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MPS Commissioning Procedure

THE COMMISSIONING OF THE LHC MACHINE PROTECTION SYSTEM

MPS ASPECTS OF THE COLLIMATION SYSTEM COMMISSIONING

Abstract

This document describes the set of tests that will be carried-out to validate for operation the machine protection functionality of the **LHC collimation system.** The tunnel area concerned by these tests extends over 7 out of the 8 long straight sections.

These tests include the Hardware Commissioning, the machine check-out and the tests with beam, to the extent that they are relevant for the machine protection functionality of collimation.

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History of Changes

Rev. No.	Date	Pages	Description of Changes
0.1	2007-10-08		First draft for circulation.
0.2	2007-10-10		Comments from S. Redaelli, R. Losito, M. Jonker.
1.1	2009-01-16		Update with detailed procedure for the MP commissioning as implemented in 2008 (S. Redaelli).
1.2	2009-06-25		Final version for the first engineering check (R. Assmann, S. Redaelli).
2.0	2014-06-19		First update in 2014 (B.Salvachua, S.Redaelli)

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1. INTRODUCTION

The LHC collimation system has several core functions:

1. Efficient cleaning of the beam halo.
2. Concentration of beam losses and activation at collimation insertions.
3. Passive machine protection.
4. Background control in the experimental detectors.

The system has been designed and optimized for halo cleaning. However, its function of passive protection makes the system a crucial part of the overall machine protection system (MPS) for the LHC. In the MPS it must fulfil its protection functions together with the other protection systems in order to ensure that the machine safety is always guarantee. This requires adequate interlocks to dump the beams if the collimators are not at their correct positions or if the system has faults that prevent its correct functioning.

In this note, we describe the tests that will be performed in order to guarantee that collimators always safely maintain the required passive protection settings or otherwise generate a beam interlock. The detailed presentation of the beam commissioning of the cleaning functionality is not part of the machine protection functionality and therefore is not described here. Details on beam commissioning of the LHC collimation system can be found in [1,2,3,3a]. Also, commissioning and interlocks on vacuum are not part of this procedure [4].

2. SCOPE

Areas concerned: **LSS1, LSS2, LSS3, LSS5, LSS6, LSS7, LSS8, TI2, TI8**.

The following movable collimators and fixed masks that are part of the 2015 collimation system [5,5a] are addressed:

1. Collimator-like objects (movable collimator jaws inside the LHC vacuum system) for position, gap and temperature interlocking: **TCP, TCSG, TCSP TCTPH, TCTPV, TCLA, TCL, TCLIA, TCLIB, TCDIH, TCDIV**. Compared to the LHC Run 1 system, new collimators with embedded BPMs replaced the secondary collimators in IR6 (TCSG replaced by TCSP) and the tertiary collimators in all IRs (TCTVA, TCTVB and TCTH replaced by TCTPV and TCTPH).
2. Absorber-like objects (fixed absorbers outside of LHC vacuum system) for temperature interlocking: **TCAPA, TCAPB, TCAPC, TCAPD**.

Other collimator-like objects for position, temperature and, where applicable, gap interlocking like the **TDI, TCDD, TCDQ** and the **TOTEM** and **ATLAS-ALFA Roman pots** are not part of this note.

It is noted that the set-up for halo cleaning and optimization of cleaning efficiency is not discussed in this note.

3. PURPOSE

This document

1. gives a comprehensive list of the components which will be the object of the tests.
2. describes in detail the procedures which will be applied for these tests and their sequence.

Each test has in front one of the following letters, defining at which interval or at which occasion the described test needs to be repeated (in the column labelled Repetition):

N	Not to be repeated. Executed only at the beginning of a Run i.e. after Long Shutdown.
S1, S2	To be repeated after every Shutdown. S1: to be repeated after every Xmas-like shutdown. S2: to be repeated after every technical stop.
P	Periodical repetition required, like 1 x per month; details to be defined in text
O	To be repeated when LHC optics is changed
X	To be repeated when crossing scheme is changed

This document is meant to be the reference document for the checklist that will be used during the commissioning of the MPS. Results of the tests will be documented in the MTF database [3a].

4. THE LAYOUT

For the Run II operation, the full Phase I system is available. The latest version of the layout can be found at the LHC layout database [5b]. A summary of the post-LS1 system can also be found in [5c].

During LS1 the LHC collimation system has been upgraded. The main changes are:

- Replacement of 18 collimators with collimators with embedded Beam Position Monitors, 16 of them Tungsten TCTs and 2 of the Carbon TCSG in IP6.
- Modification of IR8 TCT layout (removing the 2-in-1 collimator design for the tertiary collimators).
- Addition of 2 passive absorbers in IR3 (TCAPD), one per beam.
- Addition of 4 TCLs Copper physics debris collimators in cell 4 of IR1 and IR5 (1 per beam per IR).
- Addition of 4 TCLs Tungsten physics debris collimators in cell 6 of IR1 and IR5 (1 per beam per IR).

After LS1 the collimation system consists of 118 collimators and passive absorbers, 108 of them movable. The post LS1 LHC collimation layout is shown in Fig. 1. Note that one primary collimator (TCP) in IR7 was replaced with a spare without changes of the system functionality.

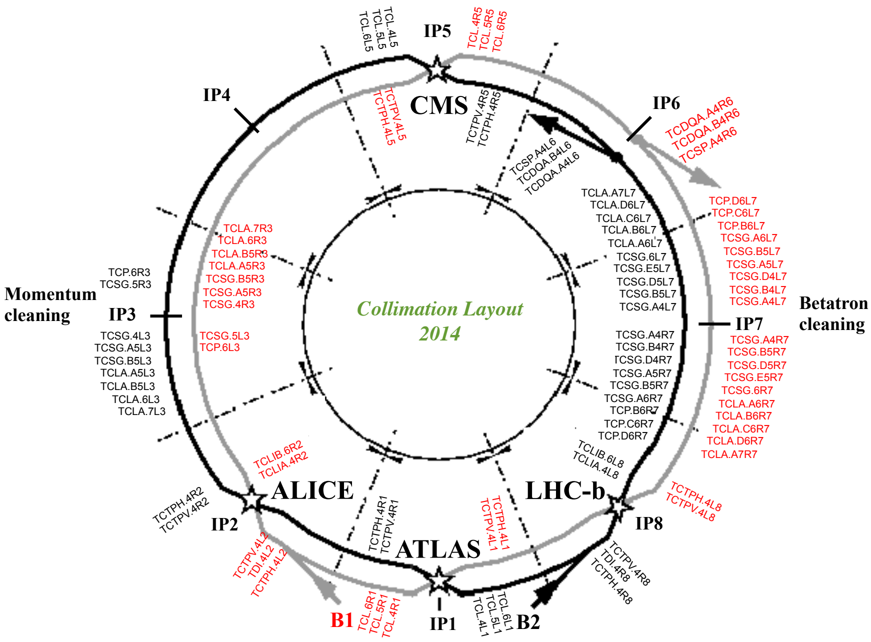

Figure 1: LHC collimation layout of movable devices after LS1 upgrades.

5. LINK TO OTHER EQUIPEMENT

The interfaces listed in this paragraph concern only the ones in relation with the Machine Protection aspect of the collimation system.

5.1 BEAM INTERLOCK SYSTEM

The details of the various collimator input channels into the BIC are given in Appendix 1 (see also [6]). For the injection BIC's and each LSS BIC (except LSS4) in the LHC we have two separate maskable collimator inputs, which each are constructed by an "AND" over the inputs from up to 19 collimators plus passive absorbers:

- **Collimator Position Readout & Survey (BIC channel 8):**
  Interlocks from jaw position and collimator gap measurements: this includes limits versus time (IN and OUT thresholds for 6 degrees of freedom per collimator, i.e. 12 limits), maximum allowed gaps versus beam energy (2 limits per collimator) and gap thresholds versus beta* (IN and OUT thresholds for 2 gaps, i.e. 4 limits per collimators).
  In addition to the position and gap survey, beam dump requests are also triggered if the system does not received beam energy and beta-star information at the expected frequency (fail safe approach).
  An interlock is also generated when a collimator is set to a safe "local" mode for sensor calibration.
  Note that failures of the motor drive system do not cause direct interlocks, which are only generated in the survey system when detects positions outside safe limits.
- **Collimator Environmental survey (BIC channel 9):**
  Interlocks from temperature sensors: minimum and maximum temperature thresholds adjustable independently for 5 sensors per collimator.

5.2 LHC CONTROLS SYSTEM: SAFE MACHINE PARAMETERS

The LHC control system must provide the following input to the collimation system as Safe Machine Parameter (SMP) [6a]:

- **Beam energy;**
- **Beta-star** (independently for each IR).

These parameters are received by the timing card in each collimator front-end (1 per point) and are processed to compute beam energy and beta-star. Signals are expected with a frequency of 10 Hz and a beam dump request is issued if more than 3 data points are missing or incorrectly received.

5.3 LHC CONTROLS SYSTEM: COLLIMATOR CONFIGURATION DATABASE

Critical inputs for the collimation calibrations must be stored in collimator configuration database tables. In particular, the following information must be provided:

- Metrology calibration of the collimator end-stop positions and of the minimum achievable gap values;
- Collimation orientation: collimator plan angle and assignment of collimator corner labels ("A, B, C, D" notation to beam notation "left"/"right", "upstream"/"downstream") [6b, 6c].

This information is made available under the responsibility of the BE/ABP collimation project team after verification of the collimator layout in the tunnel.

5.4 BEAM LOSS MONITORING SYSTEM

There are several links implemented for operational set-up of LHC collimators. However, in the collimator control system **no interlock will be generated due to BLM measurements**. This is fully handled through the BLM system and is therefore not part of the machine protection checks for LHC collimation.

The collimation team has provided appropriate maximum allowed proton loss rates for each collimator type [7, 7a], as used in the design and confirmed in tests of the collimation system. This information has been used to calculate the corresponding thresholds for the BLM system [8].

5.5 OTHER BEAM DIAGNOSTICS

The LHC collimator control system might access data from the BPM system, the beam current signals, emittance measurements, etc. (partly through the database). **None of these will be used to generate hardware interlocks** and they are therefore not part of the machine protection checks for the collimation system (we note that this input can be used later for software interlocks).

The same applies to the collimators with embedded BPMs installed during the LS1. These BPMs will not generate hardware interlock in the first implementation deployed for the start-up in 2015 [8a].

5.6 ALARMS, LOGGING AND POST-MORTEM SYSTEMS

Alarms will be sent if warnings or errors occur in the collimator hardware, if warning or interlock thresholds are reached, or if errors occur in the controls architecture. Presently it is **not foreseen to generate additional interlocks associated with these alarms**. However, all interlocks generated from the collimator system are associated to alarms that will be reported to the operation crew within the standard LASER system.

There is no need for safety-critical fast post-mortem data to be recorded for the whole collimation system in case of beam abort. Therefore, the collimation system does not respond to global post-mortem events. Post-mortem data at 100 Hz will be recorded over 10 s for any collimator generating an interlock. This is part of the post-mortem system.

Logging of collimator data will be performed for analysis of halo and beam losses and for set-up and analysis of collimator settings. Typical logging frequency is 1 Hz. Since collimator data are not part of the post-mortem system, the **availability of logging data is considered critical for the system diagnostic**. Therefore, the status of collimator logging should be monitored during LHC operation.

5.7 INTERFACE TO THE LHC SOFTWARE APPLICATION (LSA)

The operational settings for all collimators will be managed in a standard way within the LSA environment. It is worth noticing that the high level software will manage collimator settings that are expressed in unit of beam size and convert them to real jaw coordinates in millimetres [9].

The middle-level (FESA) and the low-level (PXI) exclusively use interlock values that are expressed as absolute collimator coordinates (the unit applied is mm). This is the case for all tolerance values handled by the system: discrete settings, time-dependent functions for positions and gaps, energy-dependent functions for gaps, upper and lower warning and interlock values, beta-dependent.

The conversion between high-level collimator parameters such as beam centre and beam size is done within the LSA collimator application or with separated tools [9a], relying on beam-based calibration results. These parameters are critical for the generation of limit functions and therefore will require safe handling (RBAC, MCS sanity checks).

The orchestration of the collimator settings defined for each machine context will be under the responsibility of the LHC sequencer.

6. HANDLING OF CRITICAL PARAMETERS

The collimation system and its parameters play a crucial role for the safe operation of the LHC. They must not only maintain safe collimator positions to provide cleaning and passive protection but they must also ensure that collimators that are not robust cannot be exposed to losses beyond safe limits.

6.1 HUMAN INPUTS, POSSIBLY INFREQUENTLY UPDATED

Some basic protection parameters will be defined via human input, after detailed analysis and agreement among all parties involved:

1. Interlock and warning thresholds for jaw temperature.
2. Interlock and warning thresholds for the jaw positions and gap values (discrete or time functions depending on the machine operational mode).
3. Interlock thresholds for collimator gaps as a function of beam energy.
4. Interlock thresholds for collimator gaps as a function of beta-star.

The last three parameter sets are fully handled through MCS. The temperature thresholds are instead defined as configuration parameters for the PVSS system that controls the temperature acquisition chain (like for all other LHC temperature measurements handled by the PVSS system). Changes of temperature thresholds are protected by RBAC and restricted to authorized users.

6.2 COLLIMATOR SENSOR CALIBRATION

Automatic or semi-automatic procedures are used to calibrate the position and gap sensors (LVDT's) on all collimators. This is an expert manipulation that requires bypassing the collimator switches to approach in a controlled way the mechanical end-stops of each degree of freedom. Thus, this can only be done with validated software, under the responsibility of EN/STI.

The LVDT sensor calibration is performed as a part of the collimation hardware commissioning [9b] and requires the availability of relevant parameters in the LSA configuration database: collimator orientation and mechanical end-stop positions.

The LVDT calibration data are stored as persistent variables in collimator front end. The validated values are also stored in EDMS under the responsibility of EN/STI and can be recovered in case of data corruption. Consistency checks are put in place to verify at 10 Hz the consistency between FESA table and low-level values.

The calibration of collimator LVDTs is required:

- For the full system after every long shutdown
- For isolated cases after short shutdowns, if the collimator expected consider it necessary;
- Every time a collimator component relevant for the positioning system is changed.
- As part of the collimator hardware commissioning, with the final tunnel configuration (e.g., if a collimator is replaced during the run, one cannot use calibrations performed on surface).

During the LHC operation, **changes of collimator LVDT calibration must be decided by the collimation project team responsible for operation**. In case of changes and depending on the validation measurements performed, calibration changes might require a re-alignment of the collimator with beam-based procedures and/or repetition of loss map campaigns.

The sensor calibration can only be performed in a safe "local" mode without beam in the machine. An interlock in generated when this mode is set for a collimator.

6.3 COLLIMATOR BEAM-BASED PARAMETERS AND FUNCTIONS

Manual and/or automatic procedures will be used to calibrate beam size and beam centre at each collimator:

1. Beam-based collimator calibration will be performed with beam during beam commissioning of the LHC. The data will be stored in the settings database as critical parameters but is neither available nor needed at the low level. In order to change this data one needs a collimator expert role and MCS authorization (MCS collimator role). MCS and RBAC control this data against any changes, for example due to data corruption or unauthorized modification.
2. The collimator beam-based parameters are then used to calculate settings, warning and interlock functions for all parts of the operational cycle. These functions are then sent through FESA to the low-level control.
    a. The data is stored in the settings database as critical parameters. Note that only dump thresholds are critical parameters. Motor positions can be changed by OP even in this is not expected to happen for the standard mode of operation of the system.

   b. The LHC operator can load pre-defined settings for a new cycle into the low level system. The function execution is triggered, as for the other systems, during ramp, squeeze and collision setup phases.
   c. In order to change the calculated functions one needs a collimator expert role and MCS authorization (MCS collimator role). MCS and RBAC control this data against any changes, for example due to data corruption or unauthorized modification.
3. The energy-dependent and beta-star-dependent gap limits are also calculated with collimator beam-based information but are generated independently of beam-based settings. This avoids accidental corruption of the energy-dependent gaps due to human error during collimator setup.
   a. The data is stored in the settings database as critical parameters. **The data are cycle independent and resides always in the low level**.
   b. The LHC operator can load pre-defined settings into the low level system, for example after reboot of parts of the collimator control (even if the data should be reloaded automatically at the low level) and check them at anytime during the cycle.
   c. In order to change the calculated functions one needs a collimator expert role and MCS authorization (MCS collimator role). MCS and RBAC control this data against any changes, for example due to data corruption or unauthorized modification. An extra role for changing this data can be envisaged.

The new BPM functionality available for 18 collimators will speed-up the beam-based alignment procedures. This will enable continuous orbit measurements at the BPM-equipped collimators. However, it is foreseen that the settings generation and handling will not change compared to the other collimators without BPM. Automatic change of collimator positions will in theory be possible but an adequate strategy for this advanced functionality will be established after gaining sufficient operational experience with the new collimators.

7. INDIVIDUAL COLLIMATOR TESTS

This part describes the tests that are validated during the equipment's hardware commissioning period and have to be validated also for the machine protection system commissioning. The complete list of hardware commissioning tests is described in [9] and the reports of results have been implemented into MTF.

Every single collimator will be tested during hardware commissioning.

7.1 CONDITIONS REQUIRED TO PERFORM TESTS

- Installation of collimator.
- Installation of cables.
- Installation of controls racks in tunnel and on surface.
- Collimator orientation and mechanical reference data inserted in the LSA database.
- Remote positioning controls tested at all levels.
- Connection to the BIC checked for each device.
- Timing signals available.
- Distribution of energy and beta squeeze factor signals distributed.

- Electrical power, communication systems up, collimator controls applications up, expert applications, access to collimator.
- Logging should be available for the beginning of the remote tests.

7.2 CONDITIONS DURING THE TESTS

Initial MP tests require people in the tunnel at the collimator and at the controls rack positions, e.g. to verify the connections to the BIC. Most of the other tests can be done remotely, but require the possibility to move the collimator and/or a monitoring of the BIC status. Logging should be available when remote commissioning tests are executed.

7.3 DESCRIPTION OF THE TESTS

It is noted that some sanity checks will be included in operational control procedures at the end of each fill, for example the verification of the energy interlocks when collimators are moved to parking positions. These are not considered to be part of the commissioning of MP functionality even thought they provide a crucial verification of the system. Here, we summarize the commissioning steps required for the MPS functionality of the collimation system:

	Rep.	Action	Group(s) Responsible
1	N	**Calibration of position and gap sensors (LVDT)**	EN/STI
2	N	**Verification of BIC connections of position interlocks**	EN/STI
3	N	**Verification of BIC connections of temperature interlocks**	EN/STI
4	N	**Verification of collimator orientation**	BE/ABP

Clearly, tests must be repeated in case of new collimators are installed to replace the existing one, or in case of changes that are considered critical (e.g., replacement of LVDTs).

The BIC connections are listed in Table A1.1 and Table A1.2. It is clear that various types of collimators, absorbers, movable detectors etc. have different connections to the BIC's, which will be taken into account for the tests. Details are visible in the BIC table. The results will be recorded per device with details on the tests performed.

7.4 STATUS OF THE SYSTEM AFTER TESTS

The full functionality of the tested collimator will be established at the end of hardware commissioning. After the system tests, the collimators are released for remote operation from the CCC.

8. SYSTEM TESTS DURING THE MACHINE CHECKOUT

After the Individual System Tests have been successfully completed, the integral system must be tested from the CERN Control Centre (CCC) to establish machine protection functionality.

8.1 CONDITIONS REQUIRED TO PERFORM TESTS

- Successful completion of the individual tests for collimators during HWC.
- Successful completion of the tests mentioned in the previous sections.
- MCS system and RBAC available and fully tested.
- LHC controls system operational (trim, functions, …).
- Logging system available.
- Alarm system available.
- Timing event distribution available.
- Sequencer available.

8.2 DESCRIPTION OF THE TESTS

Tests to be performed for each individual collimator are listed in the next table. These tests fully validate the MP functionality of each device.

	Rep.	Action	Group(s) Responsible
1	S1	**Verification of position interlocks (discrete) by violating limits**	BE/ABP, BE/OP
2	S1	**Verification of position interlocks (functions) by violating limits**	BE/ABP, BE/OP
3	S1	**Verification of energy interlock by violating limits**	BE/ABP, BE/OP
4	S1	**Verification of temperature interlocks by violating limits**	BE/ABP, BE/OP, EN/STI
5	S1	**Verification of interlocks from status faults**	BE/ABP, BE/OP, EN/STI
6	S1	**Ensure safe system performance during and after power cut**	BE/ABP, BE/OP, EN/STI
7	S1	**Test safe update of collimator sensor calibration table, using RBAC**	BE/ABP, BE/OP, EN/STI
8	S1	**Test safe update of time-dependent warning and interlock values, using MCS and RBAC functionality**	BE/ABP, BE/OP
9	S1	**Test safe update of energy-dependent interlock values, using MCS and RBAC functionality**	BE/ABP, BE/OP

These tests have to be performed to every collimator installed in the machine after a Xmas-like shutdown (S1). However during shorter shutdowns, like a technical stops it it is recommended to repeat the tests in a representative subset of collimators, for example one collimator per BIC.

These tests have been performed in the previous Run I operation [11, 12, 12a] and detailed operational procedures are available and attached in the appendices Appendix 3 and Appendix 4.

Tests 7-9 are bound to the availability of RBAC and MCS. They essentially consist in using the implemented collimator control architecture (no special procedures are required) and to verify that non-authorised user cannot change critical system parameters.

The test 6 consists in provoking a power cut and analysing the system behaviour during and after the power outage, ensuring that an interlock is generated before collimator jaws reach unsafe positions. Since several power cuts are expected during a run, a dedicated procedure for the recovery has been established [12b].

These tests will be performed for each collimator, absorber, movable detector etc. It is clear that the various types have different types of limits, which will be taken into account for the tests. The results will be recorded per device with details on the tests performed.

8.3 STATUS OF THE SYSTEM AFTER THE SYSTEM TESTS

After these tests the **collimation machine protection functionality (defined with collimator gaps, collimator position sensors and MCS data) will be fully established.** This means that after this phase one can be sure that the interlock will be correctly triggered for all the scenarios designed.

9. TESTS WITH BEAM

The machine protection functionality of the collimation system is affected by changes in orbit, beam energy, optics, aperture and other factors. The functionality of the system can only be established after a beam-based setup of the system followed by appropriate validation. Details of the collimation setup and the settings choice are not part of this document, which is instead addressing the set of tests that must be done after collimation alignment to qualify the cleaning efficiency of the collimator system. This verification is mandatory before injecting high intensity in the machine.

In addition it is clear that it must also be revalidated if any of the relevant machine parameters changes with time (drifts). It is re-iterated that collimator setup and tests for cleaning efficiency are not described in the machine protection context.

9.1 TESTS DEPENDING ON MACHINE CHANGES

The MP functionality of the collimation system has to be verified with setup beam at low and high energy for any new machine configuration before injecting higher intensity beams. The following tests must be performed:

1. Check of sensors readings and controls for beam-induced pickup noise.
2. Each collimator that moves during the corresponding machine mode has to be aligned to the correct beam orbit. The beam-based collimator parameters must be updated after each beam-based alignment, these are:
    a. Update of beam-based collimator parameters after beam-based calibration of collimators and taking into account the available machine aperture at 450GeV.
    b. Update of beam-based collimator parameters for collimator settings after the energy ramp (flat-top settings).
    c. Update of beam-based collimator parameters for collimator settings during and after the squeeze, with separated beams.
    d. Update of beam-based collimator parameters for collimator settings in collision.
    e. Possibly update of overall collimator settings is required for system consistency.
3. After any update of collimator parameters, the collimation cleaning hierarchy must be validated. The responsible for these tests is BE/ABP. The validation must be done at setup beam intensity and with the final machine configuration,

i.e. loading positions and thresholds and driving collimators with standard sequences. Ideally, validation should be done in cycles when the final operational sequences are used (settings of key are automatically orchestrated without human intervention). Then we generate controlled losses artificially to validate the settings. The following lossmaps must be acquired:

a. Betatronic losses for Beam 1 and Beam 2 separated.
b. Negative off-momentum losses for Beam 1 and Beam 2 together.
c. Positive off-momentum losses for Beam 1 and Beam 2 together.
d. Trigger an asynchronous beam dump.

Table 1shows the table of lossmaps and asynchronous dumps required to validate the system and to continue with the intensity ramp up.

4. The timestamps and the result of the lossmap analysis should be stored in a place to be defined.

9.2 ADDITIONAL TESTS WITH LOW INTENSITY BEAM

Provided that the orbit is stable and that there are no changes in the machine configuration (optics, beam energy, aperture, collimator settings, etc) and the collimation system have been qualified for those settings, no additional tests have to be done during the intensity ramp up provided that a regular monitoring of orbit and optics ensures that the machine configuration is stable (adequete tolerance must be defined).
However, a minimum validation of the cleaning must be guaranteed through unfrequently loss maps. In 2012, after 2 years of operational experience, the time for loss map repetition was set to 3 months. This will have to be re-assessed in 2015 depending on the machine performance at energies close to 7 TeV. At startup, we recommend frequent monitoring of losses and a repetition of a sub-set of loss maps.
Table 2 shows the tests needed for this regular validation.

Table 1: Minimum qualification loss maps required to validate the MP functionality of the system after collimation alignments.

	Betatron loss map				Off-momentum loss map (B1 + B2)		Asynchronous beam dump (B1+B2)
	B1H	B1V	B2H	B2V	Negative	Positive	
Injection	X	X	X	X	X	X	X
During Ramp	-	-	-	-	-	-	-
Flat top	X	X	X	X	X	X	X
During Squeeze	-	-	-	-	-	-	-
Squeezed	X	X	X	X	X	X	X
Stable Beams	X	X	X	X	X	X	X

Table 2: Minimum regular qualification to validate the MP functionality of the system.

	Betatron loss map				Off-momentum loss map (B1 + B2)		Asynchronous beam dump (B1+B2)
	B1H	B1V	B2H	B2V	Negative	Positive	
Injection	X	X	X	X	X	X	X
Flat top	-	-	-	-	-	-	X
Squeezed	X	X	X	X	-	-	X
Stable Beams	X	X	X	X	X	X	X

9.3 ADDITIONAL TESTS DURING INTENSITY RAMP UP

The following steps must be performed:

1. Check of sensors readings and controls for beam-induced pickup noise.
2. Study an update of interlock thresholds for jaw temperature.
3. Check of interlock thresholds for jaw temperature
4. Check overall collimator settings.

10. APPENDIX 1: COLLIMATOR BIC CONNECTIONS

The BIC connections for all the collimator in the LHC ring and transfer lines are listed in Tab. A1.1 (see also [x8]) and connection for passive absorbers in Tab. A1.2. For each beam, the inputs number 8 and 9 are reserved for the collimator interlocks of position and temperature survey, respectively. In point 6, and additional input is dedicated to the connections of the TCDQ devices (not listed in the table).

Table A1.1: BIC connections for all the collimators in the LHC ring and transfer lines.

Ring location	Collimator	B1	B2	INJ
IP1 L	TCL.6L1.B2		X	
	TCL.5L1.B2		X	
	TCL.4L1.B2		X	
	TCTPH.4L1.B1	X		
	TCTPV.4L1.B1	X		
IP1 R	TCTPV.4R1.B2		X	
	TCTPH.4R1.B2		X	
	TCL.4R1.B1	X		
	TCL.5R1.B1	X		
	TCL.6R1.B1	X		
IP2 L	TCTPH.4L2.B1	X		
	TCTPV.4L2.B1	X		
	TDI.4L2	X	X	X
	TCDD.4L2	X	X	X
IP2 R	TCLIA.4R2	X	X	X
	TCTPV.4R2.B2		X	
	TCTPH.4R2.B2		X	
	TCLIB.6R2.B1	X		X
IP3 LR	TCLA.7L3.B2		X	
	TCP.6L3.B1	X		

	TCSG.5L3.B1	X		
	TCLA.6L3.B2		X	
	TCSG.B5L3.B2		X	
	TCLA.B5L3.B2		X	
	TCSG.A5L3.B2		X	
	TCLA.A5L3.B2		X	
	TCSG.4L3.B2		X	
	TCSG.4R3.B1	X		
	TCLA.A5R3.B1	X		
	TCSG.A5R3.B1	X		
	TCLA.B5R3.B1	X		
	TCSG.B5R3.B1	X		
	TCLA.6R3.B1	X		
	TCSG.5R3.B2		X	
	TCP.6R3.B2		X	
	TCLA.7R3.B1	X		
IP5 L	TCL.6L5.B2		X	
	TCL.5L5.B2		X	
	TCL.4L5.B2		X	
	TCTPH.4L5.B1	X		
	TCTPV.4L5.B1	X		
IP5 R	TCTPV.4R5.B2		X	
	TCTPH.4R5.B2		X	
	TCL.4R5.B1	X		
	TCL.5R5.B1	X		
	TCL.6R5.B1	X		
IP6 LR	TCSP.A4L6.B2		X	
	TCSP.A4R6.B1	X		
IP8 L	TCLIB.6L8.B2		X	X
	TCTPH.4L8.B1	X		
	TCTPV.4L8.B1	X		
	TCLIA.4L8	X	X	X
IP8 R	TCTPV.4R8.B2		X	
	TCTPH.4R8.B2		X	
	TDI.4R8	X	X	X
IP8 R + TI8	TCDIH.87441			X
	TCDIV.87645			X
	TCDIV.87804			X
	TCDIH.87904			X
	TCDIV.88123			X
	TCDIH.88121			X
TI2 Up	TCDIH.20607			X
IP2 L + TI2	TCDIV.29012			X
	TCDIH.29050			X
	TCDIH.29205			X
	TCDIV.29234			X
	TCDIH.29465			X
	TCDIV.29509			X
IP7 LR	TCLA.A7L7.B2		X	
	TCLA.D6L7.B2		X	
	TCLA.C6L7.B2		X	
	TCP.D6L7.B1	X		

	TCP.C6L7.B1	X		
	TCP.B6L7.B1	X		
	TCLA.B6L7.B2		X	
	TCSG.A6L7.B1	X		
	TCLA.A6L7.B2		X	
	TCSG.6L7.B2		X	
	TCSG.E5L7.B2		X	
	TCSG.D5L7.B2		X	
	TCSG.B5L7.B1	X		
	TCSG.A5L7.B1	X		
	TCSG.B5L7.B2		X	
	TCSG.D4L7.B1	X		
	TCSG.A4L7.B2		X	
	TCSG.B4L7.B1	X		
	TCSG.A4L7.B1	X		
	TCSG.A4R7.B1	X		
	TCSG.A4R7.B2		X	
	TCSG.B4R7.B2		X	
	TCSG.D4R7.B2		X	
	TCSG.B5R7.B1	X		
	TCSG.A5R7.B2		X	
	TCSG.B5R7.B2		X	
	TCSG.D5R7.B1	X		
	TCSG.E5R7.B1	X		
	TCSG.6R7.B1	X		
	TCLA.A6R7.B1	X		
	TCSG.A6R7.B2		X	
	TCLA.B6R7.B1	X		
	TCP.B6R7.B2		X	
	TCP.C6R7.B2		X	
	TCP.D6R7.B2		X	
	TCLA.C6R7.B1	X		
	TCLA.D6R7.B1	X		
	TCLA.A7R7.B1	X		

Table A1.2: BIC connections for passive absorbers.

	Collimator Name	Temperature
Passive Absorber IR3 and IR7 (not movable)	TCAPA.6L3.B1	X
	TCAPA.6L7.B1	X
	TCAPA.6R3.B2	X
	TCAPA.6R7.B2	X
	TCAPB.6L7.B1	X
	TCAPB.6R7.B2	X
	TCAPC.6L7.B1	X
	TCAPC.6R7.B2	X
	TCAPD.5L3.B1	X
	TCAPD.5R3.B1	X

11. APPENDIX 2: TEST PROCEDURE FOR INDIVIDUAL CHECKS OF POSITION AND GAP INTERLOCKS

The collimator position interlocking is based on the comparison between the measured jaw positions and collimator gap values against user-defined limit thresholds that can be expressed as a constant (discrete) value, as time-dependent functions and energy-dependent functions. If the measured values exceed the interlock thresholds, the collimator survey unit (PRS=Position Readout Surveillance) removes the beam permit. Detailed operational procedures are documented in [x9].

Each LHC collimator has 6 **LVDT** (Linear Variable Differential Transformer) sensors for direct jaw position and gap measurements. Each of them can trigger a beam interlock if the measured readout exceed **INNER** or **OUTER limit values**. In total, there are therefore 12 interlocks per collimator that have to be tested in order to validate the machine protection functionality of the PRS unit.

In addition, there are **energy-dependent and beta-star-dependent limit functions** (one OUTER limit for each of the gap LDVT for the energy limits and one OUTER and one INNER limit for each of the gap LDVT for the beta-star limits, i.e. six additional interlocks per collimator (2 for the energy-dependent and 4 for the beta-star-dependent). An example of the offline analysis test is given in figure bellow.

An example for one LVDT is given in Fig. A2.1. It is noted that at the same time the warning thresholds are also verified.

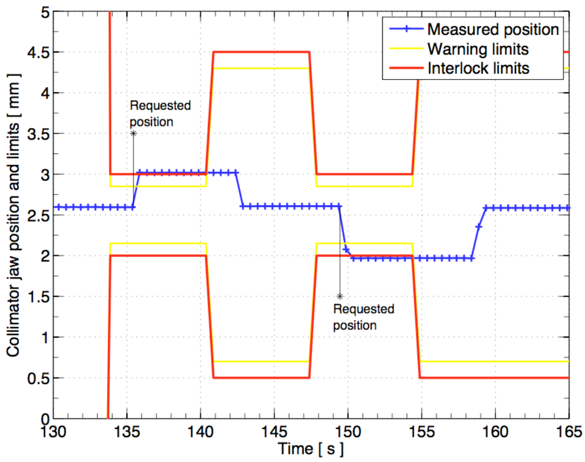

Fig. A2.1: Example of machine protection sequence for one collimator axis. The limits are set around the local position (blue line) and then are violated by requesting a position outside the inner and outer warning (yellow) and interlock (red) limits. Correspondingly, the BIC status must change to false when unsafe collimator positions are reached.

Internally, the low-level controls perform verification of the limits at a frequency of 100 Hz and treat in the same way discrete thresholds and time-dependent thresholds. The machine protection functionality is verified for each collimator by changing discrete values. It is also noted that the validation of the energy-dependent limit functions can be done at constant energy, even if global system test with real or simulated energy ramps are also foreseen.

Hardware commissioning sequences are available to hit all the possible limits (14 in total). The execution of this automatic sequence is triggered from a dedicated command in the top-level collimator application. For each BIC, the commissioning sequences can obviously be run for one collimator at a time to verify the individual behaviour of all the devices.

The validation of the machine protection functionality is achieved if the three following steps are successfully passed:

- Successfully perform the commissioning sequence to hit all 18 limits (with monitoring and verification of the internal collimator status);
- Verify that correspondingly the collimator input in the BIC react as expected;
- Extract from the logging database the relevant data that document the results.

As a prerequisite, the **COLL#MOT** channel (input 8) of the BIC must be **ENABLED** and **UN-MASKED** and should be in a **BEAM_PERMIT=TRUE** state in order to carry out the test.

The results of the 2008, 2011 and 2012 system commissioning are available in [x9] together with detailed operational procedures. An example of the analysis is shown in Figure 2.

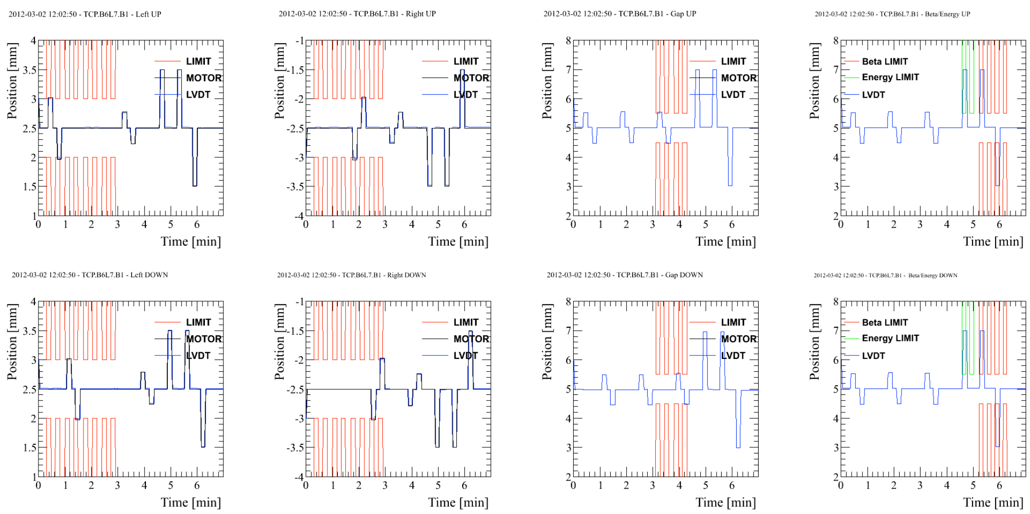

Figure 2: Individual MPP test to check position, energy-dependent and beta-star dependent interlocks.

12. APPENDIX 3: TEST PROCEDURE FOR INDIVIDUAL CHECKS OF TEMPERATURE INTERLOCKS

Each movable LHC collimator as well as each passive absorber has four or five temperature sensors: two per jaw and one for the cooling water (the latter is not mounted on the collimators that are not water cooled). The thresholds for each temperature sensor can be defined individually and each will trigger a beam bump if the measured temperature exceeds pre-defined thresholds. The logical sum of all sensors is used as BIC input according to the connections of Tab. A1.1. Similarly to the case of the position survey, the response of each sensor is verified by violating the interlock thresholds.

This is achieved by forcing the temperature reading to a value larger than the safe limit, as illustrated in Fig. A3.1. This is done automatically. Correspondingly, the status of the corresponding BIC channel is monitored to verify that the beam permit is correctly removed. It is noted that forcing the reading of the sensors is preferred to changing the limits because in this way we can verify at the same time the implementation of alarms that are defined independently of the interlock limits.

As for the position sensors, the full 2008,2011 and 2012 system was commissioned [x9].

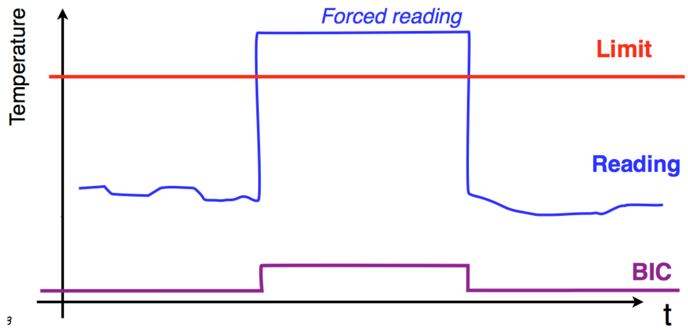

Fig. A3.1: Illustrative scheme of a commissioning test for the collimator temperature interlocks.

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