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CRYSTAL COLLIMATION OF HEAVY-ION BEAMS*

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Abstract

An important upgrade programme is planned for the collimation system of Large Hadron Collider (LHC) for lead–ion beams that will already reach their high-luminosity target intensity upgrade in the LHC Run 3 (2022-2025). While certain effects like e-cloud, beam-beam, impedance, injection and dump protection are relaxed with ion beams, halo collimation becomes an increasing challenge, as the conventional multi-stage collimation system is about two orders of magnitude less efficient than for proton beams. Ion fragments scattered out of the collimators in the betatron cleaning insertion risk to quench cold dipole magnets downstream and may represent performance limitations. Planar channeling in bent crystals has been proven effective for high-energy heavy ions and is now considered as the baseline solution for collimation in the High-Luminosity LHC (HL-LHC) era. In this paper, simulation and measurement results, demonstrating the observation of channeling of heavy-ion beams and improvement of collimation cleaning in the multi-TeV energy regime, and the efficiency of the collimation scheme foreseen for HL-LHC are presented.

INTRODUCTION

In addition to operation as a proton-proton collider, the Large Hadron Collider (LHC) at CERN also operates as an energy frontier heavy-ion collider. Typically one month of each operational year is dedicated to heavy-ion or proton-ion collisions. As part of the High-Luminosity upgrade of the LHC (HL-LHC) [1], several important hardware upgrades are being implemented to ensure a reliable operation of the LHC with higher brilliance $^{82+}Pb^{208}$ beams provided by the LHC Injector Upgrade (LIU) upgrade [2]. The complete LIU upgrade was deployed in the second long shutdown of the LHC (LS2, 2018-2021) and provides brighter beams already for the ongoing Run 3 (2022-2025). This, and the implementation of the key upgrades for ion beams in the LHC during LS2 [3], means that the HL-LHC era for heavy-ions has already started. The HL-LHC proton upgrade will be deployed in LS3 (2026-2029).

The achieved and target Pb beam parameters at the LHC are summarized in Table 1. The key LIU upgrade that enabled increasing the number of bunches in the LHC was the possibility for so-called slip-stacking RF manipulation in the Super Proton Synchrotron (SPS) injector that halves the bunch spacing compared to that of the LHC design for ions. This technique was successfully commissioned in 2022 and 2023 (see, for example, Ref. [4]). The ion bunch intensity is also significantly increased compared to the LHC design. The improved beam parameters increase the stored heavy-ion beam energy to unprecedented values, to more than 20 MJ for the HL-LHC running scenario at 7 Z TeV. This plan poses particularly critical challenges for beam-halo collimation.

Table 1: LHC Design, Achieved and Run 3 Target Pb Beam Parameters at the Start of Collisions [6, 7]

	Design	2018	Run 3
Beam energy (Z TeV)	7	6.37	6.8
Total number of bunches	592	733	1240
Bunch spacing (ns)	100	75	50
Bunch intensity (10^7)	7	21	18
Stored beam energy (MJ)	3.8	12.9	19.9
Norm. trans. emittance (µm)	1.5	2.3	1.65

The LHC features a highly-performing collimation system designed to safely handle in an operationally efficient way stored proton beam energies up to about 700 MJ, as foreseen for the HL-LHC [3]. Collimating heavy-ion beams is more challenging, despite the much lower stored beam energy. As studied extensively in simulations and measurements (see for example [5] and references therein), the fragmentation and electro-magnetic dissociation of heavy ions upon interacting with the collimator material makes the collimation process less efficient than with protons. The lower stored beam energy compensates this effect to a large extent, but beam losses remain a serious concern for the future performance of the HL-LHC as a heavy-ion collider.

Following the exploration of crystal applications at CERN by the UA9 collaboration [8], crystal-based heavy-ion collimation has been pursued as an R&D topic within HL-LHC. It was integrated into the upgrade baseline in 2019, following the empirical demonstration of excellent improvements in the achievable betatron cleaning performance [9] compared to the standard collimation system and the confirmed needs to handle the upgraded heavy-ion beams [3].

In this paper, the crystal collimation concepts are reviewed and the application to LHC heavy-ion beam collimation is discussed. Hardware and control solutions that were elaborated and deployed for HL-LHC heavy-ion collimation are presented. Recent developments include significant improvements of measurement techniques and simulations of crystal

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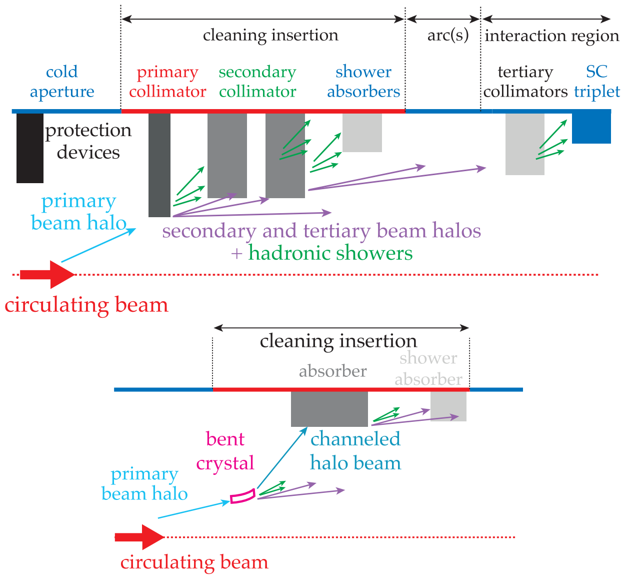

Figure 1: Conventional multi-stage collimation system at the LHC (top) and crystal collimation scheme for the betatron cleaning insertion (bottom).

collimation processes at LHC energies. The improvement of the simulation tools is of general interest to other accelerators. They are the result of a long-lasting effort triggered for the specific case of the LHC. The achieved performance is reviewed by comparing LHC beam measurements with detailed simulations. The performance achieved in 2023, when the crystal collimation was operationally deployed for the first time, is reviewed by presenting the achieved performance and the first operational feedback. Finally, some conclusions are drawn.

CRYSTAL COLLIMATION CONCEPTS

Planar Channeling for Beam Collimation

The use of bent crystals for beam collimation considered in this work relies on *planar channeling*, where charged particles, impinging on a crystal with specific impacting conditions, are trapped by the potential well produced by the parallel lattice planes of the crystal. If channeling conditions are met, particles can follow the “channel” along the full crystal length. If the crystal is bent, the channeled particles experience a net deflection. Bent silicon crystals, specified to provide a 50 µrad deflection [10], are used for LHC collimation applications. Channeling can occur for impinging angles

$$|\theta| \leq \theta_c = \sqrt{\frac{2U_{\max}}{pv}\left(1 - \frac{R_c}{R}\right)}, \qquad (1)$$

where $U_{\max}$ is the height of the potential well generated by neighboring crystalline planes, p and v are the momentum and speed of the incoming particle, R is the bending radius of the crystal, and R_c is the *critical bending radius* below which channeling becomes impossible due to the deformation of the potential well [11]. For the LHC crystals (see for example Ref. [12, 13]), $R = 80$ m and $\theta_c = 2.4$ µrad at 7 TeV. The

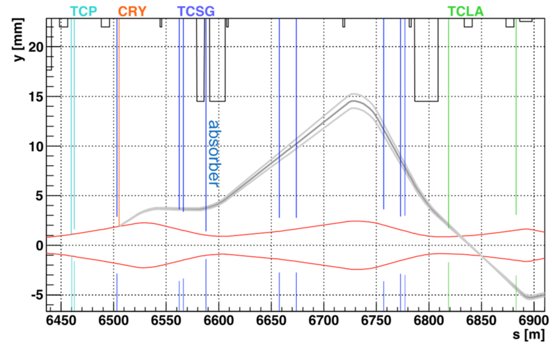

Figure 2: Vertical trajectory of a channeled halo particle for LHC Beam 1 (grey) in IR7 for a crystal (orange) at 5 nominal beam sigmas at 7 TeV. Blue and green lines indicate the positions and settings of TCSG and TCLA collimators.

latter poses critical challenges for the angular control of the crystal. While electromagnetic and nuclear interactions differ for various beam types, the crystal channeling process does not. It also does not exhibit dispersion, thus, if Eq. (1) is fulfilled, the same deflection is induced on protons or ions channelled along the full crystal length, independent of their energy.

Channeling in bent crystals can serve beam collimation by exploiting the kick experienced by halo particles. At the LHC, this kick is roughly ten times larger than the RMS scattering experienced by protons interacting with the full length of the primary collimators. The crystal deflection is coherent and steers halo particles onto a dedicated absorber for each beam and plane. This approach is simpler than the multi-stage collimation scheme previously used for heavy-ions at the LHC. More importantly, it improves the cleaning performance because particle-matter interactions, limiting the collimation performance in the standard multi-stage scheme, are considerably suppressed in crystal channelling.

These potential advantages come with critical challenges. A new technology had to be developed to ensure the required angular control of the crystal throughout the entire LHC operational cycle. In addition, steering the power of the full halo onto a single absorber, instead of spreading it over several devices, poses obvious machine protection issues. For HL-LHC proton beams, the design halo losses reach nearly 1 MW. Crystal collimation for protons would therefore require designing a dedicated beam-halo dumping system in the collimation insertion. The lower stored energies for heavy-ion beams are compatible with the design loss rates in the order of 30 kW that can be handled by existing secondary collimators. This makes crystal collimation particularly interesting for heavy-ion collimation at the LHC.

Layouts for Crystal-based Betatron Collimation

The LHC betatron cleaning system relies on the multi-stage collimation hierarchy [14, 15] shown in the illustrative scheme of Fig. 1 (top). This is based on (i) primary (TCP) and secondary (TCS) collimators and shower absorbers (TCLAs), installed in the interaction region IR7,

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Table 2: Layout names, distance from LHC interaction point 1 (s) and betatron functions ($\beta_{x,y}$) of the four bent crystals installed in IR7. The labels "H" and "V" in the names indicate the installation planes: horizontal or vertical.

Name	s [m]	β_x [m]	β_x [m]
TCPCV.A6L7.B1	19843.62	33.4	255.7
TCPCH.A4L7.B1	19919.50	342.2	64.9
TCPCH.A5R7.B2	20090.16	201.6	135.0
TCPCV.A6R7.B2	20144.70	33.4	255.7

(ii) on tertiary (TCT) collimators in the interaction points to protect the superconducting inner triplet magnets and LHC experiments and (iii) on dedicated machine protection devices in IR6. A multi-stage layout is also used in IR3 for the off-momentum halo cleaning, and other devices are used for injection protection, physics debris collimation, passive absorption against radiation loads, ... [15].

The illustrative layout for a crystal-based collimation scheme is shown in the bottom graph of Fig. 1. Crystals are deployed in IR7 and provide an alternative scheme to the multi-stage betatron scheme, while leaving all the present collimators fully operational. Thanks to the coherent steering of halo particles to a specific location, in an ideal crystal collimation scheme only a single absorber is needed. In the LHC the present IR7 secondary collimators (TCS) can be used to intercept the channeled halo [16]. Fig. 2 shows how they are used for Beam 1 horizontal losses. The TCSs are made of carbon-based material with limited absorbing power, thus additional shower absorbers are also needed to contain the products of induced hadronic showers within IR7 and protect the downstream superconducting magnets [17].

It is noteworthy that the crystal scheme could be deployed in the LHC by using only existing IR7 collimators. The hardware upgrade only involved the addition of new crystal-based primary collimator assemblies, called TCPCs. Only 4 devices were added to IR7 (see Table 2). We will show below that the two schemes can be employed concurrently in heavy-ion operation, with TCPCs inserted closer to the beam than the TCPs, providing an improved cleaning without impacting other functionalities of the IR7 system.

CRYSTAL COLLIMATOR DESIGN

Given the large beam energy stored in the LHC already at the injection energy of 450 GeV, beam collimation is needed in all the phases of the operational cycle. Movable collimators must follow the evolving beam size during the energy ramp and betatron squeeze. The crystal collimators must respect the same specifications and additionally provide precise angular control. The requirement of controlling the crystal angle with a precision below µrad is, to the authors' best knowledge, unprecedented in particle accelerators.

Figure 3 shows 3D models of the full TCPC assembly as installed in the LHC (left) and with a cut view of some key internal components (right). In order to minimize the impedance during high-intensity proton operation, when the crystal is not used, a replacement chamber can be inserted.

While the linear movement system is derived from that of the LHC collimators, providing a 5 µm step resolution and an overall accuracy at the 20 µm - 50 µm level [18], a novel approach needed to be elaborated for the precise angular control [19]. A detailed presentation of this system is beyond the scope of this paper. We just recall that the angular controls are based on a novel piezo-actuated rotational stage with interferometric feedback, enabling sub-µrad precision.

CHARACTERIZATION WITH HIGH-ENERGY HADRON BEAMS

In preparation of the deployment in heavy-ion beam operation, dedicated studies with low-intensity proton and heavy-ion beams were carried out to characterize the performance and properties of the crystal devices after installation. Such measurements were conducted at the LHC at 450 GeV and at top energy (6.8 TeV in 2023), following well-established procedures defined in Run 2 (2015-2018) [20–22].After aligning each crystal device to the circulating beam halo [23] and retracting all collimators that could generate unwanted losses, two types of measurements were performed. In an *angular scan*, the crystal collimator is rotated at constant speed along the deflection plane to identify the orientation that maximizes the probability of halo channelling (see Fig. 4). In a *linear scan*, the crystal collimator is set at the optimal orientation, while the collimator intercepting the deflected halo is retracted and subsequently reinserted in steps to measure the separation of the deflected halo from the main beam (i.e. the acquired angular kick) and the multi-turn efficiency of the channeling process [24]. Both these procedures rely on data gathered via Beam Loss Monitors (BLMs) [25] at the locations of interest (i.e. the crystal and the absorber of the channeled halo).

The results gathered during the first years of Run 3 are summarized in Table 3. In all instances, there is a satisfactory agreement with the required specifications and previous experiences. More details on these measurements can be found in the recent publication [27]. The loss reduction factor in the optimum channeling orientation and the multi-turn channeling efficiency established at 6.8 (Z) TeV from linear scans are also reported. Note that, due to time constraints, at the time of writing, it has not yet been possible to perform linear scans with the Beam 1 horizontal crystal at top energy. This TCPC was installed in 2023 as a part of the HL-LHC upgrade but had to be temporarily removed for fixing a mechanical issue with the linear movement that developed at the start of the run [27]. However, measurements at injection indicate a similar performance to the three other crystals.

HEAVY-ION CLEANING PERFORMANCE

The integration of crystal collimation in the HL-LHC upgrade baseline was the result of a solid experimental demonstration of heavy-ion collimation cleaning improvements with this technique compared to the conventional collimation scheme. Beam validation was carried out in Run 2 (2015-2018) with a range of beam species (protons, Pb ions and Xe

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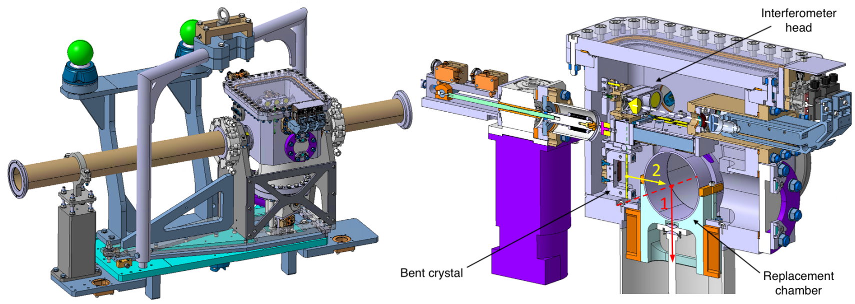

Figure 3: Left: Schematic view of the horizontal TCPC assembly installed on the LHC beam pipe. Right: Detail of the goniometer with its replacement chamber and the crystal, with their directions of movement: (1) and (2), respectively.

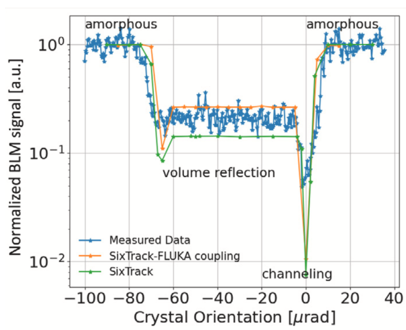

Figure 4: Results of an *angular scan* performed for proton beams at 6.5 TeV for a prototype LHC crystal: measurements (blue) and simulations with two different codes [26].

Table 3: Crystal parameters measured at 6.8 Z TeV with p and Pb beams [27]:bending angle (B), loss reduction factor in channeling (R), see Fig. 4, multi-turn channeling efficiency [22] (E). The low R_p of B2H is possibly due to non-standard measurement conditions.

		B1H	B1V	B2H	B2V
B_p	[μrad]	-	46.3	45.4	51.1
B_{Pb}	[μrad]	-	46.3	-	49.7
R_p		6.1	22.6	2.8	19.2
R_{Pb}		2.7	4.6	4.6	3.8
E_p	[%]	-	68	70	73
E_{Pb}	[%]	-	34	-	50

ions) and at three beam energies (450 (Z) GeV, 6.37 (Z) TeV and 6.5 (Z) TeV) [20–22, 28] by using a prototype crystal-collimation test stand in IR7 installed in 2015 [29]. The most relevant results for heavy-ion collimation were achieved in 2018 at 6.37 Z TeV, in the closest conditions to the final configuration for HL-LHC [9, 30]. An example of the beam loss distribution ("loss map") with crystal collimation, while inducing losses for both beams and planes, is shown in Fig. 5. It was found that the measured improvement in cleaning efficiency compared to the standard collimation scheme reached up to a factor 7 for the best crystals [9].

Various simulation tools are available to model the interactions of hadron beams with the crystal and to combine this with the multi-turn beam dynamics required to model the collimation processes. At CERN, simulations [31] use a native

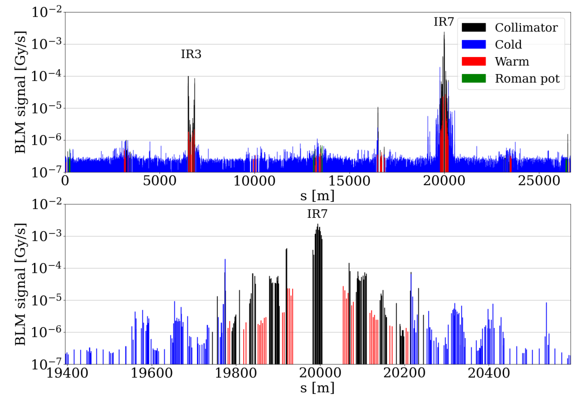

Figure 5: Loss pattern observed while generating sustained losses on all four planes at the same time, with 20 circulating Pb-ion bunches and using crystal collimation: full ring (top) and the IR7 region (bottom) [9].

crystal-interaction routine integrated in SixTrack [32], now ported to XSuite [33]; the SixTrack-FLUKA coupling [34] with a dedicated FLUKA routine for crystals [35];a Geant4 crystal routine [36] coupled to SixTrack or XSuite. A comparison of these simulations with an angular scan for proton beams is shown in Fig. 4. Simulation results for heavy-ion collimation performance are discussed in the next section.

RUN 3 PERFORMANCE

Crystal-collimation Setting Strategy

The 2023 collimation settings were devised from simulation studies and experience gathered in machine tests. The results collected during the run also served as a benchmark for the simulation tools. The collimator settings employed are given in Table 4. The benchmark between simulated and measured loss patterns is depicted in Fig. 6, showing a good agreement. To ensure optimum phase-space coverage by the IR7 system, the operational settings are more complex than the illustrative scheme in Fig. 1. The full set of TCP and TCS collimators are kept in place while the TCPCs have apertures slightly closer to the beam than the TCPs. With this approach, a gain in cleaning is provided by the crystal collimators, while TCP/TCS protection is maintained in case of failures. Note that this approach is acceptable from an impedance point of view given the relatively small charge of heavy-ion bunches.

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Table 4: Final Collimator Settings for the 2023 6.8 Z TeV Pb Ion Run at Start of Collisions

Collimator family	IR	Half-gap [σ]
TCPCH/V	7	4.75/5.0
TCP	7	6.0
TCS	7	6.5
TCLA	7	8.0
TCT	1/5/8	10.5
TCT	2	13.0 (B1)/10.5 (B2)

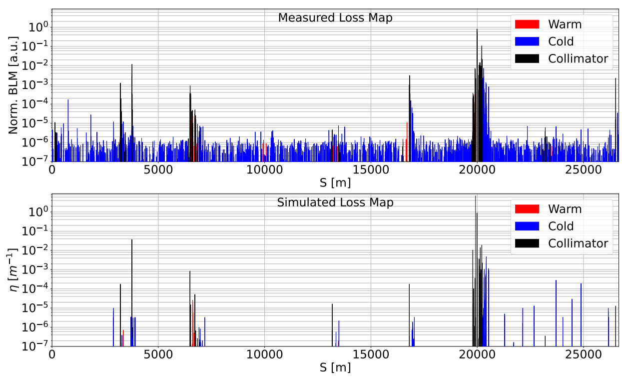

Figure 6: Measured (top) and simulated (bottom) 2023 loss map in B1H with 6.8 Z TeV $^{208}Pb^{82+}$ and final collision collimation setup (Table 4).

Operational Experience with High Intensities

In 2023, crystal collimation was deployed for the first time for the full Pb ion run at 6.8 Z TeV, with record stored beam energies up to 17.5 MJ. The use of machine learning tools [37, 38] accelerated the beam commissioning phase of the crystal setup. Alongside the initial tests, many software tools and functions have been developed to support the use of crystals during operation. To guarantee that the crystal stays in channeling mode during the energy ramp of the beam, operational functions have been established to vary angle and position as a function of energy [22]. A software tool was created to allow fast realignment during operation.

Issues Encountered and Follow-up Items

A loss pattern not compatible with optimal channeling was observed when increasing stored beam intensities. Several investigations were carried out to identify the possible correlation to machine and/or beam parameters. Clear conclusions could not be drawn, although uncontrolled heating of the TCPC components leading to a change in crystal angle is suspected to be the source of the problem. The issue was mitigated by deploying an automatic software that performs periodic angular re-optimizations as soon as the 6.8 TeV flat top energy is reached, with time intervals of about 5 minutes to avoid losing channeling. The observed trend is shown in Fig. 7, where the angular shifts required to recover optimum channeling conditions are plotted versus time at top energy. The null ordinate value is the reference setting established with low intensity. Deviations larger than 20 µrad were measured, which can hardly be explained by beam dynamics effects (typically ten times smaller). Further investigations are ongoing and upgrades of the controls are also envisaged. A deployment of real-time feedback-based loss pattern recognition to allow counteracting hardware instabilities during the dynamic parts of the LHC cycle is also foreseen [39].

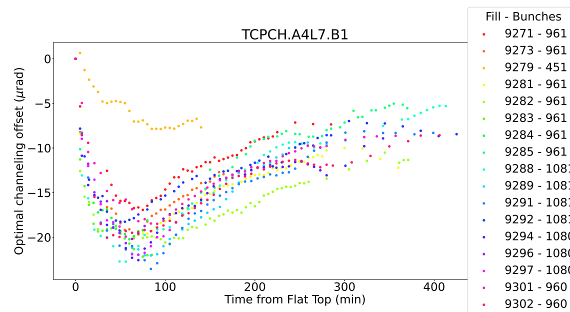

Figure 7: Evolution of the optimum channeling angular orientation for the TCPCH.A4L7.B1 as measured in different ion physics fills at 6.8 Z TeV as a function of time after reaching the top energy.

CONCLUSIONS

Crystal collimation has been studied for several years as a higher-performing alternative to the classical multi-stage collimation systems for hadron beams. Thanks to the recent advancement in crystal manufacturing and bending techniques as well as in the technology for angular control of bent crystals in an accelerator environment, a crystal-based betatron collimation system was deployed for the first time for halo collimation in the LHC for heavy-ion beams. This deployment provides an ideal test bed for future machines. The limited total beam power in these heavy-ion beams allowed the use of existing collimators for the safe disposal of the channeled halo.

The overall experience in the first year of operation is positive, with crystal collimation measured to be at least a factor 5 better than with the standard system. Some concerns were however identified, which will need continuous operational experience at high intensity for a better understanding. One concern was the observation of changes in the optimal angular orientation, which requires continuous optimization to maintain channeling. A possible cause that is being studied is a small heating of the crystal assembly due to beam-impedance effects. The possibility to mitigate this through automated tools for crystal angle optimization is now under investigation.

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