FIRST OPERATIONAL EXPERIENCE WITH THE LHC MACHINE PROTECTION SYSTEM WHEN OPERATING WITH BEAM ENERGIES BEYOND THE 100MJ RANGE

Ralph Assmann, Bernd Dehning, Massimilioano Ferro-Luzzi, Brennan Goddard, Mike Lamont, Rüdiger Schmidt, Andrzej Siemko, Jan Uythoven, Jörg Wenninger, Markus Zerlauth, CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider (LHC) at CERN has made remarkable progress during 2011, surpassing its ambitious goal for the year in terms of luminosity delivered to the LHC experiments. This achievement was made possible by a progressive increase of beam intensities by more than 5 orders of magnitude during the first months of operation, reaching stored beam energies beyond the 100MJ range at the end of the year, less than a factor of 4 from the nominal design value. The correct functioning of the machine protection systems is vital during the different operational phases, for initial operation and even more when approaching nominal beam parameters where already a small fraction of the stored energy is sufficient to damage accelerator equipment or experiments in case of uncontrolled beam loss. Safe operation of the machine in presence of such high intensity proton beams is guaranteed by the interplay of many different systems: beam dumping system, beam interlocks, beam instrumentation, equipment monitoring, collimators and absorbers. The strategy applied during 2011 to allow for an efficient but yet safe increase of the beam intensities is presented along with the associated risks and drawbacks of a too aggressive approach. The experience gained with the key systems of LHC machine protection since start-up of LHC luminosity operation will be discussed along with possibilities to further enhance machine availability whilst maintaining the current level of safety.

LHC MACHINE OPERATION BETWEEN 2010 AND 2012

Already during the first year of beam operation with beam energies of 3.5TeV in 2010, the commissioning of the LHC has made remarkable progress, allowing with the chosen bunch spacing of 150ns an increase of the beam intensities from the initial pilot beams (~1e9p/beam) to 368 nominal bunches (~5e13p/beam). This corresponds to stored beam energies of more than 25MJ per beam, whereas only ~10mJ of this energy is sufficient to quench a superconducting magnet of the accelerator. For a further increase of luminosity, the bunch spacing was decreased for the 2011 run to 50ns and the beta squeeze initially brought down to 1.5m. After a full re-commissioning of the machine, following the regular maintenance period between operational years, the beam intensities were progressively increased to finally reach the 2011 target value of 1380b on the 28th of June. Initial commissioning is always done with less than 3 nominal bunches (an intensity considered safe once the primary collimators aligned), followed by fills with 8, 32, 64, 136, 200, 336, 480, 624, 768, 912, 1092, 1236 and finally 1380 nominal bunches as shown in Figure 2. This was pushing the energy stored in each particle beam well beyond the 100MJ range. The progressive increase of beam intensity provided some integrated luminosity for the LHC experiments and was very useful for the initial validation of the full operational cycle, from beam injection to collisions. It also allows an early detection of intensity related effects such as increased vacuum activities, electron clouds, UFOs [1] and radiation induced effects to electronics (R2E) installed in underground areas. These effects became increasingly apparent after reaching 1092 bunches, requiring an extended period at this intensity level to allow for scrubbing and the deployment of several R2E mitigation measures. During summer, machine operation became increasingly smooth, allowing for a further decrease of the beta squeeze to 1m in the beginning of August.

Currently, the LHC operates for its last year before the first long shutdown, with an increased beam energy of 4TeV, a beta squeeze to 0.6m and associated tighter collimator settings. This latest operational envelope has shown to increase the sensitivity of the machine to alignment tolerances of collimators, beam-beam effects, beam losses, equipment failures etc. rendering the machine less reproducible between fills.

Each fill and in particular each dump of the LHC beams is documented and analysed by the operation crews and Machine Protection System experts to assure a continuous monitoring of the dependability and redundancy of the various detection and protection systems [2].

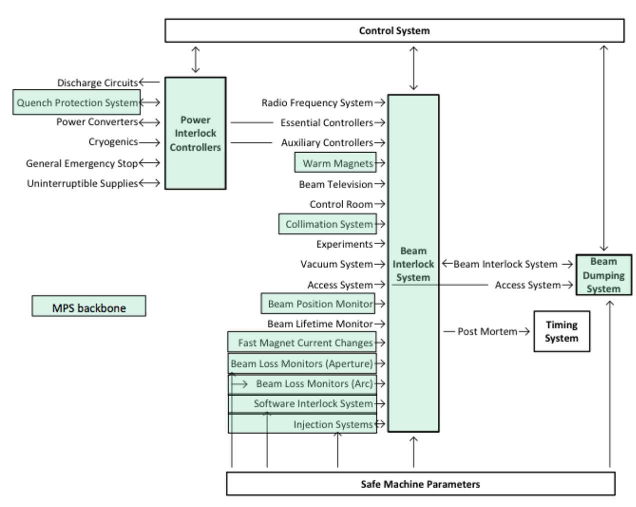

Figure 1: Architecture of LHC Machine Protection Systems and associated client systems.

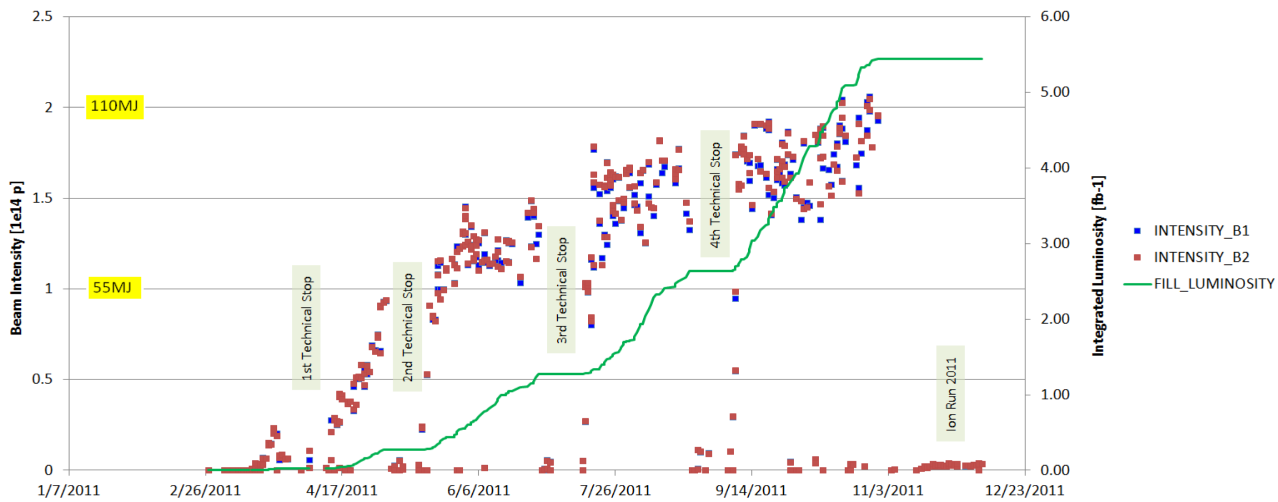

Figure 2: Increase of beam intensities and integrated luminosity during LHC operation 2011.

LHC MACHINE PROTECTION SYSTEM

The backbone of LHC Machine Protection Systems (MPS) consists of the magnet and beam interlock systems, the LHC Beam Dumping System, a number of active protection systems such as Beam Loss Monitors (BLMs), Quench Protection System (QPS) the Software interlock system (SIS), the injection protection system and passive absorbers (Collimators) as shown in Figure 1.

In addition, many equipment systems provide direct inputs to the interlock systems to preventively dump the beams in case of malfunctioning, in total many 10.000 interlock conditions. The MPS architecture is constantly evolving, and more than 100 major changes were recorded during the operational year 2011.

Operational Experience

During the operational year 2011, the LHC machine protection systems cleanly executed around 1200 beam dump requests, corresponding to a slight decrease of 10% with respect to the previous operational year 2010. As already in 2010, no beam inducted quench was observed with circulating beam at 3.5 TeV. Even during the various machine development phases devoted to the understanding of the quench margin of the LHC magnets, no magnet was quenched with circulating beam, namely due to the many existing redundancies in the protection architecture and efficient and timely detection of equipment failures. The so far quench-free operation indicates the presence of operational margins that will become important for the understanding of the future performance reach of the machine with respect to effects of electron clouds and UFOs. As a consequence, no equipment damage was recorded since the restart of beam operation, apart from some damage that occurred in the SDD calibration unit of the ALICE experiment following an injection kicker erratic during beam injection from the SPS. Other than for operation with circulating beams, injection protection has to ultimately rely on passive protection and beam absorbers to capture wrongly steered particles. Therefore this area will remain a major concern, in particular for the nominal injection of 288 nominal bunches with a bunch spacing of 25ns after LS1.

Origin of Beam Dump Requests

With respect to the previous operational year, 40% more of the fills were successfully ramped during 2011 to 3.5 TeV, demonstrating a much improved mastering of the machine and the operational cycle. At the same time, a small relative increase of false triggers from the Machine Protection Systems itself was observed, mostly due to the much accentuated effects of intensity and luminosity related issues in the LHC equipment systems. The most remarkable change with respect to the 2010 run was however a relative decrease by a factor of 3 of beam dumps from beam monitoring equipment such as beam loss monitors and interlocked beam position monitors (as shown in Figure 3).

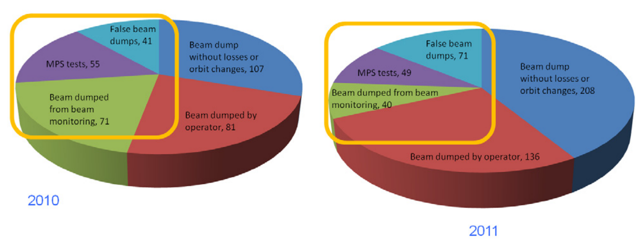

Figure 3: Causes of beam dumps for the past two operational years 2010 (left) and 2011 (right).

This confirms that the numerous mitigations and additional protection systems being put in place during the 2010 and 2011 runs considerably improved the redundancy of the active machine protection systems. The dependability of the backbone systems of LHC machine protection remained mostly constant and consistent with the initial predictions of dependability [3], with the exception of a strong increase in Single Event Upsets (SEU) and environment related triggers (such as failures of the electrical distribution…) for particularly exposed or sensitive equipment systems. The observation that 95% of

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false positives occurred above injection energy confirms the correlation with intensity and/or luminosity related effects on electronics. Such failures were predominant in systems like the Quench Protection System (QPS) or the Powering Interlock System (PIC) based on industrial Programmable Logic Controllers (PLC) as shown in Figure 4. For both systems corresponding mitigation actions have already been prepared and put in place, like for example the deployment of a new failure tolerant firmware version for QPS controllers in exposed locations or the full relocation of all interlock PLCs during the TS3 of the 2011 run.

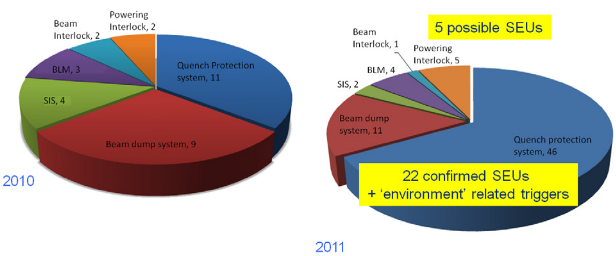

Figure 4: Fraction of false dump triggers from machine protection systems in 2010 (left) and 2011 (right).

Beam Dumps from Beam Monitoring

The number of beam dumps triggered by beam loss monitors and interlocked beam position monitors is a good measure to assess the effectiveness of the active protection systems. Some 40 fills that reached physics energy have been prematurely dumped from such systems during the 2011 run, indicating possible further improvements of the redundant active detection. The beam dumps were mostly a consequence of slow losses, caused by vacuum activities, feedback issues or other transverse beam instabilities. Despite the fact that the machine always has been very well protected in these cases (namely by the very performing beam loss monitoring system), maintaining the current good level of orbit stability is absolutely mandatory. To maintain the current level of dependability also when exploring a new operational envelope after LS1, additional interlocks assuring the orbit stability and beam current change monitors should be developed for future runs.

FUTURE IMPROVEMENTS OF THE MACHINE PROTECTION SYSTEMS

One of the most promising systems to introduce additional redundancy is the so-called beam current change monitor, which was a vital part in many other MPS systems such as e.g. HERA. It was proposed for a use in the LHC as early as 2005 and aims at detecting changes of less than 0.1% of the total beam current within some 10 turns. A second system, to become operational already during the 2012 run, is a new software interlock system monitoring the power converter currents of corrector circuits to protect against operations- and feedback-failures. While this system will be redundant to an already existing software interlock for the arcs it will add a level of protection in the insertion regions due to its capability of tracking bump shape amplitudes and variations as illustrated in Figure 5. It therefore has a key interest for all other (non-COD) power converters where currently no current tracking is being performed.

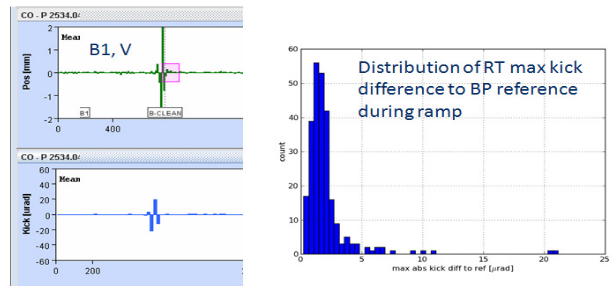

Figure 5: Orbit bump >2mm developing during a ramp of fill 1717. The system clearly identifies the unusually high kick applied by calculating the difference between the applied kick and the BP reference.

Another important improvement already partially implemented for the 2012 run is the finalization and full commissioning of the transverse damper (ADT), which allows for abort gap cleaning and increased efficiency and dependability when performing loss-maps and machine developments (MD) as e.g. for the quench tests [3].

CONCLUSIONS AND OUTLOOK

The LHC Machine Protection and Equipment Systems have been working extremely well during the initial years of beam operation, and ever more failures are captured before effects on the particle beams are seen. Not a single quench with circulating beam has been observed, although the machine has been routinely operated with more than 100 MJ stored in each particle beam, 10 orders of magnitude more than needed to quench a superconducting magnet. The machine is routinely re-commissioned after technical stops. A fast intensity ramp up is hereby not a risk with machine protection, but rather with the potential effect of decreasing the efficiency. The focus of attention remains with injection protection and machine development periods. Such periods by definition explore new operational and machine protection territory, imposing particular rigour as to the implementation and follow-up of the required modifications of the machine protection systems to maintain the required dependability of equipment protection.

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