OPERATIONAL HANDLING OF CRYSTAL COLLIMATION AT THE LHC*

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Abstract

A non-negligible risk of a magnet quench occurring due to the reduced cleaning performance of the LHC collimation system with lead ion beams is expected at an energy of 6.8 Z TeV. Crystal collimation has therefore been integrated into the High Luminosity LHC (HL-LHC) upgrade baseline to overcome present limitations. This involves the installation of 4 new crystal primary collimators. Upgraded devices were installed based on the experience and experimental evidence gathered with a previously-installed test stand. In preparation for the new operational challenges, the controls of the new devices were integrated in the high-level LHC collimation control system, which is used to orchestrate the operation of these devices in harmony with all the other components of the machine. A dedicated application was also developed to address three main tasks: to efficiently find planar channeling using Machine Learning models developed at CERN; to optimise the angular orientation to maximise the channelling efficiency; to monitor that the optimal channelling orientation is kept throughout the fill. This paper will present and discuss all of these aspects.

INTRODUCTION

The increased total stored energy of LHC ion beams after the LHC Injector Upgrade (LIU) [1,2], calls for an improved cleaning performance of its collimation system [3,4]. The main limitations of the present system with heavy ion beams originate from fragmentation and electromagnetic dissociation experienced in primary collimators. Fragments acquire a deflection that is not sufficient to be intercepted by the secondary stage and are therefore able to emerge from the collimation insertion (IR7). However, their momentum deviation is sufficient for them to be lost at the first dispersive peak in the Dispersion Suppression region (IR7-DS), which becomes the limiting location in terms of performance.

While the LHC collimation system has achieved a remarkable low cleaning inefficiency of $\eta \sim 10^{-4}$ (i.e. ratio between losses on primary stage and highest losses in IR7-DS) with proton beams, the mechanisms described above lead to a worsening of performance with heavy ion beams down to $\eta \sim 10^{-2}$ [5]. This makes ion collimation more challenging even if the planned total stored beam energy is about 30 times less than for protons.

Quench tests with heavy ion beams carried out in 2015, showed that a maximum of about 10 MJ of stored beam energy can be safely handled by the standard LHC collimation system, in the loss scenario where the beam lifetime is reduced to 0.2 h [6]. However, the targeted stored energy in heavy ion beams after the LIU upgrade is about 22 MJ. Thus, an improved cleaning performance was deemed necessary for the LHC collimation system.

The initial upgrade scenario, relying on the installation of additional collimators in the IR7-DS [4] before the LHC Run 3, had to be deferred because of delays with the 11 T dipole required for this scheme. Therefore, crystal collimation, initially studied as an alternative scenario, became the baseline. A significant effort was therefore put in place to upgrade devices initially designed for feasibility studies of crystal-assisted collimation in the LHC, and to deploy all the required architecture to allow their efficient operation in a nominal heavy ion run.

Four devices are present in the LHC, one per beam per plane, providing a complete layout for crystal-assisted collimation. They are composed of a goniometer featuring a linear and a rotational stage holding a bent crystal. A replacement chamber is used to hide the crystal when not used during high intensity proton operation. The crystal primary collimators are single sided as the betatron motion will ensure cleaning of the entire halo. However, having bent crystals on both sides for each plane would provide a faster cleaning and better coverage in case of orbit drifts. Studies on this need are ongoing and possible solutions to build such a system have already been identified [7].

UPGRADED DEVICES

Bent crystals are hosted in high-precision goniometers, which provide an angular resolution below 0.1 µrad and a stability below 1 µrad even during the execution of combined linear and angular motion required to follow the beam envelope during the energy ramp [8,9]. The linear stage is actuated by a stepper motor used for all standard collimators, with 5 µm resolution [3]. Moreover, the control of the stepping motor for the linear axis is in closed loop using the resolver as feedback to guarantee a smooth motion eliminating vibrations on the crystal angular positioning. Several improvements were implemented along the years based on operational experience gained with first prototypes: the first mechanical resonance was brought above 130 Hz by increasing stiffness; high temperature piezo actuators and feedthroughs were developed to increase the bakeout temperature [9]. However, the main weakness was the long-term maintainability and robustness of the interferometric system

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* Work supported by the HL-LHC project

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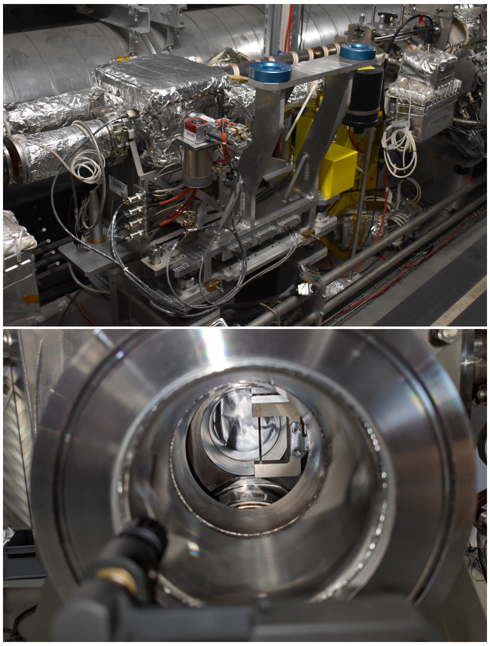


Figure 1: Pictures of a crystal collimator assembly installed in the LHC tunnel (top) and crystal as seen by the beam (bottom) acting in horizontal plane of Beam 2.

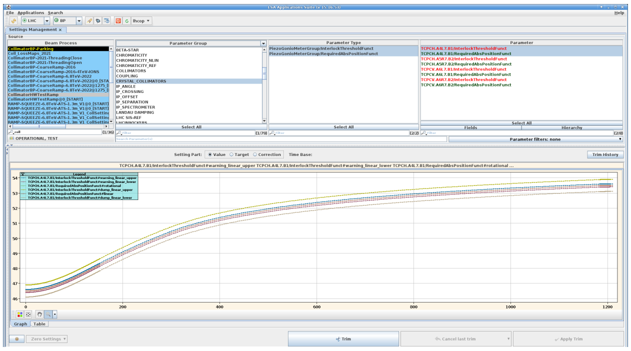
used to keep the angular feedback loop closed. This was addressed by a complete re-design of the interferometric system which now also includes a secondary redundant interferometric measurement to further improve the angular reference reliability.

The experience gathered during experimental tests in the LHC between 2015 and 2018, with both proton and heavy ion beams, was used to guide the decision on the manufacturing technology for operational crystals. In particular, it was demonstrated that strip crystals are best suited for heavy ions crystal-assisted collimation [7]. Thus, a set of 12 new strip crystals was extensively tested at CERN using both test beams extracted from the Super Proton Synchrotron (SPS) and X-ray techniques to asses their channeling performance and miscut angle[1], respectively. The four crystals showing the best overall performance (i.e. matching specifications for bending [10], highest channeling efficiency, lowest torsion and miscut) were selected for installation, with two selected as spares.

Two upgraded devices were installed in the collimation insertion during the Year End Technical Stop (YETS) 2021-2022, and two in the YETS 2022-2023. A picture of a full assembly composed of a crystal installed inside the goniometer is shown in Fig. 1.

FRONT-END SOFTWARE ARCHITECTURE

An upgraded Front-End Software Architecture [11] (FESA) class was deemed necessary for operational use of the goniometers. The main changes with respect to the initial class deployed for the feasibility studies were the centralisation of the control of the three degrees of freedom into one single class (i.e. motion of replacement chamber, linear stage, angular stage), and the deployment of redundant limits around the linear stage position. The former allows the entire assembly to be treated as a single device through high level control, while the latter allows the same safety standards to be applied for crystal handling as for any other standard collimator. For the latter, the required linear position is sent to the Motor Driver Controller (MDC), while the actual position is read independently by the Position Readout System (PRS) that checks that the position is within pre-defined and validated limits, with an additional redundant check on the allowed position as a function of beam energy [12].



CollimatorBP-Parking
Coll_LossMaps_2021
CollimatorBP-2021-ThreadingClose
CollimatorBP-2021-ThreadingOpen
CollimatorBP-CoarseRamp-2016
CollimatorBP-CoarseRamp-2016-4TeV-IONS
CollimatorBP-CoarseRamp-6.8TeV-2022
CollimatorBP-CoarseRamp-6.8TeV-2022@0_[STA
CollimatorBP-CoarseRamp-6.8TeV-2022@1275_[
CollimatorBP-CoarseRamp-6.8TeV-2022@1275_[
CollimatorHWTestRamp
CollimatorHWTestRamp@0_[START]
RAMP-SQUEEZE-6.8TeV-ATS-1.3m_V1@0_[START]
RAMP-SQUEEZE-6.8TeV-ATS-1.3m_V1@0_[START]
RAMP-SQUEEZE-6.8TeV-ATS-1.3m_V1_CollSettin
RAMP-SQUEEZE-6.8TeV-ATS-1.3m_V1_CollSettin
RAMP-SQUEEZE-6.8TeV-ATS-1.3m_V1_CollSettin

coll (1/36)
OPERATIONAL, TEST

BETA-STAR
CHROMATICITY
CHROMATICITY_NLIN
CHROMATICITY_REF
COLLIMATORS
COUPLING
CRYSTAL_COLLIMATORS
IP_ANGLE
IP_CROSSING
IP_OFFSET
IP_SEPARATION
IP_SPECTROMETER
LANDAU DAMPING
LHC SIS-REF

(1/79)

PiezoGonioMeterGroup/InterlockThresholdFunct
PiezoGonioMeterGroup/RequiredAbsPositionFunct

(2/2)

TCPCH.A4L7.B1/InterlockThresholdFunct
TCPCH.A4L7.B1/RequiredAbsPositionFunct
TCPCH.A5R7.B2/InterlockThresholdFunct
TCPCH.A5R7.B2/RequiredAbsPositionFunct
TCPCV.A6L7.B1/InterlockThresholdFunct
TCPCV.A6L7.B1/RequiredAbsPositionFunct
TCPCV.A6R7.B2/InterlockThresholdFunct
TCPCV.A6R7.B2/RequiredAbsPositionFunct

(2/8)

Setting Part: ● Value ○ Target ○ Correction Time Base:

TCPCH.A4L7.B1/InterlockThresholdFunct#warning_linear_upper TCPCH.A4L7.B1/InterlockThresholdFunct#warning_linear_lower TCPCH.A4L7.B1/RequiredAbsPositionFunct#rotational ...

TCPCH.A4L7.B1/InterlockThresholdFunct#warning_linear_upper
TCPCH.A4L7.B1/InterlockThresholdFunct#warning_linear_lower
TCPCH.A4L7.B1/RequiredAbsPositionFunct#rotational
TCPCH.A4L7.B1/InterlockThresholdFunct#dump_linear_upper
TCPCH.A4L7.B1/RequiredAbsPositionFunct#linear
TCPCH.A4L7.B1/InterlockThresholdFunct#dump_linear_lower

Figure 2: Example of settings and relative limits during an energy ramp for the linear stage of a crystal acting in the horizontal plane of Beam 1, as stored in LSA.

The FESA class of standard LHC collimators was taken as a reference, to rely on well-established, high-level settings generation and handling, with a minimal set of changes required. An overview of the properties and fields used in the new FESA class is reported in [13].

HIGH-LEVEL CONTROLS

The ensemble of drives can now be treated as a single device. Thus, after declaring it in the Controls Configuration DataBase [14] it has been possible to control all its properties from the LHC Software Architecture (LSA) [15]. Moreover, the LHC operations are fully automated by means of a Sequencer [16], in which dedicated tasks are present to handle any machine component. Dedicated tasks were developed for the goniometers, mostly by adapting tasks used to handle standard collimators. Standard high-level controls can be used for the crystals, allowing the generation and storage of settings for both linear and angular stages in any machine configuration, and fully automated handling along the entire cycle. An example of settings storage in LSA is shown in Fig. 2. Thanks to these developments, crystals can now be orchestrated in harmony and synchronously with all the other components of the machine [17].

CRYSTAL COCKPIT

A dedicated application has been developed with the aim of centralising all the main needs during operation. It has been written with a modular and flexible structure, allowing for an easy extension of functionalities. Presently, it has three main features to improve the beam commissioning and

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[1] Relative angle between cutting surface and crystalline planes.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL022

the standard operation: (1) fast identification of the crystalline plane orientation; (2) optimisation of the channelling orientation; (3) monitoring of the optimal orientation.

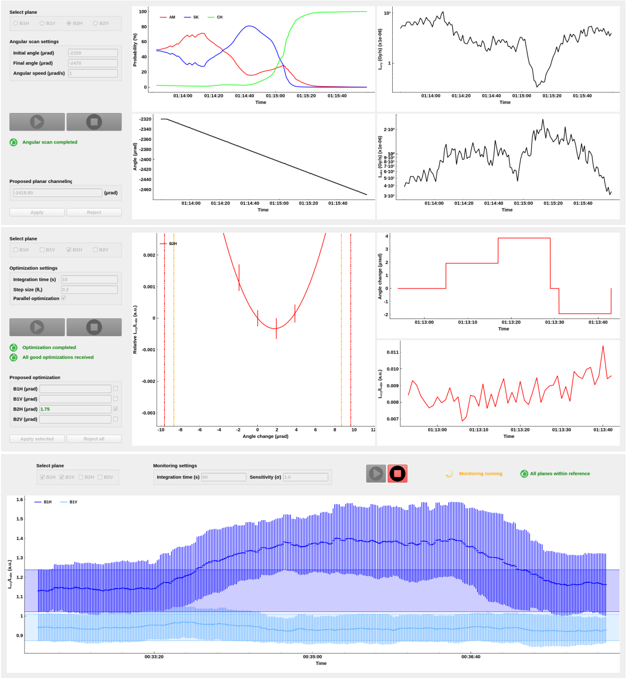
The item 1 is meant to ease the detection of channelling for newly installed crystals and if for any reason the absolute reference frame is lost. This operation can take a few hours using standard techniques, because several mrad must be scanned with the speed of a few µrad/s to identify the orientation of the crystalline plane [7, 18]. A pattern recognition model based on a 1D Convolution Neural Network has been trained to identify channelling in both main planar and skew planes [19,20]. This has been tested in 2022 for the first time obtaining promising results. The tool correctly identified the coherent processes for which it has been trained, as shown in Fig. 3 (top). The model is presently fed with 1 Hz data, and its training on 100 Hz data is on-going. This will allow the scan speed to be increased up to tens of µrad/s.

A rough angular orientation for main planar channelling is proposed to the user if crystalline planes are identified with this technique. This angular orientation can then be optimised using the optimisation functionality: a fine scan around the actual angular position is performed, with the aim of minimising the ratio $L = L_{cry}/L_{abs}$, where L_{cry} and L_{abs} are the losses recorded at crystal and absorber of the channelled halo, respectively. These two quantities are strongly correlated, because L_{cry} is reduced in the optimal channelling orientation, given the suppression of the nuclear interaction rate at the crystal, while L_{abs} increases because of the channelled and deflected halo impacting on the absorber. The ratio L is used to increase sensitivity. As a safety measure, the scan is limited to $\pm 1\theta_c$, where θ_c is the critical channelling angle that is calculated based on the actual LHC energy and crystal specifications [10]. The users can tune the time over which $\overline{L}$ is evaluated and the step size in units of θ_c. Moreover, the optimisation of the four crystals can be performed in parallel. This feature was also validated during tests with heavy ion beams in 2022, demonstrating a resolution and stability in determining optimal orientation of $\sim 0.1\ \theta_c$. An example is shown in Fig. 3 (middle).

After the identification of optimal channelling, the channelling orientation can be monitored to detect if it is lost. A reference $\overline{L}_{ref} \pm s\Delta L_{ref}$ is determined using a time window that can be tuned by the user, where ΔL_{ref} and s are the rms of recorded losses and sensitivity respectively. A sliding window is maintained with the optimal channelling considered to be lost if an acquisition if not compatible with the reference:

$$|\overline{L}_{ref} - \overline{L}_i| > s\Delta L_{ref} + \Delta L_i, \qquad (1)$$

where i the actual acquisition. The eventual loss of optimal channelling is notified by means of a vocal message using the LHC announcer [21]. The LHC shift crew can then promptly re-optimise channelling. The concept behind this functionality was successfully validated during tests with heavy ion beams in 2022, with only a few bunches circulating in the machine and losses barely visible to a human eye. The optimal channelling orientation was lost and re-established by deliberately turning the crystal by $1\theta_c$. This loss of channelling was correctly detected, as shown in Fig. 3 (bottom). Further validation will be needed with high intensity beams where much larger losses are expected. This working regime should improve the sensitivity to the minimum detectable angle change, but cross talk from losses in the other beam and planes might represent a potential detrimental effect.


Select plane
○ B1H ○ B1V ● B2H ○ B2V
Angular scan settings
Initial angle (µrad) -2320
Final angle (µrad) -2470
Angular speed (µrad/s) 1
Angular scan completed
Proposed planar channeling -2419.80 (µrad)

Select plane
☐ B1H ☐ B1V ☑ B2H ☐ B2V
Optimization settings
Integration time (s) 10
Step size (θ_c) 0.2
Parallel optimization ☑
Optimization completed
All good optimizations received
Proposed optimization
B1H (µrad) ☐
B1V (µrad) ☐
B2H (µrad) 1.75 ☑
B2V (µrad) ☐

Select plane
☑ B1H ☑ B1V ☐ B2H ☐ B2V
Monitoring settings
Integration time (s) 60
Sensitivity (σ) 1.0
Monitoring running
All planes within reference

Figure 3: Graphical User Interface panels of the application developed for crystal collimation handling: identification of crystalline planes (top), channelling optimisation (middle), channelling monitoring (bottom).

CONCLUSIONS

Crystal collimation has been integrated in the HL-LHC upgrade baseline to improve cleaning performance with heavy ion beams, aiming at the safe handling of 22 MJ of stored beam energy as of LHC Run 3 (2022-2025). A significant effort was made to achieve compliance with the operational requirements of devices that were initially developed for feasibility studies. Third generation goniometers have now been deployed, addressing the last potential issues for their operational stability and reliability over long runs. Low and high-level controls have been implemented to allow the fully automated operation of crystals as for any other device in the machine. A dedicated application has also been developed, featuring pattern recognition for the fast, first identification of the main crystalline channelling plane, channelling optimisation, and monitoring. All this will be used during heavy ion operations in order to ensure the operational stability of the crystal collimation system, which is still to be proven over long runs.

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPL022

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