COLLIMATORS AND BEAM CLEANING: FIRST RESULTS AND FUTURE PLANS

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Abstract

The LHC collimation system has been used for beam cleaning and passive machine protection this year for the first time. The hardware commissioning tests carried out in preparation for operations with beam are presented. The setup procedure towards nominal injection settings is analyzed together with reproducibility and total beam time spent for collimator setup. Locations of beam losses are reviewed and reasons for the highest losses investigated. The achieved cleaning efficiency is also discussed. Operational performance and stability of the system, interlock thresholds and interlock statistics (number of false interlocks generated) are treated. Software procedures, settings and threshold limits are analyzed, also in view of machine protection. Finally, plans for higher intensity operation and improvements (both in the short and long term) are presented.

INTRODUCTION

The LHC collimation is a dynamic system which must be active during the full machine cycle, from injection up to physics and extraction [1]. It includes 101 collimators for the two beams: 88 are installed along the LHC ring and 13 in the injection lines (TCD) [2]. Ring collimators are set to different openings to implement a multi-stage cleaning system [3]. Performance optimization and machine protection require to respect a well defined setting hierarchy [4] with tolerances which become more demanding with increasing beam energy and intensity [5]. Primary (TCP) and secondary (TCSG) collimators plus absorbers (TCLA) build up the two cleaning insertions of the LHC ring: momentum (IR3) and betatron (IR7) cleaning [6]. Tertiary (TCT) collimators and special absorbers (TCLP) are placed closed to the interaction points (IP) to protect the triplet magnets and catch the physics debris coming from the collisions at the experiments. Additional collimators are used to intercept mis-kicked beams during injection (TDI, TCLI in IR2 and IR8) and extraction (TCDQ, TCSG in IR6).

LHC collimators consist of two parallel, fully movable jaws which must be centered and aligned with respect to the beam. A new beam based alignment for the full system has to be performed after any substantial change in the beam parameters (orbit, tune, etc.), while, if the machine is stable, collimators can be put to reference positions from the last alignment.

COLLIMATOR OPERATION DURING THE NOMINAL MACHINE CYCLE

The LHC collimators must define the machine bottleneck, during the full operation cycle, in order to concentrate beam losses in the dedicated warm cleaning insertions. Collimators must be set up before injecting the beams in the LHC in order to provide the required beam cleaning and passive machine protection. Moreover, they then need to be moved during operation: TDI and TCLI have to be retracted after injection and ring collimators have to follow the change in beam size during acceleration and β^* squeeze. Two options have been defined depending on beam intensity I:

- Intermediate settings (I <156 nominal bunches, 3.5 TeV top energy [7]): primary collimator aperture scales with $\sqrt{\gamma}$ (γ relativistic factor) and is kept at 6σ during the full energy ramp ($\sigma = \sqrt{\beta\varepsilon}$, where ε is the emittance). Remaining collimators in IR3, IR6 and IR7 are closed by keeping the retraction (in mm) with respect to the TCPs unchanged. This allows to maintain the tolerance budget [7] constant during the ramp making operation easier. All ring collimators, including the TCTs, are then set to their nominal positions during the squeeze of the beam at the experiments.
- Nominal settings($I \geq 156$ nominal bunches, 3.5 TeV top energy [7]): all IR3, IR6 and IR7 collimator apertures are scaled with $\sqrt{\gamma}$. These settings provide the maximum cleaning efficiency but operation is more delicate due to the reduced tolerances when increasing the energy. TCTs are closed during the squeeze as in the previous case.

After physics, the two beams are dumped and collimators are opened to parking positions (jaws set at ± 20 mm).

THRESHOLDS AND INTERLOCKS

A correct and safe machine operation requires that collimator settings are adapted to each beam process. Moreover, jaw positions must be constantly monitored to ensure that they correspond to the settings expected [8]. To this purpose, thresholds can be defined to generate an interlock any time they are exceeded. Collimators can be set up either with discrete settings or following predefined functions. This is the case during the energy ramp when the jaw movements must be synchronized with the ramp in magnets current intensity. Limits on the collimator settings must then be adjusted accordingly.

Three different kinds of interlocks are associated to the collimation system:

- Position time dependent interlock: limits are defined around the expected jaw position for discrete settings or as a function of time, depending on the beam process. An interlock is generated if the jaw moves outside the delimited region and the jaw is blocked. The position interlock is opened when the collimators are in parking position.
- Gap energy dependent interlock: a maximum gap is established for each collimator as a function of the beam energy. If the measured gap exceeds the allowed gap the beam is inhibited but the jaws can still be moved. This limit is always active and allows to prevent the injection of an unsafe beam in the LHC when collimators are at parking position. This threshold needs to be changed when squeeze is applied. Moreover only MCS [8] collimation experts can change it.
- Temperature dependent interlock: an interlock is generated when the measured temperature is greater than a fixed limit.

Time and position interlocks are based on independent measurements providing a safe redundancy to the collimator setup control.

HARDWARE COMMISSIONING TESTS

All LHC collimators have been tested in preparation for operations with beam. Hardware tests have been performed to check minimum and maximum gap, maximum tilt and hardware switch positions and to measure the jaw mechanical play. Moreover, an automatic procedure has been implemented to execute machine protection (MP) tests in order to check if collimators generate a faulty interlock when thresholds are violated. Results of the MP tests can be found at the link: https://winservices.web.cern.ch/winservices/Services/DFS/DFSBrowser.aspx/Projects/CollimationHardware/2009/MP_tests/MPtests_summary_EDMS.xlsx.

Automatic sequences driving collimators through nominal operation cycles have also been carried out. These tests showed a reproducibility in the jaw positions over several cycles better than 10 μm. While running these sequences, collimators, which are located several km far apart along the LHC ring, have to move simultaneously. It was shown that, for a ramp up to 5 TeV (1300 s), the movement of all the collimators was triggered within 6 μs and stopped within 10 μs.

BEAM BASED ALIGNMENT

The alignment and centering of a collimator with respect to the beam relies on beam loss measurements correlated with jaw movements [4]. In particular, one jaw is moved in steps towards the beam until a spike in losses is recorded by the beam loss monitors (BLMs). Though the jaw is scraping only one side of the beam, an edge is produced on both sides of the beam due to multi-turn betatron oscillations. The second jaw is then moved in as well until BLM signals indicate that it has touched the beam edge. At this point the two jaws are centered with respect to the beam with an accuracy equivalent to the last step size. The geometric centre of the collimator gap should then correspond to the closed orbit within the defined accuracy.

The first beam based alignment of the LHC collimation system has been realized during the 2009 run. One collimator per beam line could be set up in parallel since no cross-talking in losses was recorded by the BLMs. The procedure consisted in setting the last horizontal IR7 absorber (w.r.t. the beam traveling direction), by using the described method, in order to define a reference normalized position at $\pm 5.7\,\sigma$ (i.e. nominal TCP half gap at 450 GeV; σ was calculated for ε= 7.28 nm). This collimator was kept at this position and all the other collimators in the considered plane were moved in, one by one, until touching the beam edge. In this way each collimator was calibrated to the same normalized beam position ($\pm 5.7\,\sigma$) for the reference beam orbit and local beta functions. Afterwards, each jaw could be retracted to its nominal position in order to establish the required hierarchy (i.e. IR7: TCSG at $\pm 6.7\,\sigma$, TCLA at $\pm 10\,\sigma$ etc.). Collimators were aligned going backwards w.r.t. the beam direction in order to avoid crosstalk from the upstream collimators. The same procedure was repeated for the vertical and skew planes.

Three different setups were performed during this run.

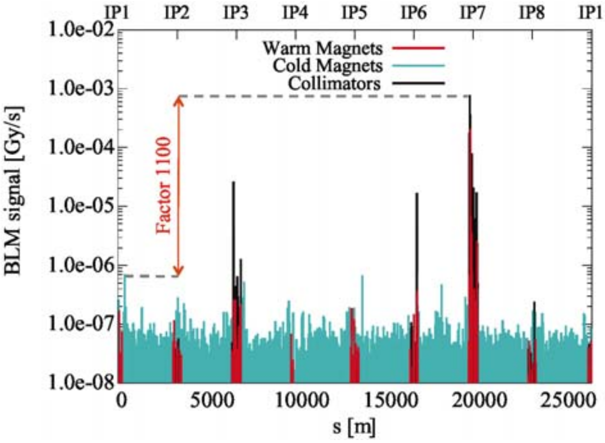

Figure 1: Loss map for injection of Beam 1 after first collimator setup performed on November 23rd 2009. The offset without beam (background) has been subtracted by the BLM readout.

November 23rd: First LHC collimator setup

Twenty collimators were set up in about 3 hours with 200 μm accuracy (used step size). The limited number of collimators aligned and the accuracy were determined by the time available for the setup.

- Beam 1: beam based alignment was completed for horizontal and vertical TCPs (5.7 σ) plus all TCLAs (10 σ) in IR7. Secondary collimators were left at a coarse position (9.7 σ = nominal + 3 σ). The setup of TCDQs and associated secondary collimator in IR6 was tried but it showed an unclear beam response. These devices were left at the assumed nominal position of 8 σ and 7 σ respectively. In IR3, only the TCP (8 σ) and one TCLA (10 σ) were aligned, while the remaining collimators were put at coarse positions (TCSGs at 12.3 σ, TCLAs at 13 σ).
- Beam 2: all IR3 collimators were set up at nominal aperture, the other collimators stayed in parking position.

All TCTs had an half gap of 15 mm corresponding to about 15-20 σ.

The loss map obtained during injection of Beam 1 with the defined collimator settings is presented in Fig. 1. It is shown, as expected, that the highest losses are concentrated in the collimation insertions and, in particular, at the primary collimators. The ratio between the highest loss peak in a cold magnet and at the TCP allowed a first estimate of a local cleaning efficiency better than 99.9%.

November 29th: Second LHC collimator setup

A new beam based alignment was performed after establishing a reference “golden orbit” (Santa Klaus). This time, 62 collimators were set up in about 7 hours with an accuracy of 50-100 μm. Nominally, an accuracy of 10-20 μm is required but the low beam intensity allowed to use larger steps to speed up the process.

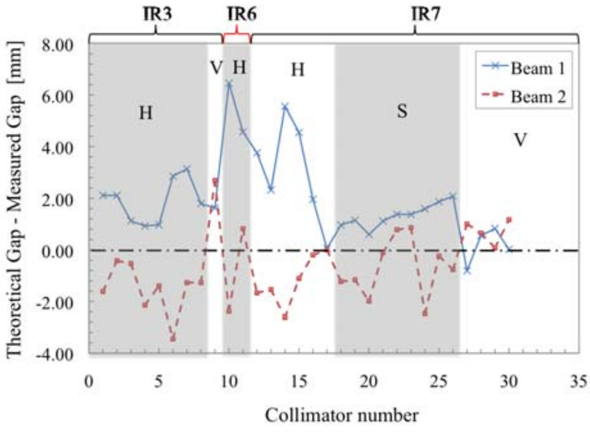

Figure 2: Difference between theoretical and measured gap of the LHC collimators after the second beam based alignment. Collimators are grouped per IR and divided in horizontal (H), vertical (V) and skew (S).

All collimators in IR3, IR6 and IR7 were aligned and set to the nominal injection aperture for both beams. Again, TCTs were set at 15 mm. Only the positions of IR1 horizontal and vertical tertiary collimators were aligned around Beam 1. This was the first full collimation setup with a four-stage cleaning. Injection of Beam 1 showed the same loss pattern as for the previous alignment.

The theoretical gaps (in mm), calculated by using the nominal beam parameters, were compared with the gaps measured after alignment. The resulting difference is shown in Fig. 2. Theoretical gaps are almost always bigger than the measured ones for Beam 1, while the opposite is true for Beam 2. Moreover, an average difference of 2.8 mm is obtained for Beam 1 collimators (horizontal H) whereas it is smaller than 1.3 mm for Beam 2. Beta-beating at the collimator locations was advanced as a possible explanation for the observed discrepancy, in particular in IR6 and IR7. However, the comparison between beta-beating measurements and calculations from collimation setup did not show a clear correlation.

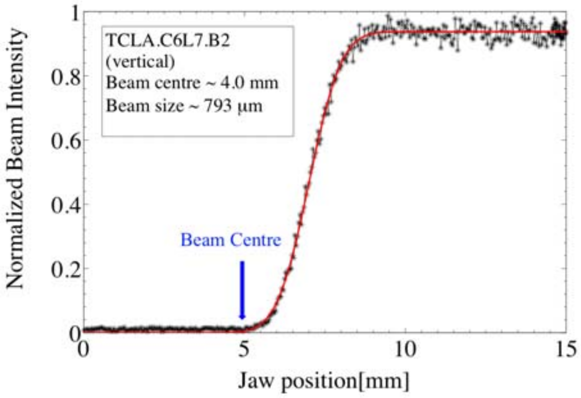

Figure 3: Normalized beam intensity I_n versus jaw position during a full beam scraping performed with the last horizontal Beam 2 absorber of IR7 (TCLA.C6L7.B2). The location were I_n = 0 determines the beam centre position, while the beam size is given by the σ of the error function fitting the curve.

The TCLAs which were used to define the reference edge for the beam based alignment were also employed to perform a full beam scraping [7]. The correlation between the normalized beam intensity I_n and the jaw position during the scraping allows to have an independent estimate of beam centre (I_n = 0 see Fig. 3) and beam size at the collimators (σ of the error function fitting the curve). The beam parameters obtained with these measurements have been compared with those calculated from the collimation setup and are summarized in Table 1. Data show a reasonable agreement, except for the Beam 2 vertical collimator for which a difference of 255μm in the beam size and 2.6 mm in the beam centre was found.

All the discrepancies presented are currently not understood and need further investigations. In addition a more accurate beam based alignment must be performed before increasing the beam intensity and energy.

Table 1: Comparison between beam parameters evaluated from the full beam scraping and the beam based alignment of last horizontal and vertical absorbers in IR7. Values for Beam 2 horizontal TCLA during the scraping are not available.

		Beam 1		Beam 2	
		Beam Centre [mm]	Beam Size [μm]	Beam Centre [mm]	Beam Size [μm]
Full beam scraping	Hor. TCLA	0.4	736	N.A.	N.A.
	Ver. TCLA	2.2	920	4.0	793
Beam based alignment	Hor. TCLA	0.2	683	0.2	693
	Ver. TCLA	1.2	1051	1.4	1048

December 5th: Third LHC collimator setup

Collimator positions had to be reset after a power cut. The golden orbit was re-established and all collimators were then closed at once at the positions defined on November 29th. No fine retuning was performed but we just relied on machine and optics reproducibility. Both beams could be injected with about 30% beam intensity loss. The loss pattern showed that the collimator setup was still valid and the hierarchy respected after six days.

THRESHOLDS SETUP AND INTERLOCK STATISTICS

The low beam intensity used during the 2009 run allowed to keep the collimators with static settings during all the phases of the machine cycle, including the ramp up to 1.18 TeV. Static position dependent thresholds could then also be applied. Limits at ±0.5 mm around the defined positions were applied to all IR3 and IR7 collimators, and at ±1 mm to all the TCT.

Energy dependent thresholds were also activated but relaxed with a maximum allowed gap of 60 mm.

This run consisted of 27 days of machine operations. During this period, collimators generated only six interlock requests. Three of these interlocks occurred without beam, and gave a beam injection inhibit. In the other three cases the beam was dumped. Only one event was induced by a real hardware problem: drift of an LVDT position sensor. All the remaining cases were caused by inappropriate user requests violating the position interlock limits.

Up to now, the system has been working as expected showing to be safe and reliable. No interventions in the tunnel were needed during this first stage of the commissioning. Collimators had to be reset by the STI piquet just once after a power cut, the intervention took about 2 hours.

BEAM LOSS STUDIES

Several beam loss studies have been performed in different loss regimes. A typical loss pattern during injection of Beam 1 has already been shown in Fig. 1. An analogous behavior was seen for Beam 2 injection with losses developing in the beam traveling direction.

During the 2009 run, the LHC beams were accelerated up to 1.18 TeV: the highest energy ever recorded for a particle accelerator. A loss map at this energy has been measured for Beam 1 and is shown in Fig. 4 (top). The comparison with a loss map resulting from SixTrack [9] simulations at 1 TeV for the same beam is also shown (4 bottom).

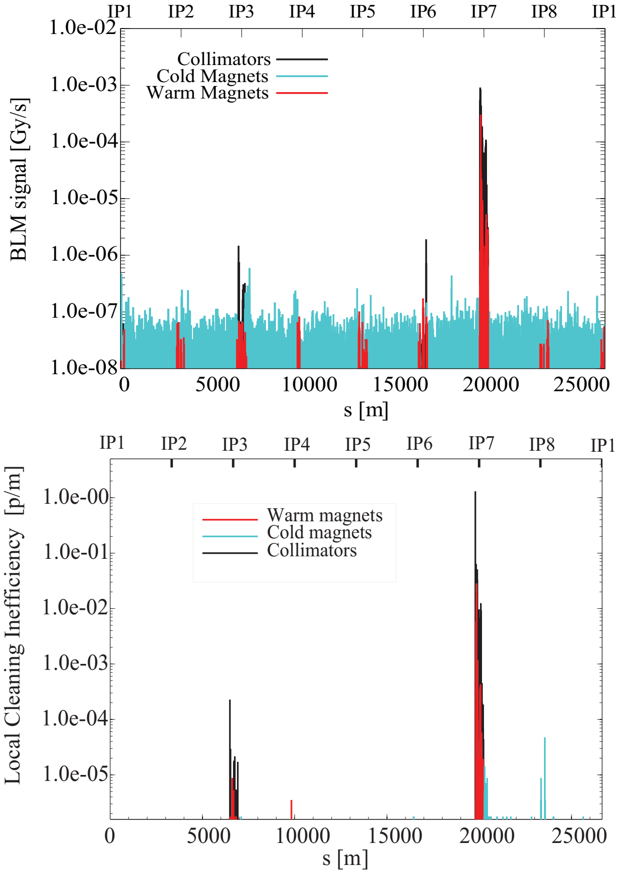

Figure 4: Top: measured beam loss map for Beam 1 at 1.18 TeV. The offset without beam (background) has been subtracted by the BLM readout. Bottom: beam loss map resulting fron SixTrack simulations for Beam 1 at 1 TeV. Only primary proton losses are shown while shower development is not included.

Measured and simulated loss patterns demonstrate a very good agreement. The BLM readout is characterized by electronic noise. Showers generated by the interaction of the primary protons with the collimator jaws are recorded by the BLMs, while the simulated loss map takes into account only losses of primary protons. The main difference between measurements and simulations are found at IR6 collimators and at the cold magnets downstream of IR3. The losses in IR6 might be due to a too tight collimator aperture. The alignment of the TCDQs was indeed problematic and a setup accuracy worse than for other collimators was achieved. IR3 losses are detailed later on.

Betatron loss studies have been carried out by crossing the third-integer resonance with the horizontal (Qx) and vertical (Qy) tunes. The highest losses were always recorded, as expected, in the betatron cleaning insertion. A detailed analysis was performed for Beam 2 when moving Qy through the resonance. The measured loss pattern showed, once more, a good agreement with simulations [10]. Moreover, the origin of losses on the cold magnets on the left side of IR6 and IR7 was investigated. It was shown that, in both cases, the peaks corresponded either to maximum vertical β-function locations or to a combined maximum horizontal β-function and dispersion.

Momentum losses were analyzed by changing the frequency of the RF cavities. This time, the highest loss rate was recorded in the momentum cleaning insertion, as shown in Fig. 5 for Beam 1.

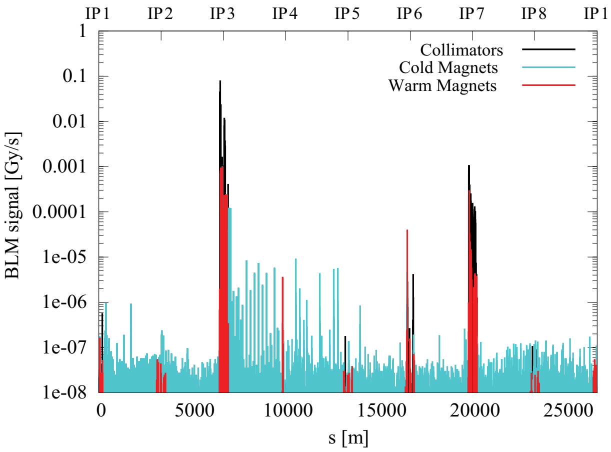

Figure 5: Loss map measured when changing the frequency of the RF cavities for Beam 1.

Showers developed several km downstream of IR3 reaching IR5, in case of Beam 1 (see Fig. 5), and IR1, in case of Beam 2. As mentioned before, suspicious losses appeared on the right side of IR3 for both beams as shown in Fig. 6.

For Beam 1, the decay pattern of the losses in the beam direction is expected to be quasi exponential. Instead, the observed losses are almost flat over a length of about 200 m (see Fig. 6 top). For Beam 2, these losses are even more puzzling because they are located upstream of the primary collimators (see Fig. 6 bottom).

At first, the constant presence of these losses was ascribed to possible leftover alignment errors of the magnets in IR3-IR4 after 2008 accident. A further analysis seemed to indicate a problem in the BLM reading. Studies to resolve this issue are on going.

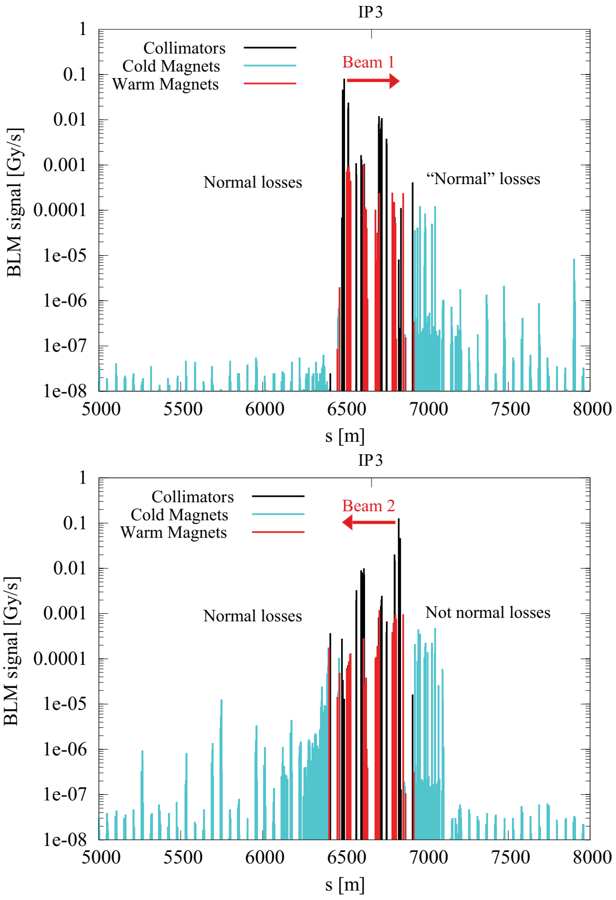

Figure 6: Zoom around IP3 of Beam 1 (top) and Beam 2 (bottom) momentum loss maps. Unexpected flat losses appear on the right side of IP3 in both cases.

Globally, the results obtained validate the predictions assessed with tracking simulations. However, more detailed studies with higher beam intensity are needed in order to provide a further understanding of loss locations and collimation leakage.

CONCLUSIONS

Basic principles and logic for a safe operation of the LHC collimation system have been presented. First results of beam based alignment have been analyzed. They demonstrate that the system is working as designed and is showing a good reproducibility. Still, some differences between beam based and theoretical settings have to be clarified.

Beam loss studies allowed to observe the expected cleaning efficiency and leakage processes. Moreover, concentration of the highest losses in the cleaning insertions and at the primary collimators permitted to validate the provided passive machine protection. Some loss locations require a deeper analysis and additional studies are needed before operating with higher intensity.

Although the promising start of beam operation, a number of further steps has to be performed in the commissioning. An accurate definition of BLM thresholds must be setup (a factor of 3 below the magnet quench limit [11]) in order to protect the machine without inhibiting operation. The change of collimator settings during the energy ramp and the beam squeeze has to be tested. The beam based alignment at higher energy has to be accomplished with improved setting accuracy. Cleaning efficiency with higher loss rate (500 kW - 1000 kW) has to be checked. Effect of collimator impedance on beam stability has to be verified. Faster analysis tools for loss maps, collimator movements and interlocks are needed together with an automatic procedure for MP temperature interlock verification.

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