COLLIMATOR IMPROVEMENTS 2011 AND UPGRADE 2012: WHAT DO WE PLAN?

S. Redaelli for the LHC Collimation Team, CERN, Geneva, Switzerland

Abstract

The LHC collimation system has provided an outstanding performance during the first year of high-intensity beam operation. The complete Phase I system was commissioned with beam and delivered routinely a cleaning efficiency close to the nominal performance with relaxed collimator settings. On the other hand, the first commissioning experience has also provided first indications of system limitations alongside of hints for possible improvements. In particular, the expected performance limitations from losses in the cold dispersion suppressors (DSs) at either side of the warm cleaning insertions have been confirmed. While some improvements of the system can already be implemented during the 2010 shutdown, the major performance limitation from losses in the DSs require a change of the machine layout that will be addresses in the long shutdown. In this papers, the proposed improvements of the system are presented. The expected gains and the implication of the proposed changes on the system recommissioning are discussed.

INTRODUCTION

The performance of the LHC collimation system at 3.5 TeV was very good [1]. Together with the other machine protection systems, this is one of the key ingredients that allowed a safe operation in 2010 without a single beam-induced quench with circulating beams, with stored beam energies up to 30 MJ. The collimation experience accumulated in 2010 is very valuable and must be used to critically assess the collimator design choices, to collect feedback on various operational aspects and to project the achievable cleaning performance to larger intensities and energies. While there is essentially no time for any hardware modification during the short 2010-2011 shutdown, the experience gained can provide very valuable inputs to steer the design choices of the system upgrade scenarios foreseen for the first long shutdown.

In this paper, after a brief introduction of a few relevant aspects of the Phase I collimation system, the highlights of the 2010 operational experience are presented, with a particular emphasis on the possible areas of improvement. Then, the changes foreseen to improve the system in 2011 are discussed in detail. This consist essentially on software improvements that do not require modifications of the hardware. The possible system upgrades that are presently considered for an implementation in the first long shutdown are then outlined. Finally, some conclusions are drawn.

Table 1: List of Phase I Movable LHC Collimators

Functional type	Name	Plane	Num.	Material
Primary IR3	TCP	H	2	CFC
Secondary IR3	TCSG	H	8	CFC
Absorbers IR3	TCLA	H,V	8	W
Primary IR7	TCP	H,V,S	6	CFC
Secondary IR7	TCSG	H,V,S	22	CFC
Absorbers IR7	TCLA	H,V	10	W
Tertiary IR1/2/5/8	TCT	H,V	16	W/Cu
Physics debris absor.	TCL	H	4	Cu
Dump protection	TCSG	H	2	CFC
	TCDQ	H	2	C
Inj. prot. (lines)	TCDI	H,V	13	CFC
Inj. prot. (ring)	TDI	V	2	C
	TCLI	V	4	CFC
	TCDD	V	1	CFC

PHASE I COLLIMATION

Brief recap. of collimation layout

The complete Phase I collimation system was installed in 2009 and has been operational throughout 2010. The system includes a total of 100 movable collimators for the ring (87) and transfer lines (13) [2], including injection and dump protection elements. The list of Phase I collimator types, including information on collimation plane, number of installed devices and material, is given in Tab. 1. Collimators are installed in all interaction regions (IRs) except IR4 (RF insertion). The back-bone of the system is given by the momentum (IR3) and betatron (IR7) cleaning collimators (28 devices per beam). Local protection of superconducting triplet and experiment is provided by tertiary collimators in all the interaction points (IPs). Injection protection and dump collimators are installed in the transfer lines and in IR2, IR8 and IR6.

Controls and machine protection aspects

With the exception of the one-sided TCDQ collimators, all the LHC collimators have 2 jaws that are controlled by 4 independent stepping motors. Motors can be moved in discrete steps at a constant velocity of 2 mm/s or following arbitrary functions of time [3], which is a specific feature of the LHC. This ensures optimum settings during ramp and betatron squeeze. Each collimator has a highly redundant survey system for jaw positions and collimator gaps to ensure correct settings for each operational phase. Six direct position measurements (4 motor axes and 2 upstream and downstream gaps) are interlocked for a total of 2750 independent interlocks [4]:

(1) 12 position interlocks as a function of time are used to interlock inner and outer reading of each LVDT is all conditions;

(2) 2 maximum allowed gap limits as a function of energy are used to ensure that the collimator gaps are reduced during the energy ramp.

In addition, 5 interlocked temperature sensors per collimator can dump the beam if temperatures above safe limits are detected.

For the position interlocks (1), a different set of settings is available for the different machine phases (injection, ramp, squeeze, collision, physics data taking). The limit and the position settings can be expressed as discrete values (injection, flat-top, physics) or as functions of time (ramp, squeeze, collision function) and triggered synchronously with power converters and RF system. The energy limits remain the same for all machine phases and are designed to catch the failure that a collimator does not move during the energy ramp and remains at injection settings within the injection limits, which can happen e.g. in case of problems with the start-of-ramp trigger.

The squeeze is done at 3.5 TeV when the energy limits remain constant. Therefore, the movements of tertiary collimators during the squeeze are presently relying on time-dependent limits only (no redundancy in addition the the time interlocks). In addition, energy limits are not operational for the injection protection collimators in the ring.

Recap. of beam-based setup

Collimator settings are calculated in local beam sigma units around the local orbit position. These parameters must be calculated with "beam-based" techniques [5] because one cannot rely of the absolute positioning between beam position monitor (BPM) measurements and collimator centre, e.g. in presence of electronics BPM offsets.

The determination of the beam position at the collimators is most critical for the establishment of the operational settings (the nominal optics can be used for the beam size calculations with acceptable errors due to the excellent optics quality [6]). The beam position at the collimator is established with beam-based techniques relying on the beam loss monitor (BLM) response. Collimator jaws must therefore be moved into the beam until they "touch" the halo particles. This becomes critical with large stored energies.

The BLM-based alignment proved to be sufficiently precise up to 3.5 TeV but is lengthy and requires dedicated machine fills with a few nominal bunches. Reduced intensities are needed to allow masking BLM interlocks that might be otherwise triggered during the alignment of metallic collimators. Good settings of the system rely therefore on machine stability and collimator position reproducibility. Dedicated fills for loss maps must then be performed regularly to validate the system settings. See details in [7].

2010 OPERATIONAL FEEDBACK

The collimation cleaning in 2010 has essentially confirmed the predictions of simulations. At an energy of 3.5 TeV and β^* of 3.5 m in all IPs, with relaxed collimator settings, the local inefficiency in cold magnets was below a few 1e-4. No beam-induced magnet quenches were experienced in 2010 with circulating beams. The LHC has profited from this good cleaning performance also in term of operation efficiency as the machine was tolerant to beam losses well above specifications. No intensity limitations are expected with the 2011 parameters from collimation aspects. See [1] for more details.

From hardware and controls view points, all the main design choices of the system have been confirmed and there are so far no indications of problems. The operational performance of the system has been addressed in [9]. Appropriate software tools were established to handle the complex setting parameter space in all operational phases. Note that about 14000 different settings - functions or discrete - were needed in 2010 for each operational cycle.

On the other hand, also some limitations and areas of improvements could be identified during the 2010 operation:

- for protons, the cleaning inefficiency is limited by the cold magnets in the dispersion suppressors at either side of the cleaning insertions [7]; no additional bottlenecks are found[1]; these losses can eventually limit the total LHC intensity;

- for ions, the cleaning performance is worst due to ion fragmentation and dissociation that induce larger effective momentum offsets after the first ion interaction with the primary collimators. The overall performance is still limited by losses in the cold region downstream of the cleaning insertions [7];

- we cannot extrapolate reliably the beam life time to higher intensities, higher energies and smaller β^* values. This is presently the main uncertainty for the final performance reach estimates [8];

- the interlock strategy in some critical phases like the injection and the squeeze are not redundant and rely still on manual execution of operational sequences;

- the system setup is manual and lengthy (average of about 15 minutes per collimator) and has to be repeated in several machine phase; the setups at top energy are particularly risky because they require to work close to the dump limits of beam loss monitors;

- the system setup depends critically on the stability and fill-to-fill reproducibility of the closed orbit; this uncertainty limits the achievable β^* and in general is a concern for the collimation hierarchy;

[1] Other cold magnets in IP3, IP6 and IP7 or some triplet magnet showed occasionally larger losses than the DS magnets. It is believed that these losses are generated by showed from the collimators close-by and hence do not represent an issue for the magnet quenches. These losses have to be handled with appropriate choices of BLM thresholds.

- collimation and machine protection matters related to setup of movable devices constrain in some case the operational flexibility, e.g. during changes of crossing angle configurations, or extended luminosity scans.
- nominal collimator settings, required at 7 TeV with minimum nominal β^* remain to be demonstrated with beam at the LHC; the corresponding impedance estimate only rely on simulations;
- even if with limited statistics, we had first indications of radiation induced effects on the electronics, e.g. in the cold region downstream of IP7 during ion operation [10][2]. There were no indications yet of single event upset in the electronics racks of the cleaning insertions.
- The recovery of the system in case of power cuts is quite cumbersome. The auto-retraction mechanisms designed to take the jaws out of the beam in case of motor powering failure [11] can cause a violation of the maximum allowed jaw tilt angle tolerance. This requires (1) a lengthy remote procedure to carefully move the jaws within tolerance and (2) a new verification of the collimator positions.

IMPROVEMENTS FOR 2011

Updated interlock strategy

No significant hardware changes have been carried out during the short 2010-2011 shutdown beyond standard hardware maintenance (e.g., replacement of isolated faulty components that caused problems in 2010). The hardware design choices (mechanics, sensors, motors, drivers, etc.) have shown no issues and a very good reliability [1].

Important improvements of the collimator controls software have been implemented to increase the safety role of the system [12]:

1. New gap limits versus β^* functions in the IPs:

   Previous implementation:
   This functionality was foreseen [13] but not yet implemented due to the missing β^* information. After initial successful tests that showed that β^* can be calculated from the current measurements of selected quadrupoles used during the squeeze [14], the β^* values in each IP will be available in 2011 and distributed through the timing system.
   New implementation:
   Additional "inner" and "outer" limits as a function of β^* will be added for upstream and downstream gap measurements (4 new limits per collimator). Different collimators will use β^* values from different IPs (e.g. TCTs in different points) or the minimum value from all IPs (e.g. for IP7 collimators). This new functionality will be available for all collimators in the ring except for the TCDQs (to be implemented) and for the TDI (not necessary). An example of gap settings and β^* versus time and of the corresponding calculated gap limits versus β^* are given in Figs. 1 and 2, respectively.

2. New gap limits as a function of energy for the injection protection collimators in the ring (TDI's, TCLI's, TCDD):

   Previous implementation:
   Limits were implemented for TCLI's and TCDD but

[2]It is noted that this effects were related to local losses caused by the poorer cleaning performance with ion beams. The radiation effects in the tunnel service areas - which are addressed by the combined momentum-betatron cleaning system discussed later - are not yet been observed.

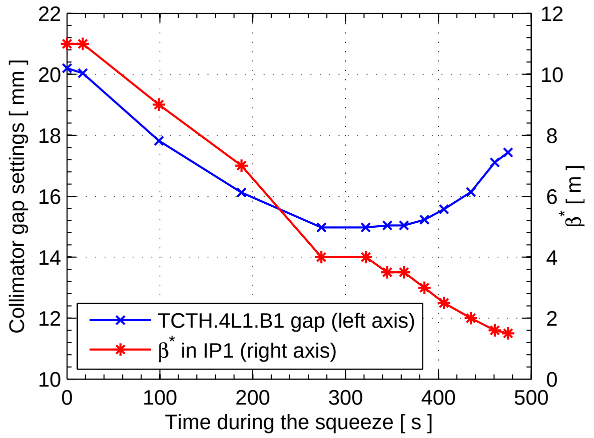

Figure 1: Collimator gap settings (blue, left axis) and β^* in IP1 (red, right axis) versus time during the squeeze. Gap settings are calculated for a normalized collimator aperture of 11.8 σ [8] by taking into account the variation of local optics at the collimator.

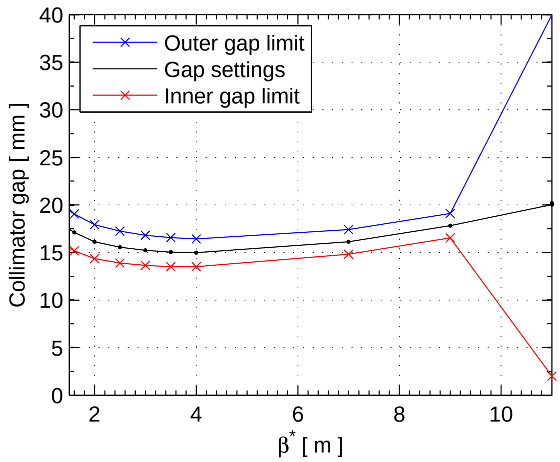

Figure 2: Example of inner (red) and outer (blue) collimator gap limit as a function of β^* calculated from the gap settings of Fig. 1 (here shown in black). The limits are open at the β^* value of the injection optics (11 m for IP1) in order to allow larger gaps at injection. In this example, if the TCT did not move, the beams would be dumped less than 90 s after the beginning of the squeeze.

with the same logic as for the ring cleaning collimators, i.e. they generated an interlock for the circulating beam if the measured gap was larger than the limit. Nothing had been foreseen for the TDI's (no direct gap measurements are available). Note that the energy limits are instead fully operational and active for the TCDI's in the transfer lines (injection interlock generated if maximum allowed gap is exceeded).
New implementation:
The new limits as a function of energy generate an injection interlock that prevents injection if the gaps of the injection collimators are larger than safe values. For the TDI that does not have direct gap measurements, the gap values are inferred from the position measurements of the jaw corners and limits are set on these calculated gap values.

3. Updated logic of the mechanism that stop the collimator motors if the position limits are exceeded:
Previous implementation:
For all collimators, the motors were stopped upon reaching the time dependent limits (discrete or functions).
New implementation:
For injection protection, it will be possible to move across the limits: the transfer line TCDI's can move across inner and outer limits whereas the injection protection collimators in the ring can only move across the outer limits (inner limits still stop the motor to prevent the jaws from running into the beam).

It is noted that in all cases, the proposed improvements provide additional redundancy to a system that proved already to be quite safe.

At the time of this workshop, the required changes are being addressed with high priority at all controls levels. The schedule is tight but there is not indication that the new implementations should not be available and tested for the start-up. Two weeks of remote commissioning and tests from the CCC are planned before the start of beam operation. In particular, the machine protection functionality of the system will have to be fully re-validated after the modifications proposed above [12].

Semi-automated beam-based alignment

A new software application for semi-automated collimator setup is being prepared and will be tested in the collimator alignment campaigns in 2011 [15]. This new software is designed to help the collimator setup in various ways: (1) define software limits for the maximum BLM signal to minimise the risks of beam dumps due to aggressive collimator movements; (2) automatize the setup/configuration of repetition of collimator movements in small steps, with reduced risk of human errors; (3) automatize the collection of data for settings generation that is presently done manually. In addition, the software will also help making the alignment procedure faster. On the other hand, in the first version, the 1 Hz BLM data will be used and this will still limit the overall alignment time.

CHANGES BEYOND 2011

Combined momentum-betatron cleaning in IP3 with DS collimators in the cold region

A combined momentum and betatron cleaning system in IP3 was initially proposed [16] to mitigate the effects of radiation to electronics. The main motivation is that the locations of the electronics racks are expected to receive up to 100 times less radiation than the IP7 ones for the same number of proton lost according to simulations [17, 18]. This proposal relies on adding vertical collimators in IP3, re-using existing installation slots with minimum layout impact, to provide a vertical cleaning in the momentum insertion that otherwise contains only horizontal primary and secondary collimators and shower absorbers. The cleaning of such a system [16] would however be about a factor 2 worst than what is provided by the present betatron insertion (without skew cleaning and with less collimators).

The cleaning limitations of the combined system are removed by adding dispersion suppressor (DS) collimators originally conceived a possible improvement for IP7 [19]. In fact, preliminary simulations without imperfections [20] show that with DS collimators, a cleaning performance compatible with the LHC nominal and ultimate beam intensities at 7 TeV can be achieved. Collimator impedance remains an issue but can be kept under control [21].

The combined momentum-betatron cleaning in IP3 with DS collimators is therefore the baseline for the system upgrade in the first long technical stop. The new DS layout is based on a warm technology for the DS-collimators and on a cryogenic by-pass in the region of the missing dipole [21]. The Phase I collimators will remain installed on operational. System readiness, implication on the schedule and required activities in the cryogenic regions are being been addressed, as reported in companion papers [22, 23].

BLM-integrated design

In order to speed up the alignment procedure, BPM buttons could be integrated into the collimator jaws (see Fig. 3) for a direct measurement of the local beam orbit [24]. This concept enables (1) a fast alignment by equalizing the signal on the two buttons (expected time is 10-20 seconds); (2) a constant monitoring of beam drifts with operational gap values, without need to touch the beam. In principle, mounting BPMs on both upstream and downstream collimator sides also allows determining the orbit angle at the collimator location. Note that the centring (1) is expected to be independent of systematics in the BPM electronics. These advantages are particularly interesting for the TCT collimators next to the experiments that presently require a new setup campaign for every crossing scheme configuration.

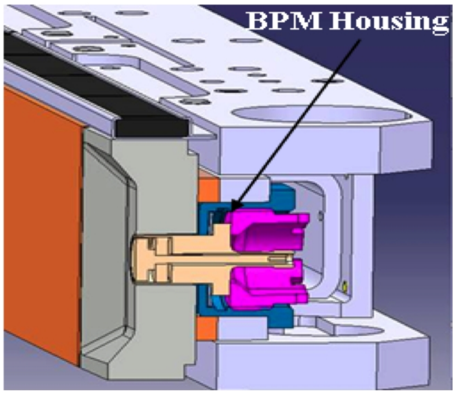

Figure 3: Illustrative drawing of the collimator jaw with BPM integrated at the end of the jaw, close to the tapered part. Courtesy of A. Dallocchio [24].

The feasibility of this BPM-integrated design has been addressed in 2010 by dedicated beam tests at the SPS that gave very promising results. For example, in Fig. 4 the BPM signal is shown as a function of the jaw position during an asymmetric scan. When one jaw only is moved, the BPM measurements shows deltas corresponding to half of the jaw movements, as expected because the total centre shifts by half of the movement of one jaw. The SPS tests have very preliminarily assessed that:

- the standard BLM-based and the BPM-based methods are in good agreement;
- showers induced by an upstream SPS collimator or by the collimator jaw itself did not affect the BPM signal. This suggests that acquisitions are possible also with small collimator gaps (operational settings) in presence of losses;
- scans of the collimator gap position showed that the BPM signals scales correctly;
- BPM measurements can be performed for a broad variety of collimator gap values (from a few mm up to above 40 mm), which covers the LHC operational range;
- the linearity of the signal seems acceptable [25];
- detailed estimates of the BPM-based setup time were not possible due to the still manual BPM acquisition chain used in the beam tests. By looking on-line at the scope, we could equalized the signals from the two bottoms within a few minutes.

The collimator prototype equipped with BPM-integrated jaws will remain in the SPS in 2011 and beam tests will continue to confirm these preliminary results.

Modified TCT layout in IP2

A new layout of the interaction point 2 [26] was proposed to remove a conflict between the ALICE zero degree calorimeter (ZDC) and the TCTV collimators installed between the ZDC and IP2. Depending on the TCTV settings, part of the spectator nucleons are caught by the collimator jaws before reaching the ZDC. This introduced a systematic error that depends on machine parameters. During the 2010 ion operation, this issue was partly avoided by opening the TCTV's: risks were considered acceptable with a limited number of ion bunches because asynchronous dump failures affect only the horizontal plane [28]. The situation could be avoided if the TCTV were installed downstream of the ZDC with respect to the IP.

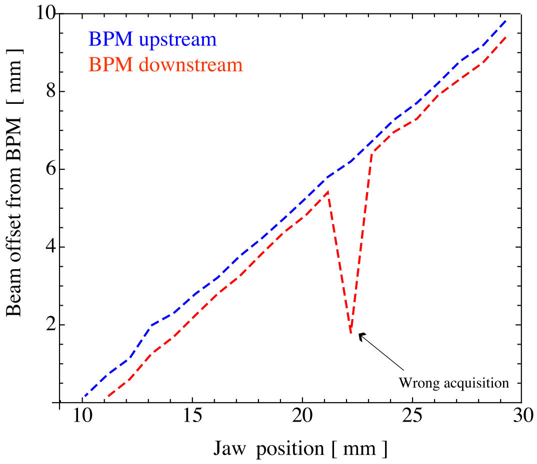

Figure 4: Beam centre measured by the up- and downstream BPMs versus jaw position during SPS beam tests. Moving one jaw at a time gives an relative shift of the beam centre that is half of the jaw movement. Courtesy of M. Gasior (BE/BI) and D. Wollmann (BE/ABP).

A technical solution has been found for an updated LSS2 layout that provides the same protection/cleaning functionality of the system without shadowing the ALICE ZDC. With a limited modification of the vacuum layout, space can be made upstream of the ZDC to fit the TCTV collimator in the region with separated vacuum chambers for B1 and B2 (i.e. close to the present location of the TCTH). This solution has implications for the vacuum layout, for the bake-out of the LSS2 and for the collimator production (two more collimators are required). The time line is being followed-up by the LMC [29]. This takes into account the possibility to perform the change in a short 2011 shutdown.

DS collimators in other IPs

The possibility to add additional "cryo" collimators in dispersion suppressor of other interaction points (IR7 or experiments), possible combined with a new design for short dispersion suppressor dipoles, in not considered viable for the first long shutdown and is not the subject of this paper.

CONCLUSIONS

The good performance of the LHC collimation system allowed a safe and efficient operation at 3.5 TeV. There are no expected intensity limitation at this energy for 2011 if the beam life time will remain as in 2010. The collimator controls have been extended in order provide more redundancy for machine protection and a faster beam-based alignment. In particular, additional limits as a function of β^* will enforce correct collimator movements during the betatron squeeze and an improved interlock strategy for injection protection will make injection safer.

The first operational experience has also confirmed the expected limitations, like the locations of the highest losses from halo leakage out of the cleaning insertions and like the long setup time from manual setup procedures. Other expected limitations, like radiation to the electronics in the tunnel service areas or like the impedance with small gaps, did not see yet a firm experimental confirmation but remain critical for achieving higher intensities. For example, the LHC efficiency has already been affected by radiation. New aspects were also identified, like the many constraints that collimation puts on the LHC operation (lengthy loss maps, constraints on separation and crossing schemes and on the luminosity scans, etc.). The operational experience is essential to guide the choice of system upgrades.

The upgrade scenarios for the first long shutdown have been reviewed. This includes a combined momentum and betatron cleaning in IP3, a new dispersion suppressor layout with warm DS collimators, a new design with BPM integrated in the jaw for faster beam-based setup. The present estimates indicate that these proposals can address satisfactorily the system limitations towards LHC nominal intensities at 7 TeV. The project resource must now be prioritized in order to maximise what can be done in the first long shutdown. The feasibility of the various options in the given time constraints are being addressed. A project review is schedule for mid-2011 to establish a final strategy, which will also take into account the feedback from the 2011 experience at 3.5 TeV, with higher intensities and smaller β^*.

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