COMMISSIONING AND OPERATION OF THE LHC MACHINE PROTECTION SYSTEM

M. Zerlauth, R. Schmidt, J. Wenninger, CERN, Geneva, Switzerland

Abstract

The energy stored in the nominal LHC beams surpasses previous accelerators by roughly two orders of magnitude. The LHC relies on a complex machine protection system to prevent damage to accelerator components induced by uncontrolled beam loss. Around 20'000 signals feed directly or in-directly into the machine protection system. Major hardware sub-systems involved in machine protection include beam and powering interlock systems, beam loss and beam excursion monitors, collimators and the beam dumping system. Since the LHC startup in December 2009 the machine protection system components have been progressively commissioned with beam. Besides the usual individual component tests, global machine protection tests have been performed by triggering failures with low intensity beams to validate the protection systems. This presentation will outline the major commissioning steps and present the operational experience with beam of the LHC machine protection system.

MACHINE PROTECTION AT THE LHC

The first priority for the LHC machine protection systems (MPS) is to prevent equipment damage in the ring and during beam transfer from the pre-accelerator SPS [1]. Uncontrolled release of even a small fraction of the stored beam energy may cause serious damage to equipment. The nominal LHC proton momentum is a factor of seven above accelerators such as Tevatron and HERA, whereas the energy stored in the beams is more than a factor of 100 higher, see Figure 1. The beam intensity that leads to equipment damage depends on impact parameters and on the equipment hit by the beam. The damage level for fast proton losses is estimated to $\approx 2 \times 10^{12}$ p at 450 GeV, to $\approx 10^{11}$ p at 3.5 TeV and to $\approx 10^{10}$ p at 7 TeV. No special protection for the LHC would be required below these intensities. At 7 TeV the damage level is four orders of magnitude smaller than the nominal beam current. To evaluate the beam intensity to reach the damage level, a dedicated experiment was performed at the SPS confirming the numbers previously assumed for the damage threshold at 450 GeV [2].

The second priority of the machine protection is to protect superconducting magnets from quenching. At 7 TeV fast particle losses corresponding to a 10^{-8} - 10^{-7} fraction of the nominal beam intensity may quench superconducting magnets. This is orders of magnitude lower than for any other accelerator with superconducting magnets and requires a very efficient beam cleaning system. The LHC will be the first accelerator requiring collimators to define the mechanical aperture through the entire machine cycle. A sophisticated scheme for beam cleaning and protection with many collimators and beam absorbers has been designed [3].

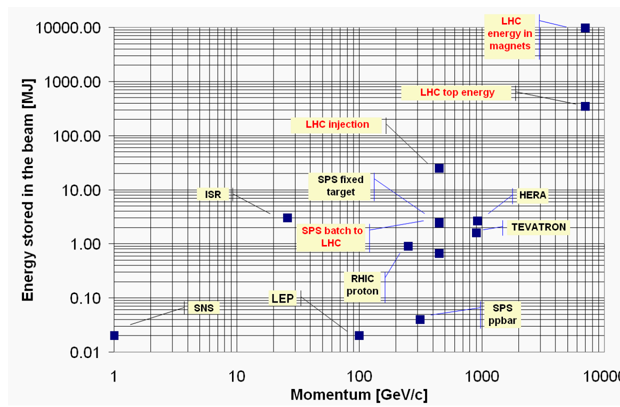

Figure 1: Stored beam energy as a function of the momentum for various accelerators.

LHC OPERATION IN 2010

In September 2008 an electrical problem in the interconnection between 2 main magnets lead to damage of over 50 magnets in one sector of the LHC which required a long repair and consolidation of the LHC of around 12 months [4]. The incident highlighted an issue affecting a large number of interconnections, as a consequence the operating beam energy of the LHC was reduced to 3.5 TeV for the LHC run of 2010-2011. The LHC will only operate at nominal energy from 2013 after a one-year shutdown in 2012 to repair all interconnections between the main dipole and quadrupole magnets in tunnel.

The aim of the LHC run in 2010/2011 is to integrate 1 fm^{-1} per experiment at 3.5 TeV. To reach this goal the LHC must operate at a luminosity of at least 10^{32} $\text{cm}^{-2}\text{s}^{-1}$ in 2011. To reach this luminosity target, approximately 400 bunches of nominal intensity (10^{11} protons) must be stored in each of the two LHC beams at 3.5 TeV. This corresponds to a stored energy of 20 MJ per beam, as compared to the nominal stored energy of 360 MJ. This target requires the LHC MPS to be fully commissioned in order to protect the LHC from damage by beams that exceed the damage level at 3.5 TeV by roughly 3 orders of magnitude.

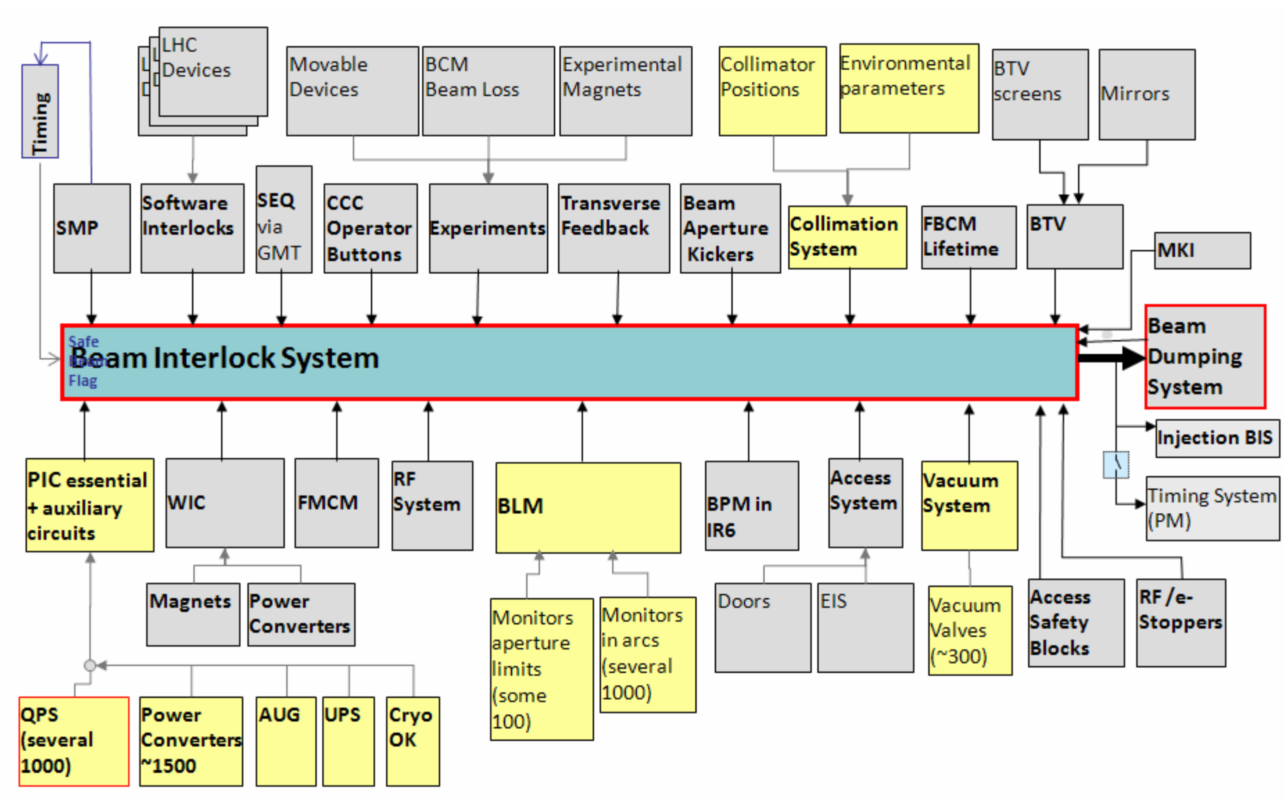

Figure 2: Schema of the LHC Machine Protection System with all its clients.

MPS COMMISSIONING

The commissioning and running in of the LHC MPS can be decomposed into 3 main phases:

- Commissioning of the MPS equipment without beam.
- Commissioning of beam related MPS systems like the Beam Loss Monitor (BLM) system, LHC Beam Dumping System (LBDS) etc with low intensity beam.
- Progressive increase of the beam intensity while carefully monitoring the performance of the protection system. Regular checks of collimator and absorber alignment are made throughout the run.

The commissioning steps with and without beam follow predefined commissioning steps and procedures. Monitoring of the performance by MPS and equipment experts aims at identifying upcoming issues.

The majority of the MPS tests without beam were completed in 2009, and a significant fraction of MPS tests with low intensity beams were performed in December 2009 when the LHC was commissioned at a beam energy of 1.2 TeV. Approximately 2/3 of individual system tests with beam were completed during that period. Following the short technical stop in January and February 2010, some tests had to be repeated due to equipment modification or upgrades. MPS tests with low intensity beams were completed at injection energy and at 3.5 TeV in March and April 2010. By end of March 2010, a first pilot physics run could be started thanks to the rapid progress in machine setup and MPS commissioning. The total integrated beam time used for MPS commissioning represents approximately two full weeks.

BEAM INTERLOCK SYSTEM

Several systems ensure early detection of equipment failures and trigger beam dump requests before the beam is affected. The Beam Interlock System (BIS) [5] receives these signals, see Fig. 2, and ensures a reliable transmission of the requests to the beam dumping systems. It also prevents beam extraction from SPS and injection into LHC in case of non appropriate conditions. The entire beam interlock system logic including the links to all systems was commissioned before beam operation and fully operational for the first beam.

Interlock Masking

Beam below an intensity of about 10^{12} protons is unlikely to cause damage at 450 GeV/c. This limit decreases during acceleration with increasing energy and decreasing beam size. At 3.5 TeV it is about 3×10^{10} protons. Initial commissioning and most machine protection tests are performed with beam intensity below these values. During this phase, certain interlocks can be masked, greatly simplifying initial commissioning. In order not to compromise protection, the so-called ”setup beam flag” is derived from energy (derived from the dipole magnet currents) and beam intensity. If this flag is TRUE, masking is possible. When the flag toggles to FALSE, for example while ramping the energy, all masks are automatically removed.

MP SYSTEMS COMMISSIONING

In this section the commissioning of the main components of the LHC MPS is briefly discussed.

Powering System

Failures in the magnet powering system are among the most likely causes of beam losses. After such failures the closed orbit deviations may increase everywhere around the ring. In addition, both emittance and beam size may growth rapidly.

A dedicated Powering Interlock Controller (PIC) system protects the super-conducting electrical circuits of the LHC. The PIC system is connected to the power converter and to the quench protection of the circuit. In the event of a powering failure or a quench, the PIC system also transmits a beam dump request to the BIS. The reaction time of the system is at the level of 1 ms, for the most critical circuits even at the level of a few microseconds. Electrical circuits can be configured to be maskable (’non-critical’ circuits) or non-maskable (’critical circuits’) at the level of the PIC. The configuration of the circuits and the connection between PIC and BIS are checked using automatic test sequences that may be repeated periodically, for example after interventions on the circuits.

A similar system (WIC) is in place for the normal-conducting magnets of the LHC. In case of a magnet temperature interlock, the WIC system first dumps the beam, and two seconds later only aborts the powering of the magnet. In case of a power converter failure the WIC system triggers a beam dump on the time scale of few microseconds after detecting the presence of a powering failure.

For circuits with very short time constants, the detection of a powering failure in time before the beam is affected requires very low detection thresholds and very short reaction times. As an example, for the LHC normal conducting separation dipoles, the detection threshold is $\approx$ 0.05% to 0.1% in 1 millisecond [1]. Fast Magnet Current Change Monitors (FMCM) [6], developed at DESY and adapted to the CERN requirements, are installed on all critical circuits of the LHC and its injection transfer line. Those devices generate a fast interlock using a current signal that is reconstructed from the voltage after appropriate filtering. The threshold that may be used is only limited by the power converter ripple which is usually in the range of some 10^{-4}. Each device was individually tested with power converter failures to ensure that the reaction time is adequate. For the most critical circuits a test with beam was performed to ensure that the FMCMs were triggering a beam dump before the beam is affected.

Beam Loss Monitor System

Since collimators define the aperture, particles will in most cases be intercepted first by collimator jaws. Beam loss monitors (BLMs) in the vicinity must detect the particle shower and request a beam dump when the loss level rises above a preset threshold. To ensure an adequate reaction time against very fast failures, the loss signal integration time and dump reaction time is only 40 μs (half turn) [7].

Accidentally applied local orbit bumps, local aperture limitations, obstacles etc may be the cause of to localized beam losses anywhere in the ring. To protect the LHC against such events, BLMs are installed at every quadrupole around the ring to detect beam losses that are not detected by monitors at the aperture limitations. The total number of loss monitors to be installed in the LHC is around 3600, the majority of the monitors consisting of a 1 liter volume ionization chamber.

The BLM system was extensively tested before beam operation (connection tests with radioactive sources, noise reduction and EMC, automatic self-tests etc). During beam operation the BLM reaction times and responses were validated by controlled losses with low intensity beams [7]. Adjustments of the dump thresholds were made for a number of monitors, in particular in the collimation regions, in the injection regions and at normal conducting magnets. Each modification must be approved by MP experts and is carefully documented for tracking purposes.

An example of a beam loss pattern on a super-conducting magnet that was intercepted by the BLM system before the magnet could quench is shown in Fig. 3. A possible cause for this event could be dust particles (or similar light ’objects’) moving across the beam.

Beam Dumping System

Beam dumps were triggered at different energies and with different bunch placements and filling patterns to demonstrate that all bunches are correctly extracted via the 700 m long transfer line onto the beam dump block [8]. To reduce the energy density on the dump block, the beam is ”painted” by fast deflection of two families of kicker dilution magnets. A 3 μs long abort gap in the beam structure for the rise of the extraction kicker field allows loss free extraction under normal operating conditions. A small number of asynchronous beam aborts is expected, estimated to once per year. A series of collimators and absorbers are installed to capture beam deflected with a small angle. Tests were performed with de-bunched beam demonstrating that particles in the abort gap are correctly intercepted by these devices. After each beam dump an automatic analysis checks kicker performance and beam losses. Operation with beam is stopped if any anomalies are detected. Not a single magnet was quenched with circulating beam above injection energy thanks to an excellent collimation setup.

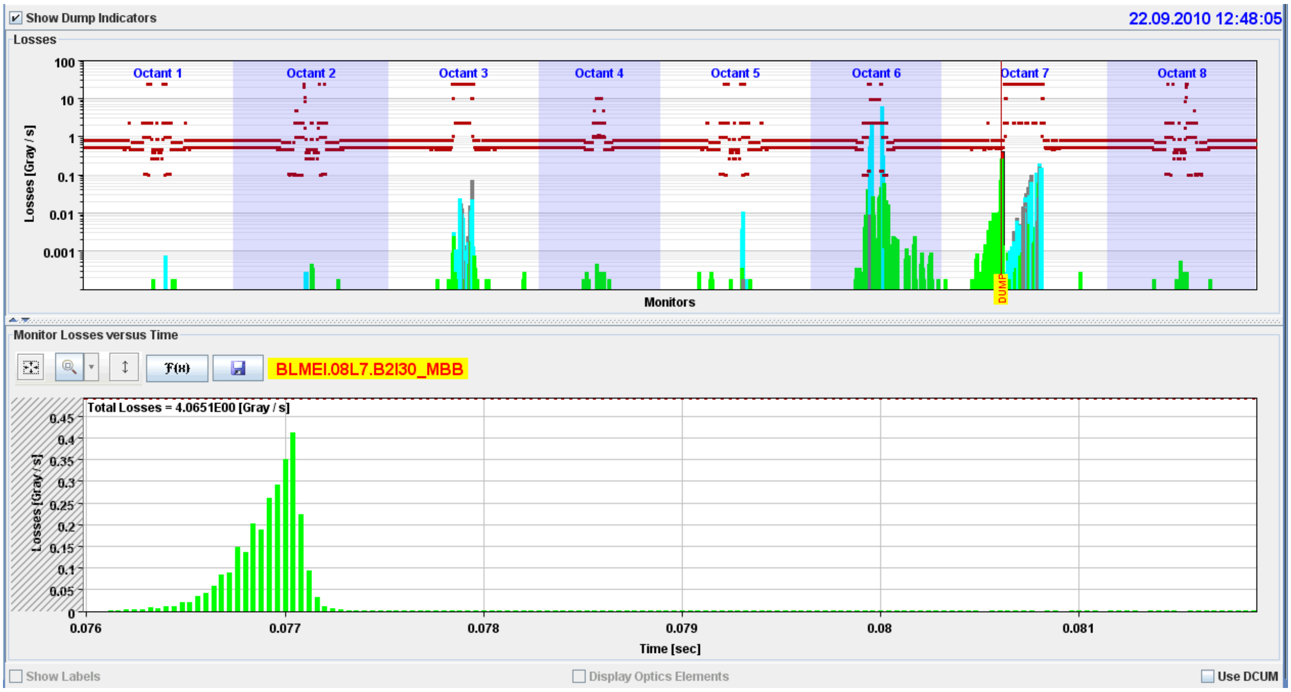

Figure 3: Beam loss pattern as recorded by the LHC Post-Mortem system indicating the loss distribution and the time profile of the loss at the BLM that triggered the beam dump.

Collimation System

The LHC aperture is defined by collimators to limit beam losses to collimator regions where normal-conducting magnets are installed [3]. Collimators for momentum and betatron cleaning are installed in two dedicated cleaning insertions, and in the experimental insertions to shadow the quadrupole triplet magnets. The cleaning efficiency depends on the precision of the jaw centering on the beam, the accuracy of the gap size and the jaw parallelism with respect to the beam. The collimators are aligned during the different operational phases (injection, top energy, etc). The system performance is excellent and no quench was induced by circulating beam. The collimation efficiency is measured by driving the beam on a resonance, losing particles in a few seconds. The beam loss monitors show that losses are concentrated around the collimation regions. After setup the efficiencies exceed 99.9%.

LHC PERFORMANCE EVOLUTION

The intensity of the beams at 3.5 TeV was increased very carefully, while monitoring the performance of the various protection systems. From June 2010 the LHC operated with almost nominal bunch intensities of 10^{11} protons. The number of bunches was progressively increased to 48 bunches by end of August. The evolution of the stored energy is visible in Fig 4: end of August 2010 the stored energy reached 3 MJ. The peak luminosity reached 10^{31} cm^{-2}s^{-1}, i.e. 10% of the target for 2010. In September LHC will move to operation of bunch trains with the aim of colliding up to around 400 bunches.

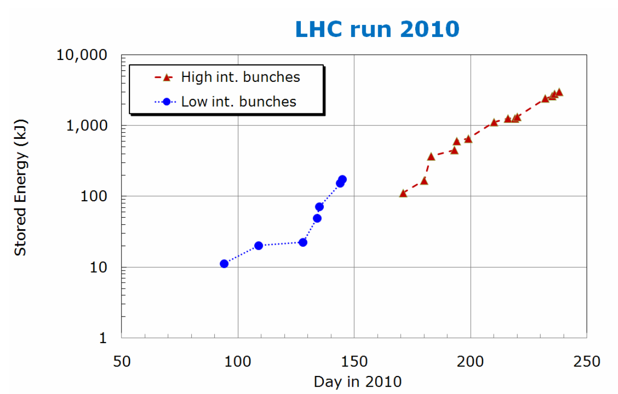

Figure 4: Evolution of the energy stored in the LHC beams as a function of the day in 2010.

MPS STATISTICS

Between March and End of August 2010, 212 beams were dumped above injection energy, most of them at 3.5 TeV. On average 1.2 dumps per day were triggered above injection energy. The reason for the beam dump are indicated in Fig. 5: only 14% of the dumps have been initiated by the operators. All other dumps were MPS systems dumps (73%) or MPS tests (13%).

More than 75% of the beams were dumped by protection systems before the beam itself was affected (i.e. no

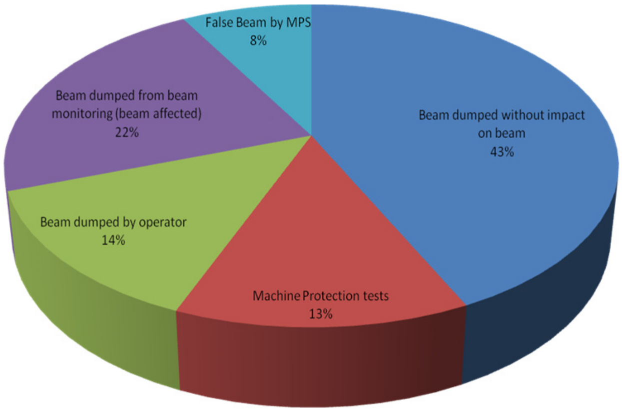

Figure 5: Classification of the beam dumps.

measurable change of beam parameter was detected). The 22% of the beam dumps where the beam was affected can be split in sub-categories as shown in Fig. 6. In roughly one third of those cases the orbit was affected, in about one third beam loss was the driving cause of the beam abort.

False beam dumps due to the MPS itself represent 8% of the dumps: in such cases a component of the MPS erroneously detects an internal error (for example loss of redundancy). Half of the false beam dumps were initiated by the beam dumping system itself.

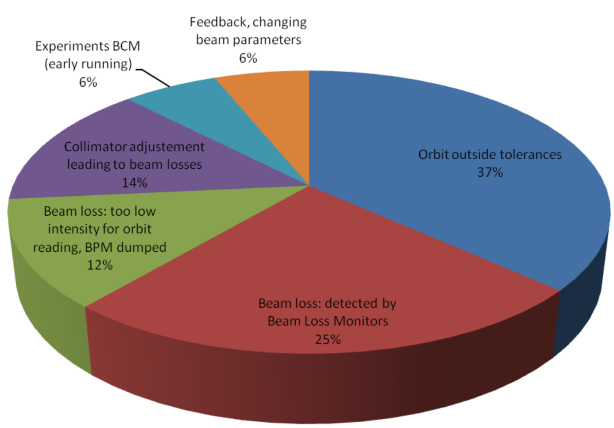

Figure 6: Cause of a beam dump for cases where the beam was affected at the time of the beam abort.

Post-mortem

At the LHC a post-mortem system (PM) has been foreseen from the start [9] and circular PM buffers have been integrated into all essential accelerator systems. The trigger for the PM buffers is derived from the state of the BIS and distributed by the LHC timing system, except for the devices that are self-triggering, like for example quench protection systems.

The Post-mortem (PM) system holds all the essential information to diagnose beam dumps (programmed or emergency). A careful analysis of the data is performed to validate the performance of the MPS, and to detect anomalies before they could lead to serious problems. Figure 3 gives an example of the PM data for a beam dump triggered by BLMs.

CONCLUSION

In 2010 the LHC entered the regime of high stored energy beams and by end of August approximately 3 MJ beams were circulating at 3.5 TeV in each ring. The LHC MPS was fully commissioned with and without beam. At the end of August 2010 over 200 beams had been dumped above injection energy. Despite the high stored energy, no quench was recorded above injection energy, highlighting the excellent performance of the LHC collimation and machine protection systems. Despite its complexity and the large number of interlock signals, the number of erroneous dumps remained very small, at the level of a few percent.

ACKNOWLEDGEMENTS

The authors would like to thank many colleagues of the LHC Machine Protection Panel for their contributions to the successful commissioning of the LHC MPS.

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