SAFE LHC BEAM COMMISSIONING

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Abstract

Due to the large amount of energy stored in magnets and beams, safe operation of the LHC is essential. The commissioning of the LHC machine protection system will be an integral part of the general LHC commissioning program. A brief overview of the LHC Machine Protection System will be given, identifying the main components: the Beam Interlock System, the Beam Dumping System, the Collimation System, the Beam Loss Monitoring System and the Quench Protection System. An outline is given of the commissioning strategy of these systems during the different commissioning phases of the LHC: without beam, injection and the different phases with stored beam depending on beam intensity and energy.

INTRODUCTION

The energy stored in one nominal LHC beam is 360 MJ, about a factor of 200 larger than the HERA or the Tevatron beams. The energy stored in the superconducting magnets is even 10 GJ. These large amounts of stored energy, with their large damage potential [1], result in requirements of the performance of the Machine Protection System (MPS) which have never been that stringent for any other accelerator. These requirements apply to the design, production, commissioning and operation of the MPS. This paper explores the requirements of the commissioning of the MPS, which will play a very important role throughout the LHC commissioning period. The MPS will need to prevent damage to the machine but also avoid quenches of the superconducting magnets and by this reduce the machine down time.

Beam Intensities and Damage Levels

One nominal LHC beam consists of 2808 bunches with a single bunch intensity of $1.15\cdot10^{11}$ protons, resulting in a total intensity of $3.2\cdot10^{14}$ protons. The nominal injected intensity is $3.3\cdot10^{13}$ protons. The expected safe limit in case of fast beam losses and nominal emittances is around $2\cdot10^{12}$ protons at the injection energy of 450 GeV and $1\cdot10^{10}$ protons at the full beam energy of 7 TeV. The expected damage level at the injection energy has been verified experimentally [2]. The quench level at injection energy is expected to be around $3\cdot10^{9}$ protons, which is about the intensity of a pilot bunch.

THE LHC COMMISSIONING PLAN

The commissioning of the LHC has started with the hardware commissioning which is presently ongoing. This will be followed by a machine checkout period and the Stage I of the LHC beam commissioning [3]. Stage I includes physics with 43 x 43 and 156 x 156 bunches with reduced bunch intensities, see Table 1. In the beam commissioning Stage II operation with 936 bunches is foreseen (75 ns bunch spacing), Stage III will see operation with the nominal 2808 bunches but with reduced bunch intensities. After the second installation phase of the beam dumping system diluter magnets, Stage IV prepares operation with nominal beam intensities.

Table 1 shows that during Stage I only about 1/100 of the nominal luminosity will be delivered. The potential to damage the machine is present from operation with 43 bunches at injection energy and already with one bunch at full energy.

Table 1: Detailed steps of Stage I of the LHC beam commissioning, from [3].

Parameters			Beam Levels		Lumi
n bunch	n p^+	β* at IP [m]	I_{beam}	E_{beam} [MJ]	$[cm^{-2}s^{-1}]$
1	$1\cdot10^{10}$	18	$1.0\cdot10^{10}$	0.01	$1.0\cdot10^{27}$
43	$1\cdot10^{10}$	18	$4.3\cdot10^{11}$	0.5	$4.2\cdot10^{28}$
43	$4\cdot10^{10}$	18	$1.7\cdot10^{12}$	2	$6.8\cdot10^{29}$
43	$4\cdot10^{10}$	2	$1.7\cdot10^{12}$	2	$6.1\cdot10^{30}$
156	$4\cdot10^{10}$	2	$6.2\cdot10^{12}$	7	$2.2\cdot10^{31}$
156	$9\cdot10^{10}$	2	$1.4\cdot10^{13}$	16	$1.1\cdot10^{32}$

THE LHC MACHINE PROTECTION SYSTEM

The core of the LHC Machine Protection System consists of the Beam Interlock System (BIS), a distributed system which collects the interlocks from the different systems [4], and the LHC Beam Dumping System. Both systems are required to be operational for every requested beam dump. There is a special injection interlock controller to allow injection.

The LHC Beam Dumping System (LBDS) is the only system which allows safe disposal of the beam. It requires orbit excursions in the beam dump insertion to be below 3 mm. Special collimators downstream of the kicker magnets (TCDQ and TCS) protect the LHC elements in case of timing failures of the dump kicker, and beam in the abort gap. If these parameters change, the beams are extracted before the conditions are violated.

The procedure to always first dump a low intensity beam, and check the correctness of this beam dump, before being able to inject any high intensity beam will need to be enforced. The commissioning procedures of the Beam Dumping System are described in detail in [5].

An overview of the complete MPS and the inter relationships of the many subsystems is schematically shown in Fig. 1. The main components and input to the BIS are:

- The Quench Protection System (QPS) is a distributed system with several thousand monitors which ensures the safe discharge of the energy stored in the superconducting magnets in the case of a magnet quench or other powering failures. Before activating the discharge, the beam needs to be dumped. The QPS generates a beam dump request and sends it via the interlock controllers to the beam dumping system.
- The Beam Loss Monitoring (BLM) system. This is also a distributed system with about 4000 individual beam loss monitors. The system triggers a beam dump if the threshold for beam loss is exceeded. The thresholds depend on the beam energy and the loss duration. The commissioning procedure of the BLM system is detailed in [6].
- The collimation system is required to protect the machine aperture from quenching during normal operation and from damage in case of anomalies. The BLMs in the collimation region are used to trigger a beam dump when beam losses at the collimators occur, but also collimator positions which are out of tolerance will generate a beam dump request. To set up the collimation system, the aperture of the machine needs to be known [7, 8].

Other inputs to beam interlock system come from the personnel access system, the vacuum system (valves), normal conducting magnet interlocks (power converters and temperatures), dI/dt of the some critical magnets, dI/dt of the beam current, the LHC experiments and the RF system. All the interlock signals for the BIS are done in hardware.

Other signals that enter into the beam interlock system can also be seen Fig. 1. The Safe Beam Parameters, which allows the masking of certain interlocks depending on the beam intensity and the beam energy, is expected to be very useful during the early commissioning stages of the machine. The Beam Presence Flag allows the injection of high intensity beam only when there is already beam circulating. This guarantees that the machine settings are about correct.

Several software based systems are required for the optimum operation of the machine protection. There is a system to analyse transients. As an example: after every beam dump the recordings from all systems involved are checked and their redundancy is verified. There will be a system to manage critical settings, such as interlock thresholds. A software sequencer will enforce the correct procedures during operation.

Reliability of the Machine Protection System

A study of the expected failure rate of a simplified MPS has been made, see Fig. 2. The system contains the large distributed systems and the Beam Dumping System (BIS, LBDS, QPS, PIC, BLM). For the calculation of failure rates a certain operational scenario is assumed [9]. The unsafety of the simplified MPS has been calculated to be 2×10^{-4} per year and the expected number of 'false dumps' (beam dumps due to a failure of the MPS) has been calculated to be 41 per year; this is 10 % of the number of machine fills used in the model. The safety of the system is based on redundant systems and well defined check procedures (post mortem) to guarantee this redundancy.

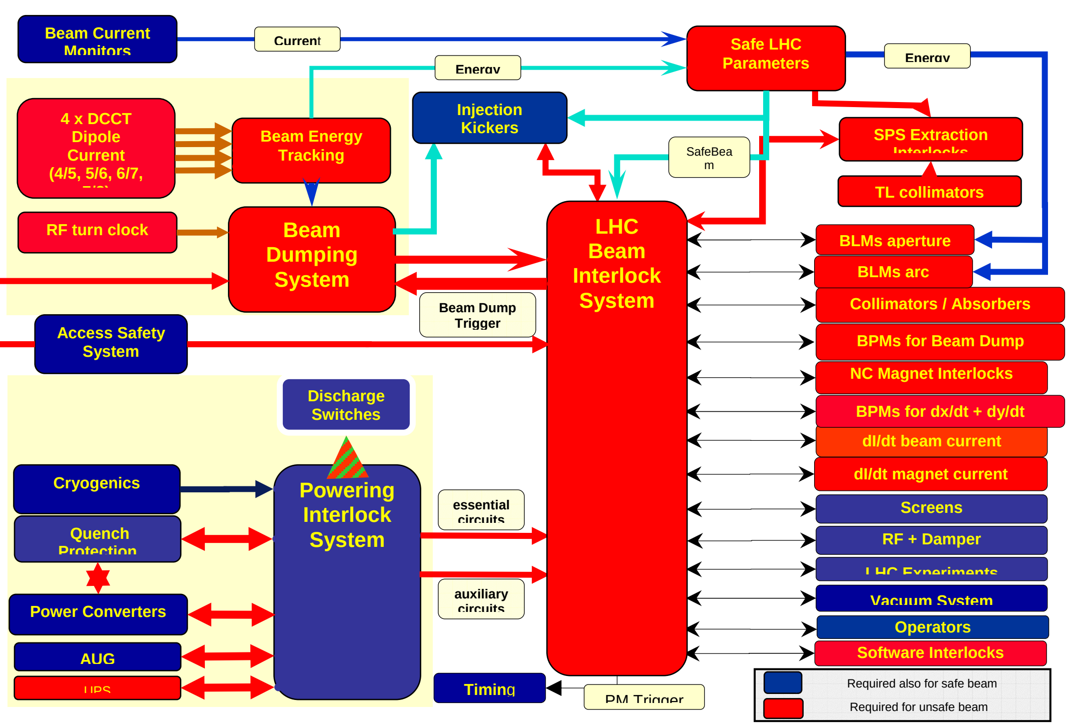

Figure 1: The LHC Machine Protection System and the connected equipment.

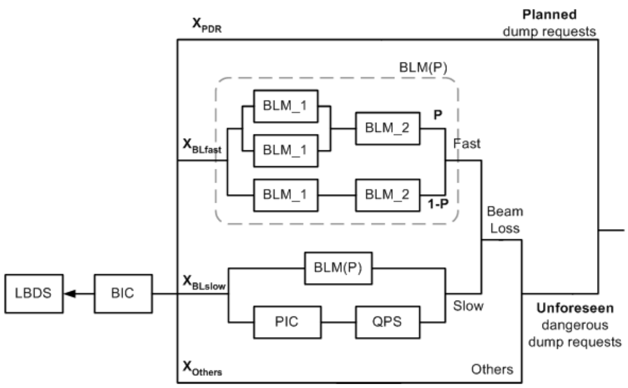

Figure 2: Simplified model of the MPS used to calculate the system's safety.

COMMISSIONING OF THE MACHINE PROTECTION SYSTEM

Without Beam

The commissioning of the MPS will start before the first beam is injected in the LHC. Quench protection and powering interlock system will become operational during the commissioning of the electrical circuits. The Beam Interlock System can be tested by checking the communication with all clients, without the need of beam. The provoked interlocks should be properly analysed (source, time) and the logging of the events needs to be checked. Some tests of other subsystems can also be performed without beam: for the BLMs (check channels), the LBDS (check magnet current signals), the collimation system etc.

With Beam: general

Some systems are rather independent of the beam conditions and only need to be commissioned once, although verification needs to take place at certain occasions (for example, during technical stops).

Other systems, which interact more closely with the beam, will need to be verified at different stages of the LHC beam commissioning: for different beam intensities, for different beam energies and for different states of the machine (optics, squeeze, polarities of experimental magnets, ion operation).

With Beam: Extraction from the Injector

Before injecting beam in the LHC, the MPS for beam transfer between the injector (SPS) and LHC will need to be commissioned. This is taking place at the moment of the workshop, using well described and agreed upon procedures [10]. Part of the system is required this year to allow CNGS operation with high intensity beams, using the same extraction channel as for one of the LHC beams.

Safe extraction from the SPS towards the LHC requires the Safe SPS Beam Intensity Flag, around 10^{12} protons. Above this intensity it is not possible to mask interlock channels. An interlock on the SPS energy is also required. Many other elements will be surveyed by hardware: the currents of many magnets in the transfer line are measured and compared with reference values, the voltage of the extraction kicker magnets are checked just before extraction, the beam position at the extraction point is verified, as is the position of the transfer line collimators.

Some critical power converters in the SPS and the LHC, such as extraction and injection septa will be surveyed by

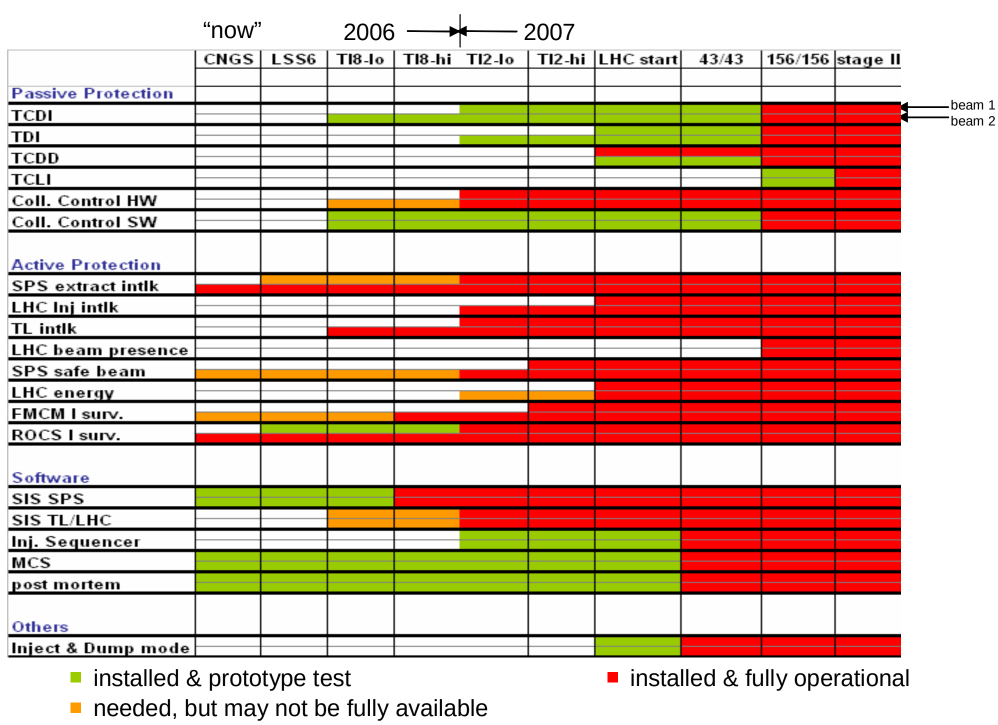

Figure 3: Commissioning of the injection system [12].

Fast Magnet Current Change Monitors, FMCM [11] (15 families in total),

Injection into the LHC

Special features of the MPS for injection into LHC need to be verified with beam. The interlocking depends on the state of the SPS injector, the transfer lines and the LHC. The injection requires the setting up of several collimators and beam absorbers in the injection region. High intensity beam can only be injected when there is circulating beam in the LHC (use of SPS safe beam intensity flag to limit the injected intensity). A shot-by-shot beam quality check will allow the next extraction / injection.

The state of the different systems involved with injection during Stage I of the LHC beam commissioning is schematically represented in Fig. 3.

Different MPS elements need to be tested with circulating beam at the injection energy: the Beam Dumping System, the ring BLM system, the collimation system, the interlocks from the RF system, etc. This is summarised in Fig. 4 for Stage I of the LHC beam commissioning.

At Full Energy

During the energy ramp, squeezing and for collision at full energy parts of the MPS will again need to be validated. The shorter bunch length at higher energy can cause different noise pick-up of the systems involved. The position of the collimators needs to adapt to the change of optics, aperture and beam size. It has not been finalised how the collimators will be driven during the ramp. At full energy, it will be more difficult to perform aperture checks, required for the collimation system, as it will be very easy to quench the magnets already with a pilot beam. The switching on of the experimental magnets will also require the verification of some of the systems involved.

An overview of the requirements of commissioning the different systems at full energy is given in Fig. 5

GENERAL STRATEGIES FOR COMMISSIONING

A proposed order for testing the different systems at a certain stage of the LHC beam commissioning is to:

1. Test the injection system;
2. Test the beam dumping system;
3. Test some other systems for their dependence on beam parameters (BPMS, RF, etc.);
4. Validate the BLM system;
5. Commission the collimation system.

Most of the systems need to be tested again when either the intensity or the energy or the machine state is changed.

The commissioning of the MPS is a complex process which involves many systems and takes place over a long period of time. This requires explicit tests procedures to be written for each phase and for each system. The procedures should be agreed upon by the different parties involved before being executed. If the test criteria are not met, the problems need to be addressed before entering the next stage of the machine commissioning. This strategy is being followed for the commissioning of the high intensity extraction at the SPS for the CNGS beams. Test results should be stored so they can be referred to when required and anomalies be recorded. The systems will need to be revalidated with partial tests after each annual shutdown, after a machine access, after a change of operating conditions are even for a new fill.

CONCLUSIONS AND DISCUSSION

The commissioning of the Machine Protection System will play a very important role throughout the LHC commissioning. As we expect to rapidly increase the

System	Commissioning before beam possible ?	First pilot beam	10^12	43 bunches 1.7 10^12	156 bunches 6 10^12<N<1.4 10^13	936 bunches >5 10^13
Powering interlock system	YES					
Beam interlock system	YES					
Safe distribution of energy	YES					
Safe beam flag	PARTIAL					
Beam presence flag	PARTIAL					
Safe distribution of mode	YES					
Safe distr. of squeezing factor	PARTIAL					
Beam interlocks SPS to LHC	YES					
Injection protection	NO					
Access system	YES					
Vacuum system	YES					
Magnet current change monitor	YES					
BLMs, collimators & apertures	PARTIAL					
BLM in the arcs	PARTIAL					
Collimators and beam absorbers	NO					
Beam position change monitors	NO					
Fast beam current decay monitors	NO					
Transverse feedback	NO					
RF	NO					
Experiments	PARTIAL					
Beam Dumping System	PARTIAL					
TCDQ / TCS	NO					
BPM for BDS	NO					

Figure 4: Commissioning stages of the MPS at injection energy [13].

beam intensity above damage level, it is not worth going to a minimal system during initial beam operation. Nearly all parts of the MPS will be required already at modest beam intensities.

The commissioning of the MPS will be a recurring task, to be repeated when the damage potential of the beam is increased but also when operating conditions change (squeeze, ions) or after a machine access. An outline of which systems are required to be operational and tested at the defined phases of the LHC beam commissioning has been summarised in this paper for the injection system, at injection energy and at full beam energy.

In principle, safe machine operation is guaranteed with a minimum system consisting of beam loss monitors and quench protection system for triggering the beam dumping system via the beam interlocks. However, additional monitors can request a beam dump (software interlocks, dI/dt of the beam, fast magnet current change monitors, etc.). This allows dumping the beams before beam losses occur and provides additional safety and redundancy. The relative importance of the different systems is difficult to quantify.

The use of vital parts of the LHC MPS has already started in the SPS, injector to the LHC. The commissioning is presently taking place following well defined procedures.

The analysis of any beam dump (‘post mortem’) is required to guarantee the safety of the machine, as this is the only to verify the assumed redundancy of the systems. Without this redundancy the MPS does not have the required safety level.

ACKNOWLEDGEMENTS

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REFERENCES

[1] J. Uythoven et al., *Possible Causes and Consequences of Serious Failures of the LHC Machine Protection Systems*, 9th European Particle Accelerator Conference EPAC04, Lucerne, Switzerland, July 2004.

[2] V. Kain, *Damage Levels: Comparison of experiment and simulation*, Proc. of the LHC Project Workshop 2005, CERN-AB-2005-14.

[3] R.Bailey, *Summary of overall commissioning strategy for protons*, Proc. of the LHC Project Workshop 2006, CERN-AB-2006-14.

[4] R. Schmidt, *Machine Protection System(s) – overview*, Proc. of the LHC Project Workshop 2005, CERN-AB-2005-14.

[5] B.Goddard, *Safe disposal of the LHC beams by extraction onto the beam dumping blocks*, these proceedings.

[6] E.B.Holzer, *Commissioning and operational scenarios of the LHC beam loss monitor system*, these proceedings.

[7] S.Redaelli, *Commissioning of the LHC collimation system*, these proceedings.

[8] S.Redaelli, *LHC beam collimation*, these proceedings.

[9] R.Filippini, *Dependability analysis of a safety critical system: The LHC beam dumping system at CERN*, PhD. thesis Pisa University and CERN.

[10] J.Wenninger, *Procedures for the commissioning of the BIS for the CNGS and SPS to LHC transfer lines*, LHC-CIB-TP-0001 rev 0.6, CERN.

[11] M.Zerlauth et al., *Requirements for the fast Magnet Current Change Monitors (FMCM) in the LHC and the SPS-LHC Transfer Lines*, LHC-CIW-ES-0002-00-10, CERN.

[12] V.Kain, *What is required to safely fill the LHC?*, Proc. of the LHC Project Workshop 2006, CERN-AB-2006-14.

[13] J. Wenninger, *What Systems Request a Beam Dump?*, Proc. of the LHC Project Workshop 2006, CERN-AB-2006-14.

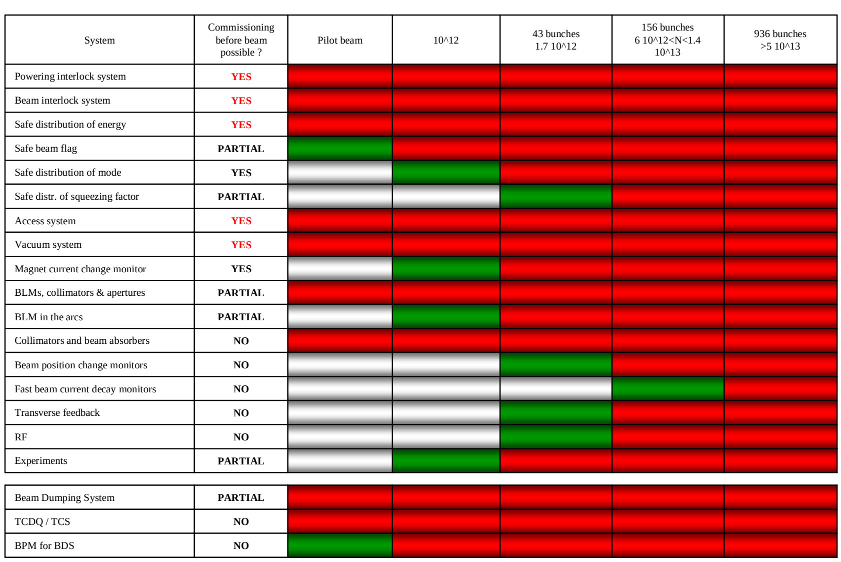

Figure 5: Commissioning stages of the MPS at full beam energy [13].