LHC COLLIMATORS AND MOVABLE DEVICES

Stefano Redaelli, CERN, Geneva, Switzerland

Abstract

About 500 movable devices have the ability to touch the LHC beams. The list includes operational devices that are moved according to pre-defined sequences in the operational cycle, like collimators, protection elements and physics detectors, as well as non-operational devices that are not used in standard operation with high intensity beams, like vacuum valves, beam stoppers, beam screens. The proper interlock strategy of these devices has represented an important concern due to the high damage potential of the LHC beams. This topic has been addressed several times in the past. In this paper, the changes that are foreseen during the first LHC long shutdown, in preparation for the LHC energy upgrade, are reviewed. The operational experience of the LHC run 1 and the problems encountered are also discussed.

INTRODUCTION

The Large Hadron Collider (LHC) run 1 showed that the machine can be operated safely with stored beam energies up to a factor 70 larger than the previous state-of-the-art in particle accelerators set by the Tevatron. The LHC was routinely running with stored energies around 140 MJ at 4 TeV. On the other hand, the safe operation of the LHC remains a concern for the future due to the unprecedented damage potential of the LHC beams. After LS1, an increase by a factor 2 of beam intensities achieved through reduced bunch spacing (25 ns instead than 50 ns) and an increase by a factor 1.6 in particle energy (6.5 TeV instead than 4 TeV) are expected. In particular, movable devices that can intercept the beams require appropriate interlocking strategies. In the LHC and its transfer lines, there are about 500 of such devices, including vacuum valves, beam stoppers, collimators, screens and physics detectors.

An exhaustive list of the LHC movable devices can be found in [1]. More recently, the adopted interlocking strategy was reviewed for the different cases [2], covering both the “operational” devices (collimators and movable physics detectors) that are moved during the operational cycle and the IN/OUT “non-operational” devices (vacuum valves, screens, etc.) that must be out during high-intensity beam operation. The latter devices rely on hardware beam inhibit signals that trigger beam abort requests in case of incorrect positions. For example, a beam dump request is issued if a vacuum valve leaves its OUT position. Instead, devices like collimators must be dynamically adjusted during the cycle in order to ensure optimum settings while optics and orbit change. The interlocking strategy in this case is clearly more complex.

More than 130 operational movable devices are installed in the LHC and its transfer lines, including 100 collimators for cleaning and machine protection, 32 Roman pots and the LHCb VELO detector. Their operational settings are carefully established by using dedicated beam-based procedures that were worked out to ensure a safe operation in all conditions. Complex and redundant interlocks were designed to minimize the risk of errors in the positions of these devices. In this paper, the overall interlock strategy is reviewed for the different movable devices. The changes planned during the LHC Long Shutdown 1 (LS1) are listed. Particular emphasis is put on the operational devices and on the problems encountered in the 2012-13 run are discussed. Procedural aspects and the influence of human errors are also addressed.

MOVABLE DEVICE INTERLOCKS AND CHANGES DURING LS1

Non-operational movable devices

The non-operational devices that are typically OUT of beam during high-intensity operation are listed below [1]:

- Equipment under responsibility of the vacuum team:
  - vacuum valves (about 250 in the rings and transfer lines);
  - electron beam stoppers in the RF zones (4);
  - safety beam stopper in IR3 (2).
- Beam instrumentation:
  - beam screens (11);
  - mirrors of synchrotron light monitors (2);
  - wire scanners (4).
- 1 movable mask of type TCDD in IR2.
- Triplet magnets that are mounted on motorized jacks (32 per interaction point). This system is used for remote alignment of the magnets that is done without beam [3] to ensure optimum magnet positions.

Details of the interlock strategies for these devices are given in [2]. Note that the position of the movable TCDD mask [4] and of the mirrors for the synchrotron light monitors in IP4 are designed such that their IN position remains outside the local aperture restrictions. Beam screens and wire scanners can only be operated at appropriate beam intensities and energies. Vacuum elements individually inhibit the beams by removing the beam permit when moving away from their OUT position.

No major changes are foreseen during the LS1 for these devices. One outstanding issue is a recent proposal to add fast vacuum valves in IP4 in order to limit collateral effects to the RF cavities from a catastrophic magnet failures as the one of 2008 [5]. The proposed valves can close in 20 ms to 50 ms, which makes their interlock particularly tricky. This aspect was discussed in [6] and the final decision of the LHC Machine Committee was to avoid the installation fast valves because the potential closure with beam was considered potentially more severe than the pollution that these valves were designed to avoid.

Operational movable devices

List of devices and recap of interlocks The operational devices that are moved in vacuum during the operational cycle, following pre-defined settings for each cycle phase, are listed below:

- Collimators and protection devices in rings and transfer lines:
    - 98 four-motor, two-sided collimators[1];
    - 2 one-sided TCDQ's (IP6 dump protection);
    - note that 44 collimators feature a "5th motor axis" for transverse jaw movements perpendicular to the collimator angle (designed to provide fresh jaw surface in case of collimator damage).
- Movable in-vacuum experiment detectors (only moved in stable beam conditions):
    - VELO of the LHCb detector [7];
    - 32 Roman pots in IR1 and IR5.

The control of the movable collimators is clearly a critical challenge for the LHC operation, since beam collimation and machine protection are needed continuously in all phases of the LHC operation. The complexity of the system is illustrated by the figures in Table 1, where the degrees of freedom for collimation movements as deployed in 2012 are listed [8]. The controls design was driven by the collimation system requirements [9].

Collimators are redundantly interlocked in order to ensure that optimum positions during the operational cycle [9]. Table 2 summarizes the different movement and interlocks types available for the four main hardware categories: LHC collimators (labelled LHC Coll), dump protection blocks (TCDQ), injection protection blocks (TDI) and Roman pots (XRP). The LHCb VELO is entirely handled by the LHCb and does not feature direct input channels on the LHC interlock system.

The collimators can be moved in discrete steps at a fixed speed of 2 mm/s or following arbitrary functions of time, e.g. like it is required in the energy ramp to follow beam size and orbit evolution [10]. This requires two different types of interlocks: limit functions and discrete limits. The latter apply when the collimators remains idle at the end of a function execution. The time-dependent position limits apply to individual jaw axes and to the collimator gap (6 sets of limits per collimator). In addition, energy-dependent limits are used to ensure that collimator gaps are reduced as expected during the energy ramp (see illustration in Fig. 1) and β^*-dependent limits are used during the betatron squeeze for the tertiary collimators[2]. All the reference settings are defined and stored by the system experts in appropriate tables and are loaded and executed repeatedly at every fill by the OP crew throught dedicated collimation sequences.

Table 1: 2012 collimation parameters table for the 98 four-motor collimators in the LHC rings and transfer lines.

Parameters	**Number**
Movable collimators in the ring	85
Transfer line collimators	13
Stepping motors	392
Resolvers	392
Position/gap measurements	584
Interlocked position sensors	584
Interlocked temperature sensors	584
Motor settings: functions / discrete	448/1180
Threshold settings versus time	9768
Threshold settings versus energy	196
Threshold settings versus β^*	384

This powerful but complex system is adopted for collimator-like devices with different hardware through an appropriate middle-ware interface that allows the operation crew to manage the settings in the same way [11]. Note that the Roman pots only move through discrete settings so redundancy cannot be achieved with the standard energy- and β^*-limits. Additional discrete redundant limits are added for this purpose by defining limits for the closest pot position to the beam that are always active in the system.

Changes foreseen during LS1 The main change that will take place in LS1 is that 18 ring collimators will be replaces with a new design with four beam position monitors (BPMs) embedded in the jaws, one at each corner [12]. These collimators will replace the tertiary collimators in all interaction points and the secondary collimators in the IR6 dump region [13, 14] for an improved operational flexibility in the interaction regions and an improved β^* reach [15]. This new design was extensively tested and validated at the SPS with a mock-up collimator with BPMs [16, 17]. In addition to the important performance gains, the new BPM feature is designed to provide a better monitoring of the collimator centre. Presently, this important parameter can only be measured by beam loss based techniques in

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[1] Even if classified as non-operational device, the movable TCDD is accounted for here because its settings are managed through the same controls as the four-motor collimators.

[2] The implementation of the limits as a function of β^* is done for all the collimators and for the TCDQ even if so far this was only used for tertiary collimators.

Table 2: Summary of different setting and interlock types used for the four main hardware types defined in the text: LHC collimators (LHC Coll), dump protection block (TCDQ), injection protection block (TDI) and Roman pots (XRP). The TCDQ is the only device that does not used stepping motors but servo loop.

	N	Stepping motors	Discrete settings	Function settings	Timing receiver	Limit functions of			'Redundant' limits	Temperature interlock
						Time	Energy	Beta*		
LHC coll.	98	√	√	√	√	√	√	√		√
TCDQ	2		√	√	√	√	√	√		
TDI	2	√	√		√	√	√			
XRP	32	√	√			√			√	

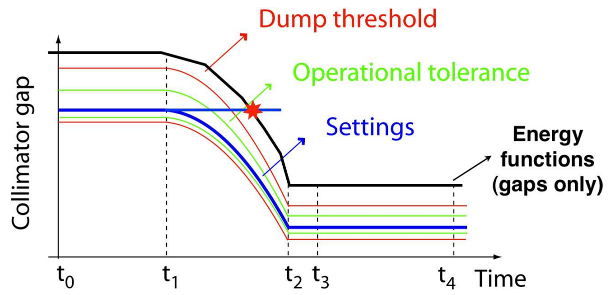

Figure 1: Illustration of collimation gap interlocks. In addition to standard limits (red) around the set point (blue), interlocks versus energy (black) are defined to ensure that the collimator gaps is reduced as expected when the energy increases. These limits are defined as arrays of maximum allowed gap versus energy [11]. The limit value at each time is calculated using as input the beam energy value distributed by the timing system. This allows catching a scenario when a collimator does not move at the start of the ramp (straight blue line), e.g. in case of problems with the start-of-ramp trigger that leaves the collimator still within the injection limits.

dedicated low-intensity fills. The BPM feature will allow an early detection of wrong collimator positions. We plan to add a software interlock that will dump the beams in case any collimator centre exceeds its pre-defined tolerance windows. See also [18].

Another change under discussion concerns the addition of redundant limits as a function of the beam separation and crossing at the IP [19], to provide redundancy when the collision functions are triggered (similarly to what is provided by energy- and β^*-limits during ramp and squeeze, respectively). This implementation, conceived to avoid some isolated problem occurred in 2012 (see below), requires the beam separation and crossing angle information to be computed and reliably distributed by the timing system, like energy and β^*. The feasibility of this implementation, which required a reliable caclulation of beam separation and crossing angles, is being addressed.

It is also planned to add new physics debris collimators cleaning the outgoing beams in IR1 and IR5 and to modify the hardware of the TCDQ [20] and TDI collimators [21]. These changes do not affect the interlocking of the system provided that the new hardware will ensure the same position accuracy. Other MP aspects specific for injection and dump protection are discussed in [20, 21]. The layouts of the Roman pots in IR1 and IR5 will also be modified by adding up to 8 new pots and by shifting the positions of the present ones[22]. The interlock philosophy will remain the same.

A crystal collimation experiment has been proposed for installation in IR7 during LS1 [23]. In its initial phase, the crystal installation is intended for MD purposes and will affect beam 1 only. Details of the interlock strategy have yet to be outlined. It is expected that "status" interlock based on monitoring the OUT position of the crystal will suffice (a maskable interlock will be activated when the crystal leaves its OUT position, it is to be masked during MD's with safe intensities).

PROBLEMS ENCOUNTERED AND OPERATIONAL FEEDBACK

Collimator settings and thresholds are stored in LSA "beam processes" and executed by the LHC sequencer. Settings are validated by loss maps [24] about every 4 weeks and/or when the machine configuration change. The following problems were encountered during the LHC operation:

1) Wrong parameters entered in the generation programs for collimator settings, causing wrong settings for two tertiary collimators and for an active absorber in IR3 [18].

2) Wrong settings of the injection protection devices after a change of optics in the transfer lines (gaps values were not updated following an optics change and kept at wrong values during some weeks [21]).

3) Operation with wrong injection protection settings in 2011 due to the use of an incorrect set of settings (wrong beam process used by the sequencer).

4) Tertiary collimators not moving in one interaction point when beams were brought in collision, due to a failure of the local timing (“start” timing event not received).

5) Similar problem as (4) during ion operation, due to a wrong sequencer usage by the operation crew (one sub-sequence skipped).

6) A few issues were encountered with setting handling (setting copy between beam processes, revert of operational settings after MD’s or special runs, problems with digital signatures of critical settings requiring expert interventions). Typically this affected operational efficiency rather than posing MP concerns.

7) A limited number of hardware problems, see [8], that were caught by the internal system monitoring. This is not discussed in this paper.

The HW timing problem (4) was detected by the operation crew through the machine state. The action taken was to call the collimation contact who requested an immediate dump of the beams. Such problems will be avoided by the new BPM features and/or by new limits versus beam separation [19]. The other issues in the list (except item 7) can be considered as human errors. It is interesting to note that they were typically identified by the system experts through internal checks. The complexity of the setting handling makes it very difficult to have people acquainted with the system within the standard operation crew. The question whether this should be changed by giving more responsibilities to the shift crew members was discussed at the workshop and needs more followup.

With the present controls environment it is very difficult to identify errors in the setting generation after settings are imported into the control system by the experts. The interlock limits described in the previous section make sure that the devices move as programmed, but cannot ensure that the settings are correct to provide the required functionality. Such verification is difficult to achieve because it must take into account a variety of sources of information (beam energy, optics, set point of IP bumps, position of other collimators, etc.) that are used to generate the settings.

There have been attempts to develop high level software to check the correct orbit and optics independently of the inputs imported at the generation phase (i.e. compare measured collimator gaps/positions to what they *should* be at a given machine condition). These were not really successful so far (see for example discussion on online model in [18]). Efforts are ongoing to improve the monitoring software but clearly the need for improved setting checks will remain crucial for the future. Note that the standard way to validate collimator settings is through loss maps. This is however not fully conclusive to detect setting problems with the accuracy ranging from a fraction of a beam sigma to a few beam sigmas, which can already be critical for MP [24].

The monitoring of collimator gaps is done efficiently in the present system by the independent collimator gap measurements (2 measurements per collimators). The addition of the BPM feature will improve significantly the monitoring of possible errors of the collimator centre. The tertiary collimators whose settings are affected by the frequent changes of IR configuration will be replaced first. The majority of the collimators will not have BPM after LS1 so improving the settings handling remain a priority. The addition of limits versus IP separation might be used to cover the issues (5) and (6) above.

An intrinsic weakness of the present setting management environment is that there is no tight protection against changes of the beam process used by the sequencer (this is done by assigning beam processes to “users” like injection, ramp, etc.). This is a manipulation that the whole OP crew is allowed to perform, as required in different operational conditions. A better protection for this manipulation against bad changes, which caused some problems when changing machine configurations for MD’s or special runs, should be put in place. For example, only authorised users should be able to change the injection beam process.

Finally, it is also important to remind that is some cases, critical validation of machine settings were not done in ideal conditions. In case of frequent changes of machine configurations, supporting teams are often required to intervene at any time during the day, under time pressure. A number of proposals were brought forwards in the discussion to improve the situation, like enforcing that no deployment of new settings and no validation of critical systems is allowed during the nights, enforcing one low-intensity fill after important setting changes and agreeing on minimal staged intensity ramp-up procedures after major machine configuration changes. Due to the increased damage potential of the LHC beams after LS1, the procedures to deploy MP-relevant settings after machine changes should be reviewed.

CONCLUSION

The operation of high-intensity and high-energy beams with damage potential well above the limits of accelerator components is a concern. The machine safety relies on several movable devices being the the right positions. The operation during the LHC run 1 was very successful from the MP viewpoint, but several improvements are under discussion to reduce even further the risk of inducing dangerous situations. A few problems occurred which could have been critical in case of combined machine failures. Online monitoring of beam losses cannot exclude in all cases dangerous conditions, so it is crucial to ensure the self-consistency of movable device settings during all operational phases.

The different types of devices and their interlock strategies were reviewed and the changes foreseen for the post-LS1 operation were discussed. No major modifications that change the overall MP protection aspects are foreseen. An important improvement is expected from the addition of collimators with embedded BPM that, amongst other benefits, will improve significantly the MP role of the collimation system: BPMs will provide – in theory – an easy way to exclude errors in the collimator centres that were experienced in a few cases. This type of errors are potentially critical and difficult to identify with the required precision by independent checks. The present controls are suited to ensure that the collimators go where they are told, but not optimum to verify that the settings are correct.

The operational experience with other encountered problem shows that the verification of settings remains a very hot topic for movable devices. Details on proposed improvements were reported in several companion papers presented at this workshop. We recall here the proposal under discussion to add new sets of collimator limits as a function of the beam separation at the collision points. This proposal becomes crucial if the production of new collimators with BPM cannot be guaranteed.

An important point of the interlock approach developed for operational movable devices is that different hardware types adopt the same interlock philosophy. This approach should be maintained for future upgrades. Hardware failures hardly caused dangerous situations because the systems reacted well in case of failures. The main concerns for movable devices arose from human mistakes in the setting handling/generation. This aspect should be improved in the future. The present setting management system is error prone when it comes to handle settings changes for multiple machine configurations. Human actions are still critical to ensure a safe operation in these cases. Some weaknesses of the present system were discussed and some suggestions for possible improvements, including the revision of procedures to ensure that critical validations are performed in optimum conditions, were outlined.

The main followup items, also presented in the summary of Section 4 of the MP workshop, are listed below. See also details in the companion papers [18, 20, 21]
– Decide on the implementation of new collimator limits versus of beam separation and crossing angles;
– Work out the detailed interlock implementation for the new BPM collimators;
– Improve protection of beam processes where settings are stored, whose handling caused several issues (in particular for injection settings);
– Review operational procedures for setting deployment and validation;
– Improve tools for the settings verification at generation level and during operation (on-line monitoring);
– Review validation procedures for MP systems in order to ensure that critical changes are done in optimum conditions.
– Deploy systematically the machine state tool.

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