimation insertion at the cold elements, where ion fragments are lost due to their different rigidity with respect to the main beam. As can be seen, these losses are significantly lower with crystal collimation, and it can also be seen that other losses at cold elements around the ring are reduced.

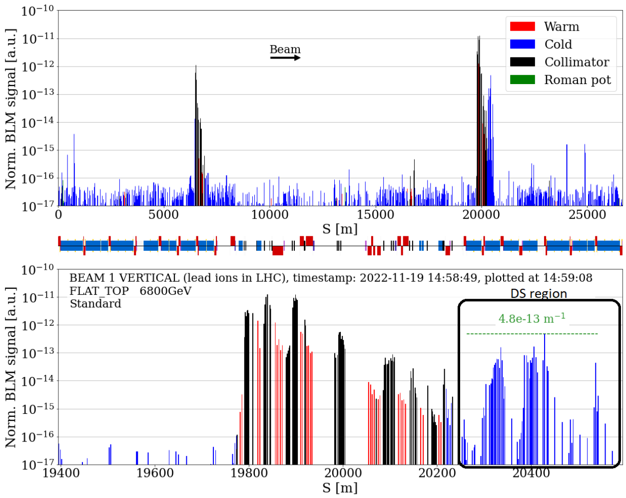

Figure 4: Whole ring B1V loss map (top) and IR7 zoom (bottom) with standard collimation system.

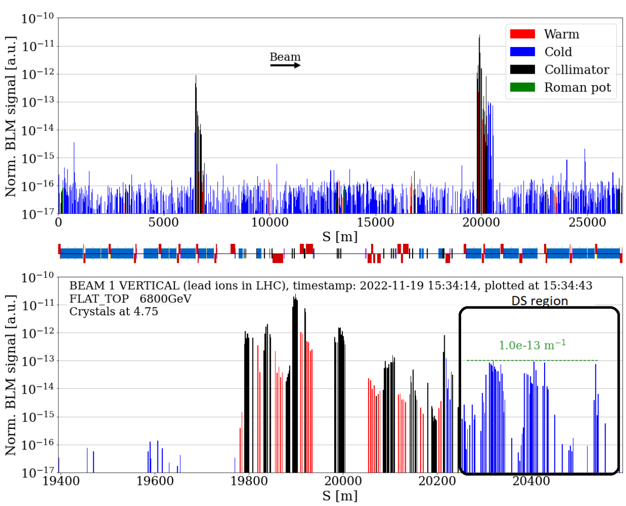

Figure 5: Whole ring B1V loss map (top) and IR7 zoom (bottom) with crystal at 4.75 σ.

To compare η in different configurations we define the global cleaning improvement $GC = \frac{\max(\eta_{\text{standard}})}{\max(\eta_{\text{crystal}})}$, where $\max(\eta_{\text{standard}})$ is the maximum η over the cold parts in the ring for the standard system without crystal, and $\max(\eta_{\text{crystal}})$ is the maximum cold η in a crystal configuration. The performance is improved by crystal collimation if $GC > 1$. The performance of the different collimation configurations have been compared using GC in Fig. 6.

There is an excellent improvement of about a factor of 5 for the previously untested vertical crystals in all cases. Only for the loss map with the crystal in amorphous orientation

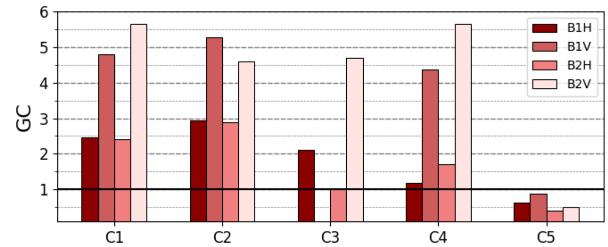

Figure 6: Measured GC for the different crystal collimation configurations tested in 2022, detailed in Table 1.

the performance was worse than the standard system, which is expected. The horizontal crystals provide an improvement of about a factor of 2.5, which is smaller than what was found with the 2018 setup [18, 33]. This may be due to the difference in primary collimator settings in the loss maps with the standard system (in the 2018 tests, an asymmetric opening was used [7]). Furthermore, due to the limited allocated time, none of the collimation systems were fully optimized. The smaller observed improvement does not represent an issue for the 2023 run, as these crystals have been replaced by new devices.

CONCLUSION

Crystal collimation will be used in future Pb ion operation at the LHC, starting with the 2023 run foreseen at a new record energy of 6.8 Z TeV. This article describes the first beam measurements of the crystal collimation performance with Pb ions at 6.8 Z TeV, and specifically the first tests with Pb ions of two newly installed crystal collimators.

Tests to characterize the crystal itself as well as the collimation performance have been carried out. Specifically, angular scans have been performed for all four crystals both at injection energy (450 GeV) and top energy (6.8 Z TeV), while linear scans have only been performed for the two new crystal at top energy. The angular scan results agree with results obtained using protons earlier in the year. However, in the linear scans, despite finding the same bending angle as in the proton scans, a lower channelling efficiency than for protons was observed.

In the cleaning performance tests, the newer vertical crystals gave excellent improvements (about a factor of 5) from the standard collimation, while the older horizontal crystals gave an improvement of about a factor 2.5. However, this might be due to the fact that the standard system used for the comparison had a slightly different configuration and was more performing in the new test. For the horizontal planes, crystal performance was measured with different crystals to the ones that will be used in the 2023 run. To conclude, these tests give confidence in the crystal collimation performance and provide essential inputs to the 2023 LHC heavy-ion run.

REFERENCES

[1] O. S. Brüning, *et al.*, "LHC design report v.1 : The LHC main ring," *CERN-2004-003-V1*, CERN, Geneva, Switzer-

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM120

land, 2004. doi:10.5170/CERN-2004-003-V-1

[2] R.W. Assmann, "Collimators and Beam Absorbers for Cleaning and Machine Protection," *Proceedings of the LHC Project Workshop - Chamonix XIV, Chamonix, France*, p. 261, 2005.

[3] R.W. Assmann *et al.*, "The Final Collimation System for the LHC," *Proc. of the European Particle Accelerator Conference 2006, Edinburgh, Scotland*, p. 986, 2006.

[4] R. Bruce, *et al.*, "Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider," *Phys. Rev. ST Accel. Beams*, vol. 17, p. 081004, Aug 2014. doi:10.1103/PhysRevSTAB.17.081004

[5] R. Bruce, *et al.*, "Reaching record-low β^* at the CERN Large Hadron Collider using a novel scheme of collimator settings and optics," *Nucl. Instrum. Methods Phys. Res. A*, vol. 848, pp. 19 – 30, Jan 2017. doi:10.1016/j.nima.2016.12.039

[6] P. Hermes, *et al.*, "Measured and simulated heavy-ion beam loss patterns at the CERN Large Hadron Collider," *Nucl. Instrum. Methods Phys. Res. A*, vol. 819, pp. 73 – 83, Feb 2016. doi:10.1016/j.nima.2016.02.050

[7] N. Fuster-Martínez, *et al.*, "Simulations of heavy-ion halo collimation at the cern large hadron collider: Benchmark with measurements and cleaning performance evaluation," *Phys. Rev. Accel. Beams*, vol. 23, p. 111002, Nov 2020. doi:10.1103/PhysRevAccelBeams.23.111002

[8] N. F. Martinez, *et al.*, "Run 2 collimation overview," *Proceedings of the 9th LHC Operations Evian Workshop, Evian, France*, 2019.

[9] R. Bruce, *et al.*, "Performance and luminosity models for heavy-ion operation at the CERN Large Hadron Collider," *Eur. Phys. J. Plus*, vol. 136, p. 745, 2021. doi:10.1140/epjp/s13360-021-01685-5

[10] V. Previtali, *Performance evaluation of a crystal-enhanced collimation system for the LHC*. PhD thesis, Ecole Polytechnique, Lausanne, 2010.

[11] D. Mirarchi, *Crystal Collimation for LHC*. PhD thesis, Imperial College, London, Aug 2015.

[12] I. B. Alonso, *et al.*, *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*. CERN Yellow Reports: Monographs, CERN-2020-0010, Geneva: CERN, 2020. doi:10.23731/CYRM-2020-0010

[13] R. Bruce, *et al.*, "HL-LHC operational scenario for Pb-Pb and p-Pb operation," *CERN-ACC-2020-0011*, 2020.

[14] V. M. Biryukov, Y. A. Chesnokov, and V. I. Kotov, *Crystal channeling and its application at high-energy accelerators*. Springer Berlin, Heidelberg, doi:10.1007/978-3-662-03407-1 1997.

[15] W. Scandale and A. M. Taratin, "Channeling and volume reflection of high-energy charged particles in short bent crystals. Crystal assisted collimation of the accelerator beam halo," *Phys. Rep.*, vol. 815, pp. 1–107. 107 p, 2019. doi:10.1016/j.physrep.2019.04.003

[16] R. Bruce *et al.*, "First results of running the LHC with lead ions at a beam energy of 6.8 Z TeV", presented at the IPAC'23, Venice, Italy, May 2023, paper MOPL021, this conference.

[17] S. Fartoukh *et al.*, "LHC Configuration and Operational Scenario for Run 3," *CERN-ACC-2021-0007*.

[18] M. D'Andrea, *Applications of Crystal Collimation to the CERN Large Hadron Collider (LHC) and its High Luminosity Upgrade Project (HL-LHC)*. PhD thesis, University of Padova, Feb 2021. Presented 23 Feb 2021.

[19] E. Matheson, S. A. S. Paiva, and M. di Castro, "LHC Crystal Goniometers: Crystal X-Ray Measurements." Presentation at the LHC Collimation Upgrade Specification Meeting, CERN, Geneva, Switzerland, 2021.

[20] R. Rossi, *et al.*, "Crystal Collimation with protons at injection energy," *CERN-ACC-NOTE-2016-0035*, 2016.

[21] R. Rossi, *et al.*, "Crystal Collimation with protons at flat top energy," 2017.

[22] R. Rossi, *et al.*, "Crystal Collimation Cleaning Measurements with Proton Beams in LHC," 2016.

[23] R. Rossi, *et al.*, "Beam 2 Crystal Characterization Measurements with Proton Beams in the LHC," 2018.

[24] R. Rossi, *Experimental Assessment of Crystal Collimation at the Large Hadron Collider*. PhD thesis, 2017. Presented 26 Jan 2018.

[25] M. D'Andrea, *et al.*, "Crystal Collimation Tests with Proton Beams," *CERN-ACC-NOTE-2019-0022*, 2019.

[26] M. D'Andrea, *et al.*, "Operational Aspects of Crystal Collimation with Proton Beams," *CERN-ACC-NOTE-2019-0023*, 2019.

[27] M. D'Andrea, *et al.*, "Crystal Collimation Tests with Pb Ion Beams," *CERN-ACC-NOTE-2019-0024*, Jun 2019.

[28] S. Redaelli *et al.*, "First observation of ion beam channeling in bent crystals at multi-TeV energies," *Eur. Phys. J. C*, vol. 81, no. 2, p. 142, 2021. doi:10.1140/epjc/s10052-021-08927-x

[29] W. Höfle *et al.*, "Controlled Transverse Blow-Up of High-energy Proton Beams for Aperture Measurements and Loss Maps", in *Proc. IPAC'12*, New Orleans, LA, USA, May 2012, paper THPPR039, pp. 4059–4061.

[30] E. B. Holzer *et al.*, "Beam Loss Monitoring System for the LHC," *CERN-AB-2006-009*, 2005.

[31] M. D'Andrea *et al.*, "Crystal collimation performance at the LHC with a 6.8 TeV proton beam", presented at the IPAC'23, Venice, Italy, May 2023, paper MOPL023, this conference.

[32] D. Mirarchi *et al.*, "Operational Handling of Crystal Collimation at the LHC", presented at the IPAC'23, Venice, Italy, May 2023, paper MOPL022, this conference.

[33] M. D'Andrea *et al.*, "Crystal Collimation of 20 MJ Heavy-Ion Beams at the HL-LHC", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2644–2647. doi:10.18429/JACoW-IPAC2021-WEPAB023

Content from this work may be used under the terms of the CC BY 4.0 licence (© 2022). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.