LHC COLLIMATION CONTROLS SYSTEM FOR RUN III OPERATION

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Abstract

The Large Hadron Collider (LHC) collimation system is designed to protect the machine against unavoidable beam losses. The collimation system for the LHC Run 3, starting in 2022, consists of more than 100 movable collimators located along the 27 km long ring and in the transfer lines. The cleaning performance and machine protection role of the system critically depend on the accurate positioning of the collimator jaws. The collimation control system in place enables remote control and appropriate diagnostics of the relevant parameters. This ensures that the collimators dynamically follow optimum settings in all phases of the LHC operational cycle. In this paper, an overview of the top-level software tools available for collimation control from the control room is given. These tools range from collimator alignment applications to generation tools for collimator settings, as well as collimator scans, settings checks and machine protection sequences. Amongst these tools the key upgrades and newly introduced tools for the Run 3 are presented.

INTRODUCTION

The CERN Large Hadron Collider (LHC) accelerates and collides two counter-rotating beams towards the unprecedented design centre-of-mass energy of 14 TeV [1]. It is made up of eight arcs containing superconducting magnets and eight straight sections that are referred to as insertion regions (IRs) [2].

The quench limit of the LHC superconducting magnets is of the order of 10–30 mW/cm^3 [3] and the damage limit of metal is of a few hundred kJ per cm^3 [4], to be compared to the stored beam energy of more than 300 MJ planned for Run 3. Therefore, a high-performance and robust collimation system is installed to safely dispose of beam losses in the collimation regions, providing a cleaning efficiency of 99.998% of all halo particles [5].

A total of 123 movable collimators are installed in the LHC for the start of Run 3 in 2022, whereby 14 betatron collimators, 6 injection protection collimators and all 12 transfer line collimators have been newly installed/replaced and 2 crystal collimators are planned to be replaced. The LHC ring collimators are mainly concentrated in two dedicated cleaning insertion regions (as shown in Figure 1); IR7 is dedicated to the betatron cleaning, and IR3, where the dispersion is larger, provides off-momentum cleaning [6]. Other collimators are installed in the experimental region to protect the inner triplet magnets, and in the high-luminosity regions IR1 and IR5, to dispose of the collision debris.

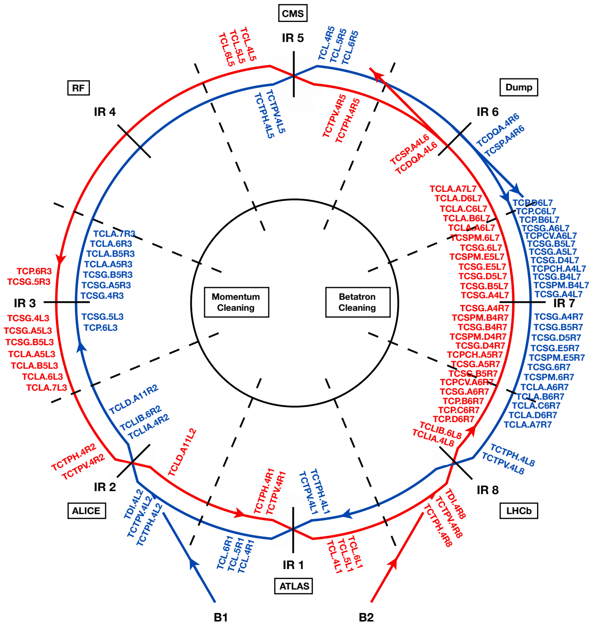

Figure 1: The Run 3 LHC ring collimation system layout.

The collimators have different designs, orientations (horizontal, vertical or skew) and roles for cleaning and protection (refer to Table 1); (1) Primary, secondary collimators, and shower absorbers are located in IR3 and IR7, (2) Tertiary collimators protect the super-conducting triplet quadrupoles in all experimental regions, (3) Injection protection devices (TDI, TCLI) protect the machine in case of injection errors (also the transfer line (TCDIL) collimators), (4) Dump collimators protect against asynchronous or unclean beam dumps in IR6, (5) Crystal collimators, in IR7, enhance ion beam cleaning, (6) Fixed aperture, passive collimators in IR3/7 shield specific magnets from high radiation doses (TCAP).

Table 1: Movable LHC Ring Collimators

Collimator	Description	Number
TCP	Primary	8
TCSG/TCSP/TCSPM	Secondary	28/2/9
TCT	Tertiary	16
TCLA	Shower Absorber	18
TCL	Physics debris	12
TCLD	Disp. Suppressor	2
TDI/TCLI	Injection Protection	6/4
TCDQ	Dump Protection	2
TCPC	Crystal collimator	4

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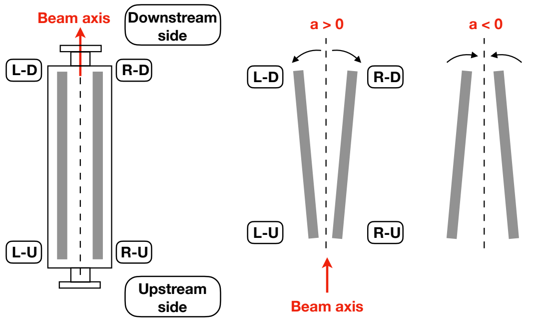
BACKGROUND

Collimator Design and Control

A collimator is made up of two parallel absorbing blocks, referred to as *left* and *right* jaws, which are typically positioned symmetrically around the beam, except for the 2 one-sided TCDQ. Each jaw is controlled by two stepping motors to precisely adjust the jaw position and angle with respect to the beam [7]. The maximum and minimum possible angles are ±2 mrad [8]. The collimation coordinate system is displayed in Fig. 2, whereby the jaw corners are referred to as left-up (LU) and right-up (RU) when they are upstream of the beam and left-down (LD) and right-down (RD) when they are downstream of the beam (or at the end of the beam).



(a) Jaw coordinate system (b) Jaw angular tilt convention

Figure 2: (a) The collimator coordinate system and (b) the jaw tilt angular convention as viewed from above, from [9].

Each collimator has Four Linear Variable Differential Transformer (LVDT) sensors and resolvers to independently measure the position of the collimators' axes in real-time at 100 Hz [10]. An additional 2 LVDTs are installed for direct collimator gap measurements, resulting in a total of 6 LVDTs per collimator used for jaw position interlocking [11, 12]. Moreover, the tanks housing 60 of the collimators have an additional motor, resolver and non-interlocked LVDT, to move the entire collimator in the orthogonal plane. This feature allows exposing a fresh surface to the beam in case of suspected collimator damage from beam losses. Finally, 33 collimators have 2 Beam Position Monitoring (BPM) pick-up button installed in each jaw, to provide a direct measurement of the beam orbit at the collimator location [13]. A third BPM is mounted on the collimator vacuum tank of 13 of these collimators, to measure the beam position on the axis orthogonal to the cleaning plane.

The tightest settings of 5 σ for the TCPs correspond to gaps of ~ 1 mm at 7 TeV, requiring ~ 20 µm position accuracy. To ensure that, in static and dynamic conditions, the jaw positions stay within safe operational windows, a complex system of threshold functions has been implemented [7]. The limits are defined as functions of time, beam energy, and $\beta*$ functions that express the amplitude of the beam oscillation in the IP (or beam size) [4].

Four limit functions (inner and outer dump and warning limits) can be defined for each LVDT, for a total of 24 functions. If the measured axis position violates any of the dump limits, which are always active in parallel, the low level control system requests an immediate abort of the circulating beams. The interlocks per collimator for jaw position and gap measurements include; limits versus time (inner and outer thresholds for 6 degrees of freedom, i.e. 12 limits), maximum allowed gaps versus beam energy (2 limits) and gap thresholds versus $\beta*$ (inner and outer thresholds for 2 gaps, i.e. 4 limits). The energy and $\beta*$ dependent limit functions catch failures in triggering the start of time functions at the start of energy ramp: a beam dump is eventually requested if the collimator gaps are not scaled down as needed by smaller beams [7]. The list of key parameters for the collimation system is presented in Table 2 for a typical LHC operational cycle that includes separate functions for the energy ramp, betatron squeeze and collision process. Injection protection collimators require a simple implementation, as they do not need to be controlled through functions of time.

Table 2: Collimation System Parameters (excluding TCDQ)

Parameters	Number
Movable collimators in the ring	109
Transfer line collimators	12
BPM pick-ups	145
Stepping motors	544
Resolvers	536
Position/gap measurements	786
Interlocked position sensors	726
Motor settings Vs Time	1452
Threshold settings Vs Energy	242
Threshold settings Vs $\beta*$	484

Collimation Controls Software Technologies

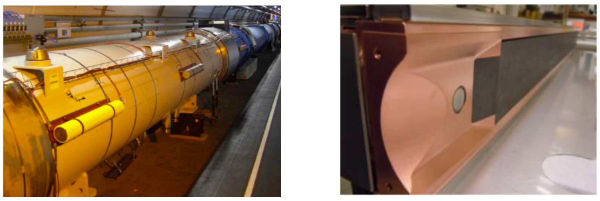
The collimation controls are used for all LHC ring and transfer line collimators. The controls consist of various software applications, each one providing a different set of user functionality, ranging from; collimator alignments and settings' controls to loss map and machine-protection check tools.

Various programming languages and tools are involved in developing the controls, including; Java for user interfaces, Front-end software architecture (FESA) [14] for device control, Python and SWAN [15] for machine learning and data analysis, LHC Software Architecture (LSA) [16] with Oracle for operational settings management, Next CERN Accelerator Logging Service (NXCALS) [17] for data logging and Apache Spark for data processing.

COLLIMATOR ALIGNMENTS

At the start of each year, the LHC goes through a commissioning phase to ensure that all collimators are correctly set up and ready for nominal operation [18]. During the commissioning phase various alignment campaigns [19] take place at different machine states, to set up the correct collimation hierarchy. Collimator alignments are performed with "setup beams" i.e. low intensity, which at the LHC typically corresponds to 3 bunches at 10^{11} p/beam. The collimator settings are monitored along the year as the beam orbit may shift over time [20], thus potentially requiring the collimators to be realigned. Moreover, different collimator setups are required when the machine parameters are changed.

Two types of beam instrumentation are available to align collimators (refer to Fig. 3); the Beam Loss Monitoring (BLM) and the in-jaw collimator Beam Position Monitoring systems. Each collimator has a dedicated BLM installed outside the beam vacuum, immediately downstream. BLMs are used to detect beam losses generated when halo particles impact the collimator jaws, such that the recorded losses are proportional to the amount of intercepted beam, measured in units of Gy/s. Meanwhile, BPMs directly embedded in the collimator jaws, allow for a faster alignment by analysing the electrode signals, without needing to touch the beam [13].



(a) BLM detector (b) BPM pick-up button

Figure 3: (a) BLM attached to LHC cryostat (yellow device) [21] and (b) BPM pick-up button embedded in collimator jaw [22].

BPM Alignment Controls

BPM collimators are aligned using a successive approximation algorithm. This takes into account a calibration of the nonlinear BPM sensitivity to beam displacement and an asymmetry of the electronic channels processing the BPM electrode signals [23].

The BPM controls allow users to monitor the electrodes and the beam position. The user can automatically align collimators by defining the minimum collimator gap (mm), the target alignment error (µm) for alignment precision when equalizing the electrodes, and the time interval(s) between each step of the successive approximation algorithm.

The BPM-based alignment procedure aims at finding the jaw positions and angles, where the beam orbit is centred, at both the upstream and downstream sides of the collimators, individually. The algorithm works by moving both collimator jaws in steps, keeping the same gap, until the signals from electrodes are equalized as shown in Fig. 4 [22].

The entire procedure is automated, able to align a single collimator at the optimal angle in ~10–20 s. In addition, all BPM alignments can be performed in parallel [13]. The method is not invasive and does not cause any beam loss.

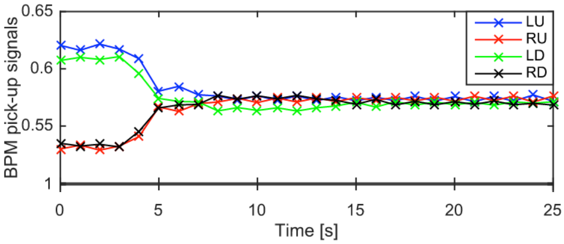


Figure 4: BPM electrode signals during a BPM-based alignment in 2017, from [13].

BLM Alignment Controls

All collimators can be aligned using the beam loss signals recorded by their respective BLM located directly downstream. A beam-based alignment (BBA) procedure [24] is used to align collimators with BLMs. This involves creating a reference halo with the primary collimators, then moving the collimator jaws separately towards the beam in steps of 5–20 µm. A collimator is said to be aligned when both jaws are centred around the beam after touching the beam halo. The alignment of any collimator relies on BLM signal distinction between alignment and spurious spikes: a collimator must continuously move towards the beam ignoring any spurious spikes, until a clear alignment spike is observed. Throughout the procedure, the jaws are kept parallel to each other with a zero tilt angle with respect to the collimator frame. The procedure can be extended to measure the jaw angle with respect to the beam [19].

The BLM controls allow users to monitor the BLM signals and the collimator position. Since 2018, the entire BBA procedure has been automated [25,26] by introducing supervised machine learning to classify alignment spikes [27] and other algorithms [28]. The user can start an automatic alignment by selecting the list of collimators to be aligned and the software will align all collimators and save the settings.

This new automatic software is able to align a single collimator in ~1–2 mins [29,30], depending on the machine state. When aligning collimators with BLMs, a maximum of two collimators can be aligned in parallel, one from each beam. However, the two collimators must be specifically selected, as one must consider possible cross-talk, i.e. having multiple BLMs around the ring detecting the losses generated by a single collimator [31].

Having the foundations for an automatic BBA opens the possibility for further research and development [32]. It also allows introducing more complex alignment techniques and changing the collimation hierarchy more frequently throughout an operational year, to provide tighter settings.

Angular Alignment The current operational settings for the betatron cleaning hierarchy requires a 1.5 σ retraction between primary and secondary collimators in IR7, corresponding to ~ 300 µm. Tighter collimator settings with smaller retractions might be used in the future to improve the LHC performance and achieve a smaller β^* [33]. Keeping collimators with a zero tilt angle with respect to the beam will not be adequate to operate the system with retractions below 1.5 σ [34]. Moreover, possible tank misalignments are a source of error that could jeopardize the performance of the system if not corrected. Aligning collimators at an angle will allow for tighter collimator settings. However, this procedure is longer, as it involves performing the standard BBA at different angles to find the most optimal one.

The angular alignment controls allow users to monitor the BLM signals and the positions of the 4 collimator jaw corners. Angular alignments are implemented on top of the BBA, therefore they have also been automated in 2018. The user can automatically align collimators at an angle by setting the start and end angles (μrad) to define the angular range to be explored, and the angle step size (μrad) to tilt the collimator between each alignment. The user can then select one of the 3 angular alignment procedures developed in [35], depending on the specific error encountered; (1) The first method aligns the collimator at different angles (keeping the jaws parallel). This is used to determine the optimal angle for the collimator tank in cases where there is an offset. (2) The second method aligns the upstream and downstream jaw corners individually, to determine the corresponding centres. The optimal angle is taken to be the average of the two. (3) The third method individually aligns the collimator jaws at different angles and aligns the other jaw (with zero tilt) to act as a reference. This method is useful in cases of asymmetries within the collimator itself, as the optimal angles for both jaws are determined independently.

At injection, methods 1 and 3 require a similar amount of time ~13 minutes, whilst method 2 requires ~3 minutes [36]. Since angular alignments rely on BLMs, one must consider possible cross-talk when aligning collimators in parallel.

LOSS MAP ANALYSIS FRAMEWORK

The collimation system performance is monitored when the configuration is changed, and at most every three months of operation, as the beam orbit may shift over time. This is done by inducing slow (multi-turn) beam losses, such that a large number of particles are purposely sent onto primary collimators in a controlled way, and the resulting electromagnetic showers can be detected by BLM devices around the LHC ring. A beam loss map, showing the spatial distribution of the measured losses along the LHC ring (Fig. 5), can then be generated to validate the collimator setup [36]. Specifically the losses in IR7 provide information on the collimation hierarchy and halo cleaning performance. In case of a degradation in performance, the collimators might need to be re-aligned to generate a new setup for the current beam state. This could be observed as a degradation of the cleaning in the dispersion suppressor of IR7, or a difference in the pattern of the beam losses at the collimators [37] or by the observation of anomalous loss locations.

A new framework was developed for Run 3, providing an automatic way to validate loss maps generated throughout the year. It allows users to import loss map metadata as new loss maps are generated, including; start date/time, plane info, beam energy, and loss map type (betatron or off-momentum). This metadata is then used to automatically extract the loss map data logged in NXCALS. The user then has the option to plot individual loss maps depicting the distribution of losses across the full ring or in specific IRs. Alternatively the user can plot multiple loss maps at a particular IR, stacked for comparison. This framework also integrates the necessary tools for automatically calculating the collimation hierarchy inefficiency by analysing the losses in the dispersion suppressor.

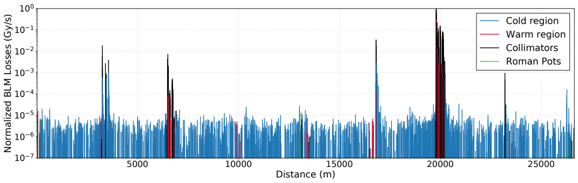


Figure 5: Proton full ring loss map performed at injection in the horizontal plane for beam 1, from [36].

SETTINGS GENERATION APPLICATION

Once the collimation hierarchy is validated, the next step is to generate the collimator settings for operation [38]. As previously mentioned, the collimator settings obtained following the BBA are saved to file. A new application was developed for Run 3 to automatically extract the relevant data and calculate and import these settings into the control system defined in LSA. A mathematical framework for defining these functions, which will now be automatically calculated by the system, can be found in [38]. This application replaces the scripts that were used in the past, creating a central and homogeneous procedure for settings' generation.

The user can automatically generate the settings by selecting the BBA results file, the list of collimators, the LSA parameters to update and the collimator settings to be used. In addition, the user can manually edit any of the settings loaded into the application and save the modified settings to a new file for future use.

SETTINGS CHECK APPLICATION

Following their generation in LSA, the settings must be validated to ensure they are consistent with the expected collimator positions. The setting-check application requires the user to select the LSA configuration, the start and end time, and the list of collimators to check their settings. This application automatically compares the settings defined in the following locations: 1) the selected LSA configuration, 2) the settings calculated by the application based on data stored in LSA, 3) the data logged in NXCALS for the selected time period, 4) the real-time positions of the collimators.

MACHINE PROTECTION SEQUENCE

The precise control of the jaw positions versus time and beam position has important relevance for machine protection (MP) of the LHC. As part of MP procedures, the collimation MP sequence, independently of the beam, checks that for every scenario, the interlocks are correctly triggered (recall Table 2). MP tests ensure the correct behaviour of interlocks to guarantee a beam abort in case of potentially critical situations, i.e. if a collimator moves beyond the safe limit [39]. A dedicated MP sequence for LHC collimators forms part of the collimation controls. It is an application which automatically tests all interlocks associated with a collimator. This application is used when new collimators are installed or replaced, and, after each long shutdown in order to test all collimators before starting a new LHC run.

To begin the testing sequence, the user simply selects a collimator. The collimator is moved sequentially to each of its limits to ensure the interlocks are correctly triggered, whilst the user monitors the results. This typically takes less than 10 minutes per collimator. Multiple sequences can be started in parallel for collimators that are not connected to the same interlock units (typically one interlock unit per IR).

BPM-CALIBRATION APPLICATION

This application is used to measure BPM non-linearities, by characterizing the BPM readout for selected jaw gaps and beam offsets, in order to validate the BPM calibration. This is achieved by performing an automatic scan which measures the beam position at different gaps and different collimator offsets, to ensure the centre is proportionate [23].

Before starting the scan the user must first align the collimator using the feedback from the BLM, to centre the jaws around the beam. To begin a scan, the user must define; the maximum offset (µm) to avoid beam scraping, the jaw step size (µm), the gap step size (µm), the initial and final gaps (µm) defining the range to be explored, and the waiting time between each movement(s).

The scan begins by opening the collimator jaws to the starting gap. The jaws are then continuously shifted by the predefined jaw step size, waiting the requested time between movements. When one of the jaws reaches the predefined limit, the jaws are moved back to the starting point and the jaw gap is reduced by the predefined gap step size. The procedure is repeated until the minimum jaw gap is reached. The jaw positions and BPM electrode signals are automatically saved to a file for offline analysis.

CRYSTAL COLLIMATION CONTROLS

The crystal collimation scheme uses bent crystals as primary collimators. These are used to channel beam halo particles and deflect them onto a single secondary collimator per beam and plane, further downstream, as opposed to the present multi-stage collimation system. The crystal-based collimation system improves the overall cleaning inefficiency in the IR7 dispersion suppressor and along the ring, with respect to the standard collimation system [40], for heavy-ion beams. In order to determine the optimal channelling angle, angular scans are performed by changing the crystals' orientation angle with respect to the beam envelope. Crystal channelling is achieved when a reduction in the local beam losses is observed in the corresponding BLMs [41].

The crystal controls allow users to control the goniometer that houses the crystal, whilst monitoring the signals of neighbouring BLMs and the linear crystal position. The user can align the crystal linearly using the BBA similar to one-axis collimators, and can perform an angular scan of the crystal to determine the optimal channelling angle for operational use [42].

Linearly aligning each crystal requires ~5–10 minutes depending on the machine state, as the automatic alignment is not yet available for crystals. Moreover, as this alignment relies on BLMs, one must consider possible cross-talk when aligning crystals in parallel. Scanning the largest angular range available of 20 mrad can take longer than an hour. Angular scans cannot be done in parallel, as any cross-talk would make it difficult to determine the optimal channelling angle.

GLOBAL MONITORING DISPLAYS

Given the numerous collimators, various global monitoring displays are available to provide an overview of their status. Four dedicated fixed displays are available for the collimators in beam 1, in beam 2, in the transfer lines and for crystals. An additional display for collimator settings is available to monitor the collimation hierarchy in case of incorrect settings. Finally, the number of BPM collimators have doubled for the start of Run 3. Therefore, a dedicated display for them is being developed to provide an overall status, comparing the collimator centre and the beam centre measured by the BPMs in real-time.

CONCLUSION

The LHC makes use of a high-performance collimation system to protect its sensitive equipment from unavoidable beam losses. A total of 123 movable collimators are readily installed in the LHC for the start of the Run 3 in 2022. This paper presents the control system of the LHC collimators that provide the functionality required to handle high-intensity beams. The system underwent a significant upgrade to improve the functionality in light of the recent system upgrade for Run 3. An overview is given of the software tools available for collimation, including; BPM alignments, BLM alignments, BLM angluar alignments, loss map analysis, generation of settings, machine protection sequence, BPM calibration, crystal collimation and global monitoring. These tools ensure precise jaw positioning during all the phases of LHC operation. The occurrence of unsafe conditions is minimized by making sure that all the critical degrees of freedom stay within safe operational windows. All these tools are readily available for the start of Run 3.

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