STUDIES OF CRYSTAL AND AMORPHOUS COLLIMATION OF LEAD, OXYGEN AND NEON BEAMS AT LHC

M. K. Zielińska*[1], R. Bruce, R. Cai, A. Donadon Servelle, P. D. Hermes, B. Lindström, C. Maccani, D. Mirarchi, G. Nigrelli, M. Patecki[1], S. Redaelli, N. Triantafyllou, F. Van der Veken, A. Vella,
CERN, Geneva, Switzerland
[1]also at Warsaw University of Technology, Warsaw, Poland

Abstract

The Large Hadron Collider (LHC) at CERN operates with lead-ion beams for about one month each year, requiring a high-performance collimation system to protect the machine from beam losses. The baseline ion-collimation scheme includes crystal collimation. In 2025, additional ion runs were carried out using oxygen and neon beams, enabling the first experimental comparison of collimation performance between crystal-based and amorphous collimators for these lighter ions. This work presents a comparative review of measured collimation performance for lead, oxygen, and neon ions at the LHC using both amorphous and crystal collimation techniques. The results offer a valuable benchmark for the simulation typically used to predict collimation efficiency and provide key input for future LHC ion runs, for which ion species other than lead are being considered.

INTRODUCTION

The Large Hadron Collider (LHC) [1] at CERN typically operates with lead-lead (Pb-Pb) ion collisions for about one month each year. A highly efficient collimation system [2–5] is essential to protect the machine from beam losses, since the stored beam energy, so far reaching 27.5 MJ, is high enough that even small losses can cause magnet quenches or even damage. Compared to proton beams, ion beam collimation presents greater challenges because of nuclear fragmentation and electromagnetic processes occurring in the collimator materials, which enhance the leakage of losses to superconducting magnets [6–8].

In 2025, a special ion run was performed with proton-oxygen (p-O), oxygen-oxygen (OO), and neon-neon (Ne-Ne) collisions [9], during which the cleaning performance was studied experimentally with different collimation techniques (crystals and amorphous) for the first time at the LHC for these ion species. In this article, we present these results and compare them with the corresponding results for Pb ions. This offers very valuable inputs to studies of potential future LHC operation with other ions than Pb, which is particularly important for Run 5 (foreseen for 2036–2041), for which a range of ions is under consideration [10, 11].

LHC COLLIMATION

The LHC has a multi-stage collimation system for betatron losses in interaction region 7 (IR7), which was primarily designed for proton operation and consists of amorphous blocks of material with lengths up to 1 m. The carbon-based primary collimators (TCP) have the tightest apertures, and they scatter the primary beam halo particles onto the secondary collimators (TCS), complemented by a set of shower absorbers (TCLA). Tertiary collimators (TCT) provide local protection to the final focus system around the experiments [2–5]. We refer to this as the standard collimation system.

The standard system is much less efficient with ions than with protons, since ion fragments scattered out of the TCPs can bypass the TCSs and TCLAs and impact the dispersion suppressor (DS) downstream of the collimation insertion [6]. Therefore, as a part of the High-Luminoisty LHC upgrades [12], one horizontal and one vertical crystal collimator (TCPC) were installed in each beam to improve the performance. These are 4 mm long bent silicon crystals [13–16], which replace the TCPs as primary aperture restrictions during ion operation. The TCPs are then typically retracted to the position of TCS, while the rest of the collimator hierarchy is identical to the standard system.

Crystal collimation relies on the channeling (CH) process in bent crystals [17, 18]. Channeled halo particles acquire a large angular kick, steering them onto an amorphous absorber, where they hit at such a large impact depth that the leakage of out-scattered fragments is minimized. The performance of the LHC crystals is quantified experimentally through angular scans, linear scans, and loss maps.

The angular scans, where the crystal is rotated in the bending plane while provoking beam losses, allow to identify the optimal channeling (CH) orientation. In linear scans, the crystal is kept in CH, and the absorber is moved toward the beam starting from an open position while provoking beam losses. They are used to measure a crystal's deflection angle and its channeling efficiency [14–16].

Loss maps are performed to evaluate the collimation cleaning efficiency. Measured loss maps considered in this study are histograms of losses around the accelerator ring collected by BLMs [19], when beam losses are provoked. Three types of losses are distinguished: on collimators, on normal magnets (warm) and on superconducting magnets (cold). The loss maps are normalized by the beam loss rate [20].

LINEAR AND ANGULAR SCANS

Examples of measured beam losses during angular and linear scans with O at top energy (5.36 Z TeV) are shown in Figures 1 and 2, respectively.

* marta.katarzyna.monikowska@cern.ch,
marta.monikowska.dokt@pw.edu.pl

The obtained channeling angles are, as expected, very similar for O, Ne, and Pb beams for each of the four crystals. Away from the channeling orientation, the crystal behaves as an amorphous material (AM). Between the right edge of the channeling well and the amorphous region on the right, volume reflection (VR) occurs (see Fig. 1), where particles are "reflected" by the interaction with the potential of crystalline planes.

Linear scans were performed with O. The bending angles for B1H, B1V and B2V crystals were around 52 rad, and for B2H crystal around 45 rad. The measured channeling efficiency was for all cases between 71 – 87%, which is fully consistent with results for Pb, except for the B1V crystal, where 49% was found with Pb.

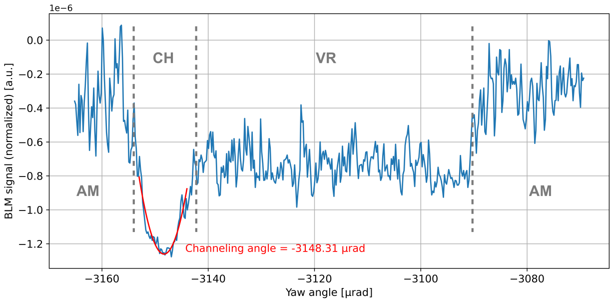

Figure 1: Measured losses at the crystal, as a function of the crystal angle, during a B1H angular scan with O at FT.

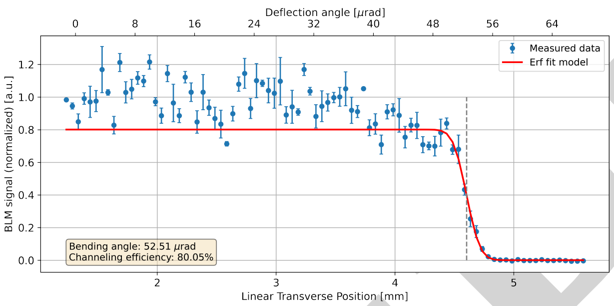

Figure 2: Measured beam losses at the absorber, as a function of its position, during a linear scan in B1H with O at FT.

LOSS MAP STUDIES

Loss maps were performed for O and Ne with both the standard and crystal collimation systems at a 5.36 Z TeV beam energy, with the machine settings in [9] and the primary collimation cuts in Table 1. Some loss maps were performed at flat top (FT), directly after reaching top energy, while others were performed in physics (PH) conditions, where the β^* is squeezed to its smallest value and the separation bumps are collapsed. In PH, the settings of the TCTs are tighter than at FT to protect the final focus system.

Figures 3 and 4 show examples of Ne loss maps in B1H for standard and crystal-based collimation at FT. The full LHC ring and close-ups in IR7 are shown, with the highest cold losses occurring in the IR7 DS area, which is below the green horizontal dashed line in Figures 4 and 7. With crystals in CH, these losses are significantly lower than for standard collimation. To compare the different collimation setups, a global cleaning improvement factor $GC = \frac{\max(_{\text{standard}})}{\max(_{\text{crystal}})}$ was proposed in [21], where $\max(_{\text{standard}})$ and $\max(_{\text{crystal}})$ are the highest losses on cold elements for standard and crystal collimation.

Table 1: Primary Collimation Cuts at Top Energy (5.36 Z TeV for O and Ne, 6.8 Z TeV for Pb) in the 2025 Ion Runs.

Beam	Collimation	TCPC σ	TCP σ
OO	Crystal	5	6.5
Ne-Ne	Crystal	5	6.5
Pb-Pb	Crystal	6	7.5
OO	Standard	OUT	5
Ne-Ne	Standard	OUT	5
Pb-Pb	Standard	OUT	6

The GC values at FT are shown in Fig. 5. In all cases with crystal-based collimation with crystal in CH, the cleaning performance improved. The most significant improvement in B1H, where the Ne beam was subject to more than a factor 7.5 times better cleaning than with the standard system. For the cases with the crystal in VR or AM orientation, the cleaning was worse than with standard collimation. This shows that a proper setting up of the crystal orientation is crucial for achieving improved cleaning efficiency.

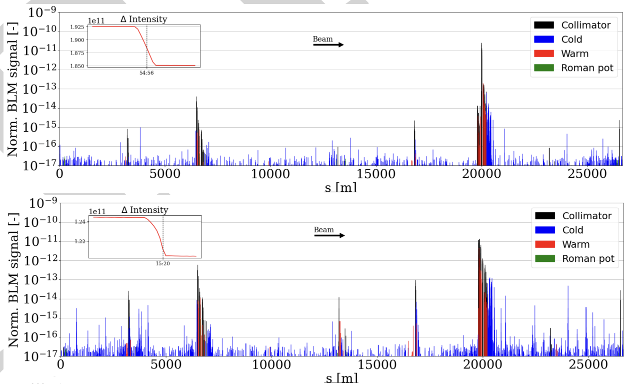

Figure 3: LHC FT loss maps for B1H with crystals (top) and standard collimation (bottom) with Ne beam.

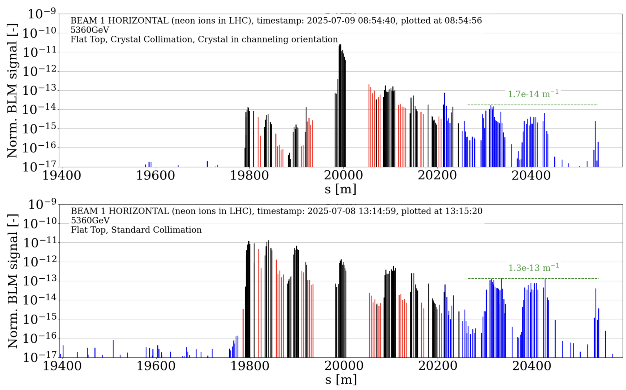

Figure 4: LHC IR7 FT loss maps for B1H with crystals (top) and standard collimation (bottom) with Ne beam.

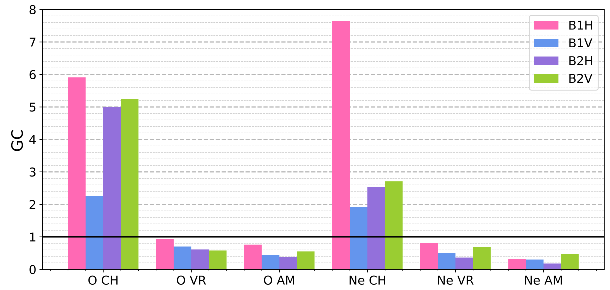

Figure 5: Measured *GC* for O beam and Ne beam at FT with crystal in different orientations.

Examples of loss maps with O in PH for B1H with crystals in CH are shown in Figures 6–7. The corresponding *GC* factors are shown in Fig. 8 together with reference values for Pb at 6.8 Z TeV with crystals in CH, VR and AM orientation. A clear improvement is observed with crystals in CH orientation for O beams. The most significant cleaning improvement, with $GC > 8.5$, was measured in B2V. For Pb, the CH orientation also gives improved cleaning performance. However, the gain in cleaning efficiency is relatively small for B1H. With the exception of B1V, crystal collimation in the VR and AM orientations performs worse than standard collimation, as also observed in the FT results.

Losses on the TCTs at FT and PH are higher with standard collimation than with crystals. High losses on the TCTs can

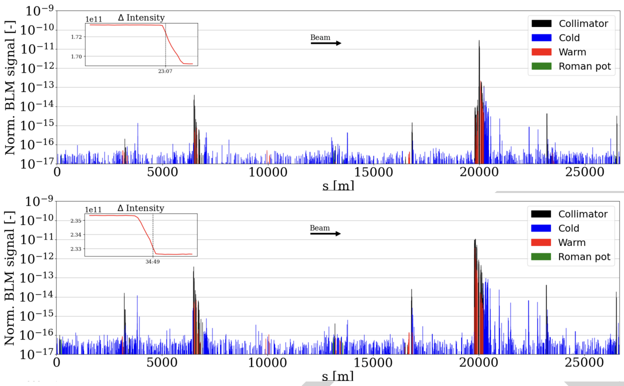

Figure 6: LHC physics loss maps for B1H with crystals (top) and standard collimation (bottom) with O beam.

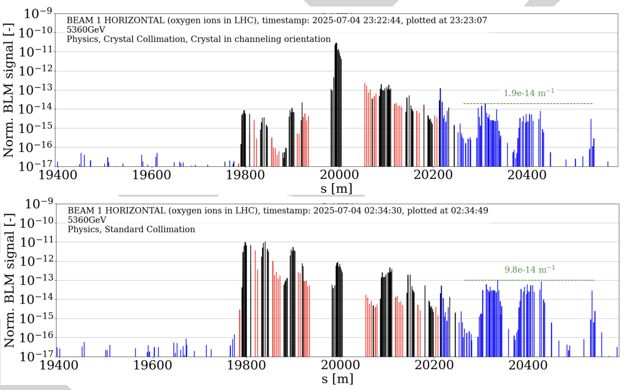

Figure 7: LHC IR7 physics loss maps for B1H with crystals (top) and standard collimation (bottom) with O beam.

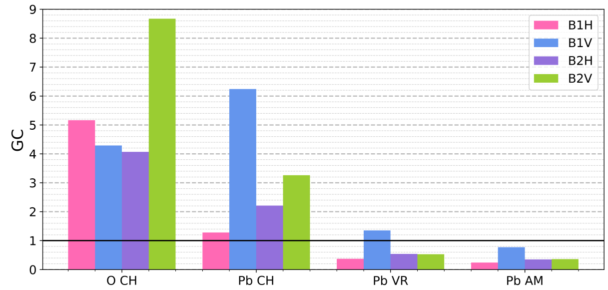

Figure 8: Measured *GC* at Physics for O beam in CH and for Pb beam with crystal in different orientations.

lead to significant backgrounds for the experiments what can disturb their data acquisition.

Comparing the cleaning efficiency in absolute between different ions with crystal in CH orientation, it is seen that the losses in the DS area are typically about a factor 5 lower with Ne and O beams than with Pb. Losses on collimators in the interaction region 3 (IR3) are around an order of magnitude higher with Pb than with the lighter ions.

The cleaning efficiency with standard collimation using O and Ne beams are relatively similar to that obtained with Pb beam. The losses observed in the DS area for O and Ne most likely come from the large number of lighter ions fragments with the same atomic-to-mass number ratio as the main O and Ne beams.

CONCLUSIONS

During the 2025 light ion run, the LHC collimation performance was tested experimentally for the first time with oxygen and neon beams, using both crystal collimation and the standard amorphous collimation system. The crystals were also characterized using linear and angular scans.

The results show that, in comparison to the standard collimation, crystal collimation provide an improved cleaning efficiency with the crystals in the CH orientation, while the cleaning is in most cases worse with the crystal in VR or AM orientation. As expected, the observations are consistent for all three ion species, which stresses the importance of crystal angular control.

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