COLLIMATION SYSTEM POST-LS1: STATUS AND COMMISSIONING

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Abstract

The LHC collimation system has undergone an important upgrade during LS1. A total of 32 collimator installations are taking place to consolidate and improve the Run 1 system. This includes 18 new collimators with embedded beam positions monitors (BPMs), additional physics debris collimators, additional passive absorbers and re-installation or displacement of existing collimators. This paper summarizes the post-LS1 collimation layout, highlighting the expected gains from each modification, and the readiness of the new collimation hardware for commissioning without and with beam. Special emphasis is devoted to the new software for the control and configuration of the BPM collimators. A proposal for the necessary beam conditions during collimation alignment and validation with loss maps at 6.5 TeV is also discussed, including a strategy for the machine protection aspects. A list of early machine development studies is proposed.

INTRODUCTION

During Run 1 the LHC collimation system has shown excellent performance at $4\ \mathrm{TeV}$ [1]. The cleaning stability in the dispersion suppressor of IR7 was shown to be very good. The cleaning inefficiency was always below $\eta_c = 10^{-4}$ for both beams. No quenches with operational beams were experienced with up to $140\ \mathrm{MJ}$ stored energy at $4\ \mathrm{TeV}$.

After Long Shutdown 1 (LS1), the LHC beam energy will increase up to $6.5\ \mathrm{TeV}$. At this energy, the destructive power of the beam is much higher. In particular for metallic collimators, like the tungsten tertiary collimators (TCTs), the onset of plastic damage can occur when single bunches of $5 \times 10^9\ \mathrm{p}$ fully impact on the collimator jaw. The limit for fragment ejection is about $2 \times 10^{10}\ \mathrm{p}$ [2]. In order to monitor the beam orbit at the collimators and perform the collimator alignment without touching the beam at $6.5\,\mathrm{TeV}$, it was proposed to replace the tertiary collimators and the 2 secondary collimators in IR6 by collimators with embedded beam position monitors (BPMs) which will also enhance the operational efficiency of the system.

In addition to the installation of collimators with embedded BPMs other activities are taking place during LS1 that will:

- Improve IR flexibility and configuration.
- Improve physics debris cleaning in IR1 and IR5.
- Improve IR8 layout: replacement of the 2-in-1 beam collimators by single-beam collimators, similar to IR2.
- Increase the protection of the warm magnets in IR3 by adding new passive absorbers in front of them.

Due to the installation of new ventilation doors in IR7, 3 primary collimators in that region were also taken out of the tunnel and re-installed afterwards. In addition to this, a primary collimator was replaced due to heating problems during Run 1. After the changes listed above, the new system post-LS1 will consist of 118 collimators, of which 108 are movable. The collimator hardware changes will be described in detail in the next section.

HARDWARE CHANGES

Embedded BPM collimators

The reasons for installing collimators with embedded BPMs in IR6 and the experimental IRs are:

- **Safer alignment:** With the online measurements of the beam orbit and a software feedback routine the collimator could be aligned without touching the beam [3] thus reducing the risk of jaw damage during alignment.
- **Faster alignment:** At $4\ \mathrm{TeV}$ the alignment tool achieved a setup time of few minutes per collimator. With the new setup tool and the input from the BPM measurements, the setup time can be reduced to a few seconds [3]. This allows for more flexibility in the IR configuration, since the new alignment of the 16 collimators could be done in parallel in a couple of minutes.
- **Reduce orbit margin in cleaning hierarchy:** Since the orbit will be more precisely known at the collimators, the margins used for the β^*-reach calculation could potentially be reduced, providing more room to squeeze the β^* [4].
- **TCT and triplet protection:** The BPM signals will be used to generate a beam interlock that dumps the beam if the orbit at the TCT changes by more than a given threshold.

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A total of 16 tungsten TCTs in all IRs and 2 carbon TCSGs (secondary collimators) in IR6 are being replaced by new collimators with integrated BPMs. The interfaces of these collimators are fully compatible with the infrastructure currently present in the LHC tunnel [5], although new BPM cables were required. The active part of the collimator jaw is still 1 m long. At each side of the jaw, BPM pick-up buttons are installed, as shown in Fig. 1. Figure 2 shows a TCTP collimator ready to be installed in the LHC tunnel.

The 2 TCSPs were internally produced by CERN and the 16 TCTPs are produced by an external company. All collimators have been installed in the LHC as of July 2014. More details on installation can be found in [6, 7].

Figure 1: New TCSP carbon jaw with embedded BPM.

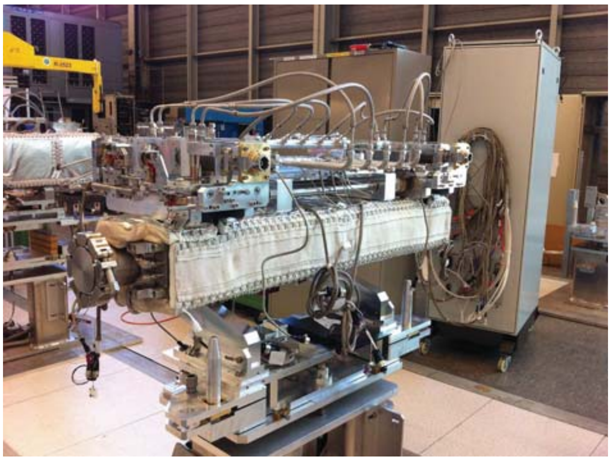

Figure 2: TCTP collimator with embedded BPMs.

Physics debris collimators

Several collimators are installed to protect the equipment in the matching sections of the high-luminosity experimental IRs from physics debris. In Run 1, two copper TCLs were installed per beam, in cell 5 of IR1 and IR5. These TCLs were positioned at 10 σ during stable beams as of 2012. Four other copper TCLs were produced prior to Run 1, and were intended for installation in cell 4 [8]. However, these collimators were not installed, as they are only required at design luminosity. These collimators have been installed during LS1, and will allow for the operation of the forward physics detectors (Roman pots), as the TCL5 can now be opened in high-intensity fills.

In addition, 4 other TCLs, recycled from previously-installed tungsten TCTs, were installed in cell 6 of IR1 and IR5 to complete the system as designed for nominal luminosity. These collimators will reduce the losses in the dispersion suppressor by two orders of magnitude, and also provide flexibility for future upgrades of the forward physics programme. The final settings for these collimators are still under evaluation due to impedance considerations [9].

Passive absorbers

Passive absorbers are fixed collimators which reduce the dose in the warm magnets in the cleaning insertions and increase their lifetime. During Run 1, 3 passive absorbers per beam were added to protect the D3 and Q5 in IR7, while only 1 passive absorber per beam was installed to protect the IR3 D3. The dose measured during 2011 and 2012 showed that the operational flexibility of the collimator settings could be compromised without additional protection of Q5 in IR3. Therefore, the installation of 1 additional absorber per beam in IR3 in front of Q5 to reduce the dose from off-momentum cleaning losses by a factor 2-5 according to simulations [10] was proposed [11]. Two passive absorbers were produced in-house in 2013 (see Fig. 3) and installed in March 2014.

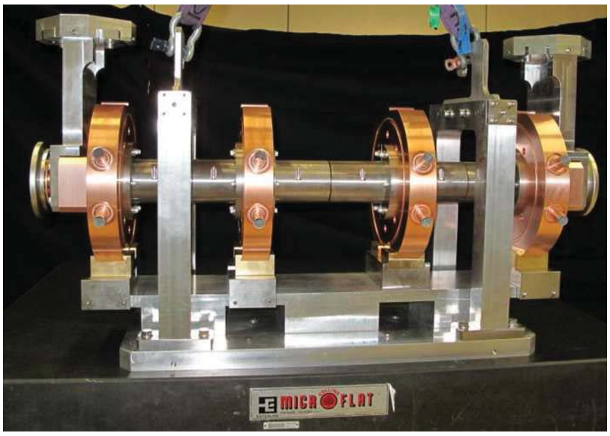

Figure 3: New passive absorber of TCAPD type installed in IR3.

Status of Installation and Production

All collimators have been installed by July 2014 as per the original schedule, after a successful production. Figure 4 shows the status of the installation of all collimators (with and without BPMs) and passive absorbers. Figure 5 shows a snapshot of the LHC collimation system for post-LS1 operation, with the type of LS1 activity for each collimator category in colour. The new system will be composed of 118 collimators, of which 108 are movable. With this new configuration the LHC collimation system is complete and there are no foreseen installations until the upgrades for Hi-Lumi LHC.

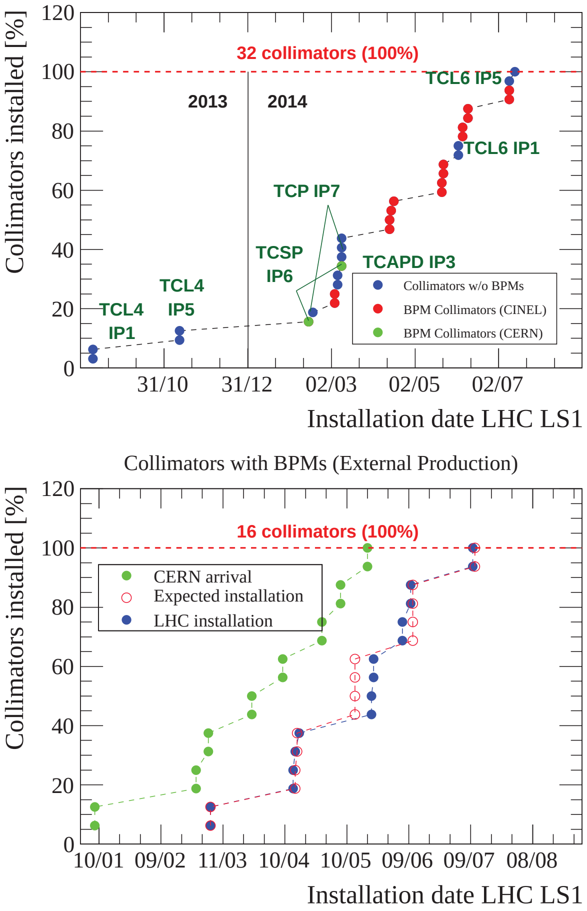

Figure 4: Status of general collimator installation (top) and BPM collimator installation (bottom).

SOFTWARE CHANGES

Several improvements have been done to low-level control system of the LHC collimators. The controls racks have been upgraded with a new PXI high availability chassis, with redundant, easily replaceable fans and a redundant hot swappable power supply, designed specifically for the collimation system. The FESA class was completely rewritten following the move to the new FESA3 framework. Beam-beam separation limits have been added, but as their calculation is difficult, it was decided to rely on the orbit measurements provided by the embedded BPMs in the tertiary collimators. In addition, 12 LVDTs affected by magnetic interference will be replaced by a new design called Ironless Inductive Position Sensor (I2PS) [12].

During Run I, improvements were also made to the software alignment tool application. The alignment of the 100 collimators was done by moving each individual jaw towards the beam until the beam halo was touched. The showers from the protons impacting the collimator jaws were detected by beam loss monitors (BLMs) installed downstream the collimators. The alignment time of a single collimator was initially of the order of 20 minutes. Beam-based collimator alignment is now performed via a feedback loop executed in a Java application. BLM data are received at 12.5 Hz, and the collimator jaws are moved in 5-10 μm steps until the losses exceeded a pre-defined threshold. The resulting spike is analyzed to ensure that the temporal pattern indicates that the is was aligned to the beam. The improvements on the alignment tool decreased the collimation setup time down to few minutes per collimator [13].

For Run 2, 80% of the collimators will still be aligned using the BLM-based technique. The feedback loop is moved to a new FESA class. In addition, this FESA class calculates the jaw gaps for the BPM-equipped collimators and forwards them to another FESA class, which will receive the BPM data and compute the measured beam positions. The alignment FESA class will use this data to align the collimators via a successive approximation algorithm, already tested with beam in the SPS [14].

The BPM-based technique will allow for the jaws to be aligned at large gaps ($>$50 mm) without touching the beam. The alignment of all BPM-equipped collimators can be performed in parallel in $<$20 s, which represents a reduction in time by 2 orders of magnitude with respect to the previous BLM-based technique. In addition, it will be possible to align the jaw corners individually. The software architecture is shown in figure 7.

COMMISSIONING

As 80% of the system remains the same as in Run 1, the commissioning plan for 2015 is strongly based on the experience accumulated so far. However, additional tests are foreseen for the commissioning of BPM collimators.

Required intensity for commissioning

Histograms of the beam intensity consumed during alignments in 2010-2013 are shown in figure 6. On average, 7×10^{10} p were consumed during an alignment campaign for all collimators. The minimum intensity required for the embedded BPMs to operate is 5×10^{9} p.

On the other hand, the minimum intensity required for qualification loss maps is defined by the minimum BLM signal needed to measure the leakage to the IR7 dispersion suppressor:

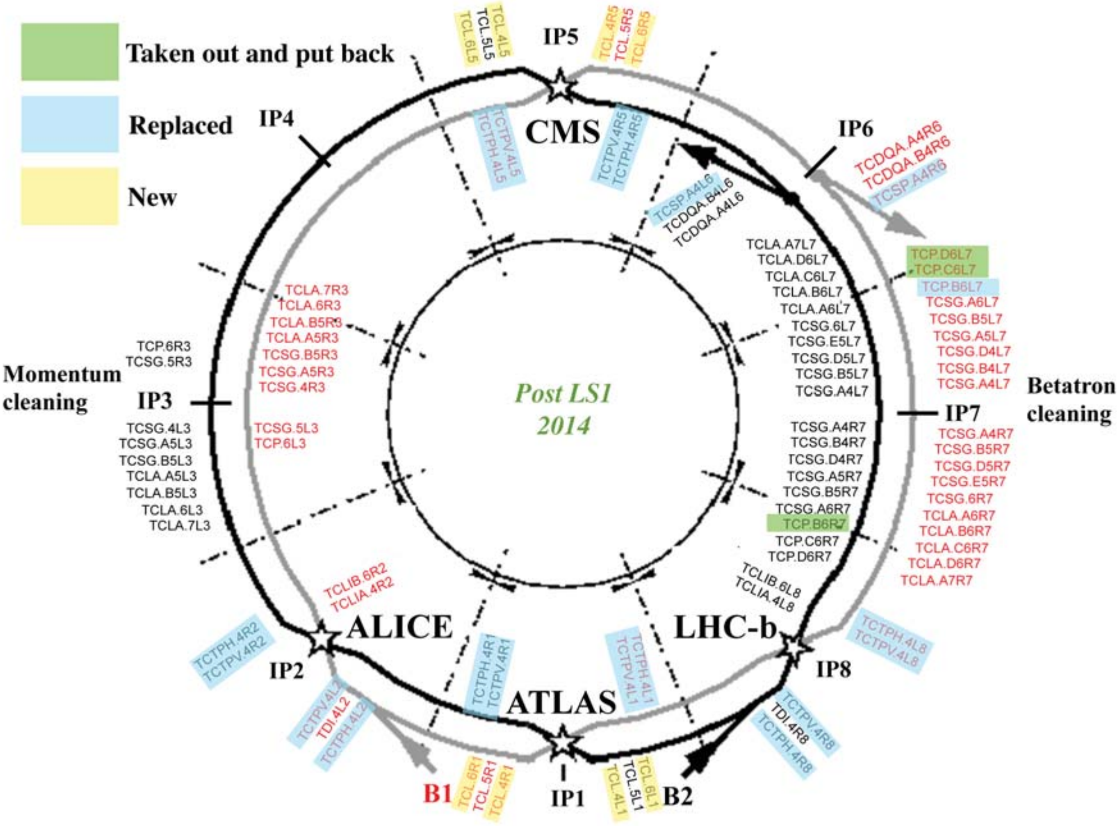

Figure 5: The LHC collimation system layout for post-LS1 operation.

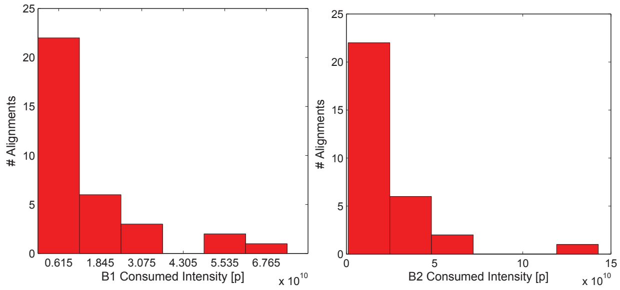

Figure 6: Beam intensity consumed during alignment for B1 (top) and B2 (bottom).

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\begin{aligned}
\mathrm{BLM}^{\mathrm{Q8}} &= \eta_{\mathrm{c}} \times \mathrm{BLM}^{\mathrm{TCP}}_{\mathrm{min}} > \mathrm{BLM}^{\mathrm{noise}} \qquad (1)\\
\mathrm{BLM}^{\mathrm{TCP}}_{\mathrm{min}} &> \frac{3 \times 10^{-7}[\mathrm{Gy/s}]}{5 \times 10^{-5}}\\
&= 6 \times 10^{-3}[\mathrm{Gy/s}]
\end{aligned}
$$

This corresponds to at least 8×10^9 protons at 4 TeV per plane (horizontal and vertical). One would expect the minimum number of protons to be lost to obtain the same BLM signal to be lower at higher energies. During 4 TeV operation in 2012, 3 nominal bunches were safe, so this minimum threshold was never encountered.

However, as a stable orbit is needed during beam-based alignments and loss maps, the operational limitation on the needed minimum intensity becomes the requirement of 2 nominal bunches to establish and optimize collisions. In addition, during collisions, the ADT blow-up cannot be performed on the colliding bunches, as crosstalk is induced in the other beam. Hence, additional non-colliding pilot bunches are required for loss maps in this machine configuration.

The required intensities and bunch configurations for the commissioning of the collimation system at the different machine stages are shown in Table 1. The intensities are below the proposed “restricted” Setup Beam Flag of 2.5×10^{11} p [15]. However, it is important to confirm as soon as possible these approximated figures with 6.5 TeV beams, as there are important uncertainties in the scaling from lower beam energies. Approximately 1 shift is required per alignment and qualification for each of the injection, flat top, squeezed separated and squeezed colliding beam configurations. Once experience is gained with the embedded BPMs, in the event of frequent machine configuration changes, the alignment and qualification after the squeeze and during collisions could be done in the same fill. Additional fills will be required for asynchronous dump qualifications at injection, flat top and during collisions in the event that the beams are dumped when per-

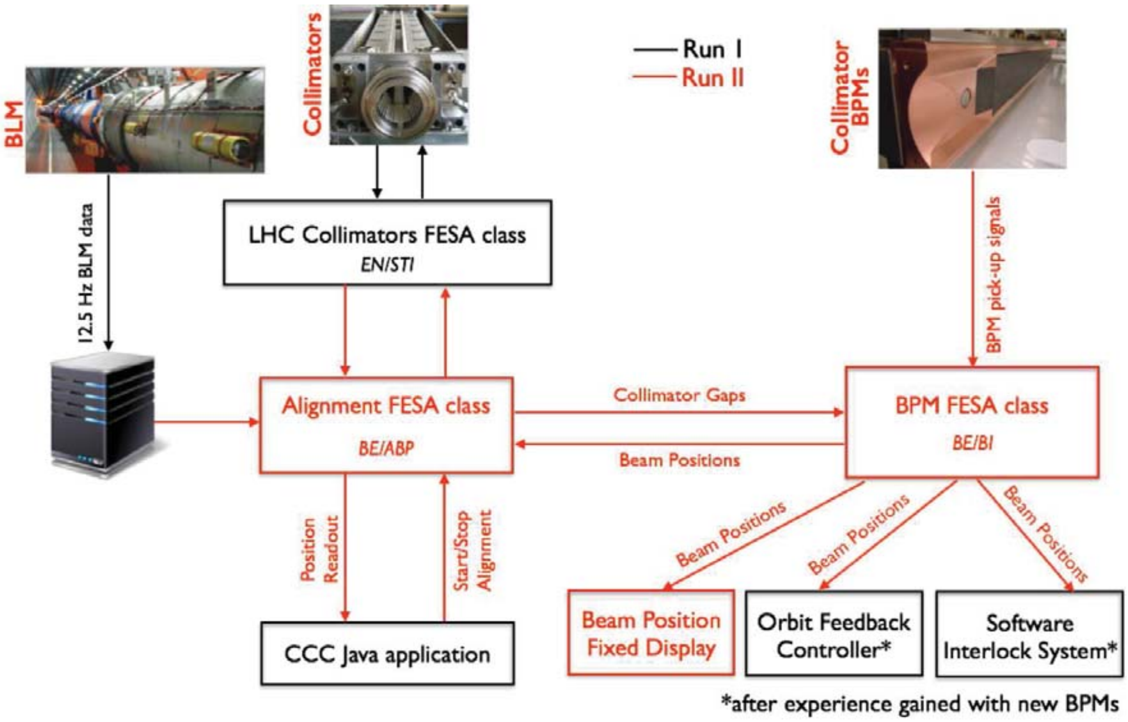

Figure 7: Software architecture for operation of the embedded BPM collimators.

Table 1: Intensity ($\times 10^{11}$ p) and bunch configuration per beam required to commission each machine stage.

Machine Mode	Alignment		Betatron Loss Maps		Off-momentum Loss Maps	
	Intensity	**Bunch config**	**Intensity**	**Bunch config**	**Intensity**	**Bunch config**
Injection	2	2 nominal	2	2 nominal	2	2 nominal
Flat Top	2	2 nominal	2	2 nominal	2	2 nominal
After Squeeze	2	2 nominal	2	2 nominal	2	2 nominal
Collisions	2.4	2 nominal + 2 pilot	2.4	2 nominal + 2 pilot	2.4	2 nominal + 2 pilot

forming the off-momentum loss maps.

Early measurements

The collimators will be used in the sector tests [16]. The jaws of several collimators in IR3, IR6 and IR7 will be positioned at the anti-collision switches at gaps of $\sim$0.5 mm and tilted to leave no clearance. In this configuration, the jaws will be at a 5 mm overshoot across the nominal beam orbit.

Beam position measurements with embedded collimator BPMs will be made parasitically from the very first fill. Collimator scans will need to be made to measure the BPM non-linearity correction coefficients, as was done in the SPS. Finally, the beam positions measured with BLM-based and BPM-based alignments need to be compared.

In order to perform more controlled off-momentum loss maps, the minimal RF trim for the right trade-off between the loss map quality and the operational efficiency (in terms of number of fills required) needs to be evaluated.

The simulations done for cleaning, impedance and R2E studies for different Roman pot and TCL collimator settings need to be validated by measurements. In addition, the proposed collimator settings for the full system need to be tested. This would be done via beam loss maps, as done in the collimation quench tests.

CONCLUSIONS

The LHC collimation system has performed very well during Run 1. No quenches were observed, and the cleaning efficiency of the system was close to the design value. Several hardware and software consolidation and upgrades are ongoing during LS1 to prepare the system for Run 2, as the the machine approaches the nominal parameters. The work is on track, and the system will be ready in time for the sector test to be held in November.

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