LESSONS FROM 2011 – MACHINE PROTECTION

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Abstract

The present architecture of the machine protection system is being recalled and the performance of the associated systems during the 2011 run will be briefly summarized. An analysis of the causes of beam dumps as well as an assessment of the dependability of the machine protection systems (MPS) itself is being presented. Emphasis will be given to events that risked exposing parts of the machine to damage. Further improvements and mitigations of potential holes in the protection systems will be evaluated along with their impact on the 2012 run. The role of rMPP during the various operational phases (commissioning, intensity ramp up, MDs…) will be discussed along with a proposal for the intensity ramp up for the start of beam operation in 2012.

PRESENT ARCHITECTURE OF MACHINE PROTECTION SYSTEM

The MPS backbone for the LHC 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 magnet and beam interlock systems to preventively dump the beams in case of malfunctioning, adding up to a total of many 10.000 interlock conditions. The MPS architecture is constantly evolving, and more than 100 major changes were recorded and followed up during the operational year 2011.

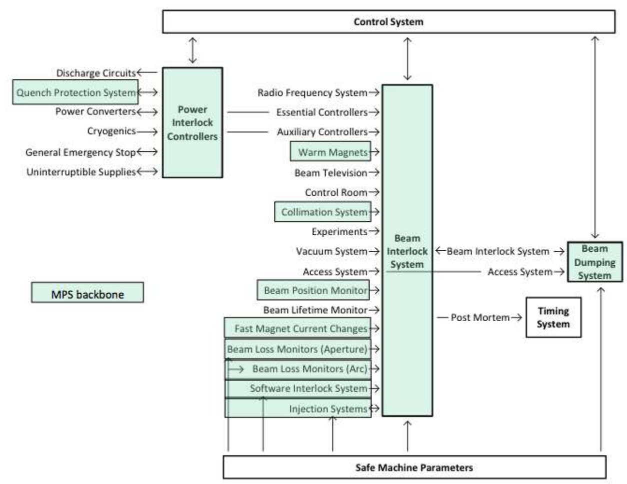

Figure 1: Architecture of LHC Machine Protection Systems and associated client systems

REVIEW OF PROTECTION DUMPS

At the end of the 2011 run, the LHC machine protection systems had 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, although the machine was routinely operated with more than 100MJ of stored beam energy per beam. 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. This indicates the presence of operational margins that will become important when understanding the performance reach of the machine with respect to effects of electron clouds and UFOs [1]. Consequently no equipment damage was recorded during the run, apart from damage that occurred in the SDD calibration unit of ALICE following kicker erratic's during beam injection [2].

As during previous years all beam dump events from 3.5 TeV, be it a programmed dump or a premature beam dump request, have been meticulously analysed and validated by the operation crews and Machine Protection System experts and have been used to build a knowledge database to assess possible long-term improvements of the LHC machine protection and equipment systems [3].

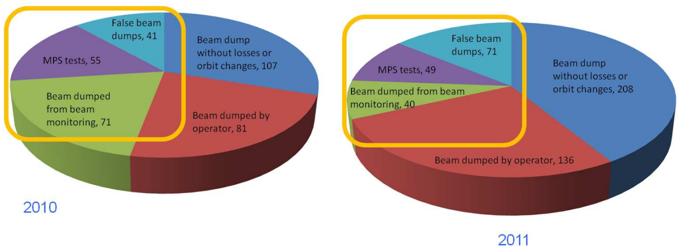

Figure 2: Causes of beam dumps for the past two operational years 2010 (left) and 2011 (right)

With respect to the previous operational year, 40% more of the fills were successfully ramped to 3.5 TeV, being proof of 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 could be observed, mostly due to the much accentuated effects of intensity and luminosity related issues in the LHC equipment systems, resulting in numerous premature beam dumps as will be discussed later in this paper. The most remarkable change with respect to the 2010 run was however that fact that beam dumps from beam monitoring equipment such as beam loss monitors and interlocked beam position monitors have decreased by a factor of 3 (as shown in Figure 2).

This confirmed that the numerous mitigations and additional protection systems being put in place during the 2010 and 2011 runs have brought a considerable improvement to the redundancy of the active machine protection systems. The dependability of the backbone systems of LHC machine protection remained hereby mostly constant, apart from a strong increase in Single Event Upsets (SEU) and environment related triggers (such as failures of the electrical distribution…). Such failures were predominant in systems like the Quench Protection System (QPS) or the PLC based Powering Interlock System (PIC) as shown in Figure 3. For both systems corresponding mitigation actions have been already 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.

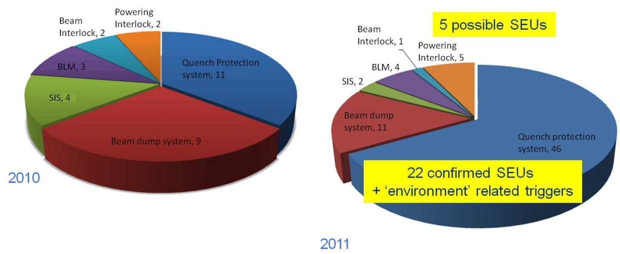

Figure 3: Fraction of false dump triggers from machine protection systems in 2010 (left) and 2011 (right)

The fact that 95% of false positives occurred above injection energy confirms the correlation with intensity and/or luminosity related effects on electronics, as it can be seen from Figure 4.

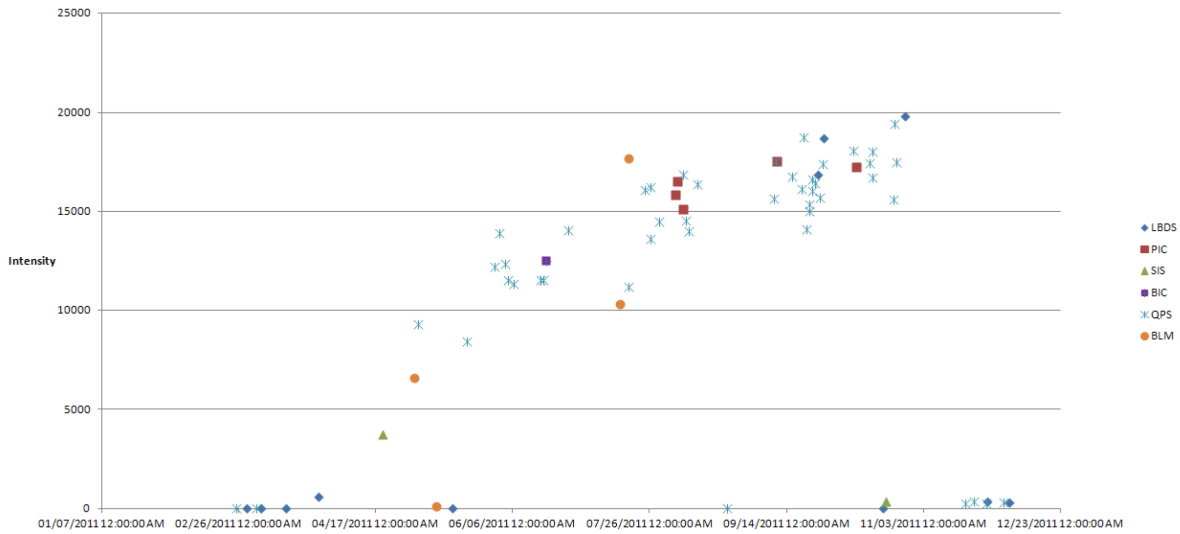

Figure 4: False beam dumps from machine protection systems as a function of time (x-axis) and intensity in the machine (y-axis)

While false positives from the LBDS, SIS, BI and BLM system are more or less equally distributed over time and in first order (due to low statistics) independent from the circulating beam intensity, it is clearly visible from Figure 4 that there is an accumulation of QPS faults with higher beam intensities towards the second part of the operational year 2011. Also all failures caused by spurious stops of the powering interlock PLCs exclusively occurred during operation with high beam intensities, and in addition occurred on all five occasions in locations of higher radiation levels such as UJ14, UJ16 and UJ56.

Beam dumps from beam monitoring

The number of beam dumps triggered through the beam monitoring systems (beam loss monitors and interlock beam position monitors) is a good measure to assess the effectiveness of the active protection systems. Some 40 fills 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), a future evolution of the machine parameters towards higher energies and smaller β* values will require tighter collimator settings and lower BLM thresholds. Therefore to maintain the current good level of orbit stability is absolutely mandatory. To maintain the current level of dependability also when exploring a new operational envelope, additional interlocks for e.g. the orbit corrector current and a beam current change monitor should be developed and put in place for future runs.

FUTURE IMPROVEMENTS OF THE MACHINE PROTECTION SYSTEMS

One of the most promising systems to introduce additional redundancy into the MPS 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 [4]. With a HERA like system it would be possible to detect changes of less than 0.1% of the total beam current within some 10 turns. The BI group in collaboration with a DESY consultant has started a development of such a system for the LHC in mid of 2010. A first prototype of the system is installed and recording first data (see Figure 5). As shown in Figure 6 (illustrating a comparison between the measurement from the DCBCT and the beam current change monitor) the system however still shows some unexplained behaviour during the first part of the flat top and the squeeze of the particle beams, which needs to be fully understood and mitigated before an active interlock can be implemented based on this measurement.

Figure 5: Prototype installation of beam current change monitor

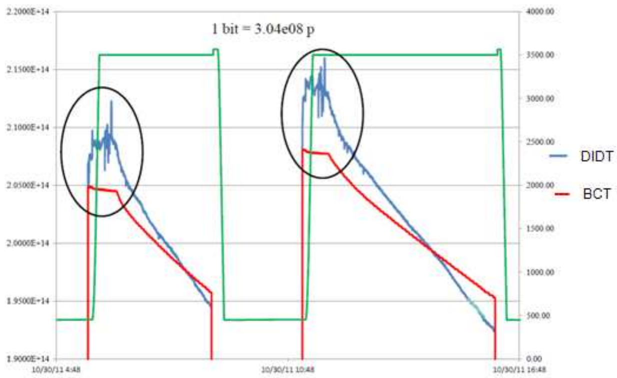

Figure 6: Comparison of beam current measurements with the DCBCT (red curve) and the beam current change monitor (blue curve)

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 the already existing SIS interlock for the arcs it will add a level of protection in LSS 1/2/5 and 8 due to its capability of tracking bump shape amplitudes and variations as illustrated in Figure 7. It therefore has a key interest for all other (non-COD) power converters where currently no current tracking is being performed.

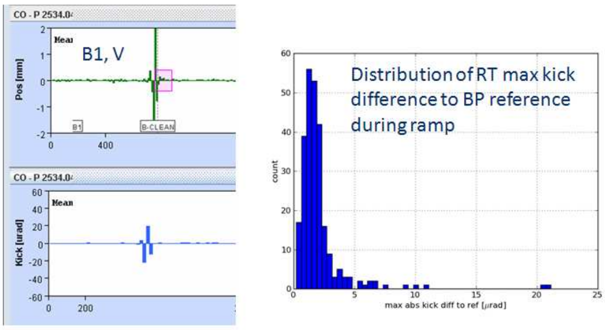

Figure 7: Orbit bump >2mm developing during the ramp of fill 1717. The system clearly identifies the unusually high kick applied by calculating the difference between the applied kick and the BP reference.

Other improvements foreseen for the 2012 run include amongst others the finalization and full commissioning of the transverse damper (ADT), which will allow for abort gap cleaning and increased efficiency and dependability when performing loss-maps and machine developments (MD) as e.g. for the quench tests. During initial MDs, the ADT has already demonstrated its capability of selectively and very deterministically blowing up selected bunches as shown in Figure **8**. First comparisons of loss-maps performed with the ADT blow-up and when crossing a 3rd order resonance show very good agreement between the two methods.

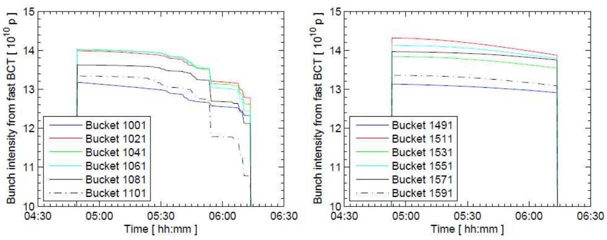

Figure 8: Blow up of selected bunches during MD (left) and the corresponding unaffected bunches (right)

In view of the increase in energy and intensity for the 2012 run, a procedure for on-demand abort gap cleaning has been developed and will be validated during the beam commissioning phase. While for the upcoming run the procedure will be semi-automatic only, improvements of the ADT hardware (to avoid kick tails that might impact the bunches next to the abort gap and thus the luminosity while cleaning) and a dependable reading of the gap population by the BSRA will allow to move towards fully automated cleaning after LS1.

Commissioning and validation procedures, Machine Developments and Change Management

The re-commissioning of the MPS system for the 2012 run will be done as in 2011 according to the well established procedures documented in the Machine protection share point site [5]. Based on the very good experience of intensity ramp ups after the technical stops in 2011 (see Figure **9**), the intensity ramp up for 2012 is proposed to be reduced to a total of 7 steps. The past year of running clearly showed the machine availability to be the driving factor for reaching 768 bunches. Only after this step intensity related effects (UFOs, vacuum activities and SEUs) started to play a determining role for further increasing the intensity.

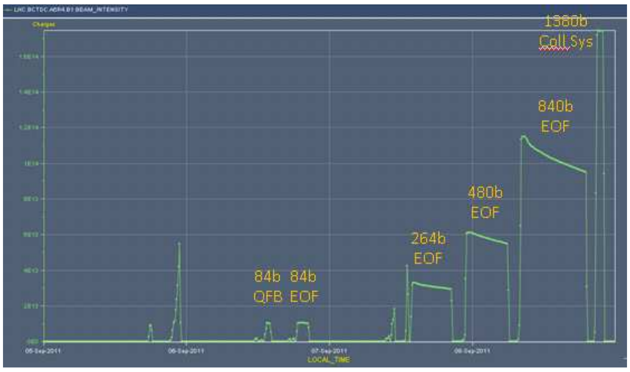

Figure 9: Intensity ramp up after last TS in September 2011

The risk with a faster intensity ramp up is hereby not a risk with machine protection, but rather with the potential effect of decreasing the efficiency. A balanced approach to intensity the increase allows however for probing and resolving of any upcoming issues while maintaining a certain integrated luminosity, as smaller β* values, new collimator settings, and tight orbit tolerances will need time to master.

The initial intensity ramp-up for the restart in 2012 is therefore proposed as follows:

- 3 bunches for initial validation and MPS checkout
- 2-3 fills and 4-6 hours of stable beams with 48b, 84b, 264b and 624b (for cycle validation)
- 3 fills and 20 hours of stable beams with 840b, 1092b, 1380b (luminosity related problems)

For future re-commissioning campaigns it is expected to introduce an even more formal approach through the use of the recently developed accelerator testing tool for HWC, which will allow for the possibility of more rigorous sequencing, dependencies and documentation as well for the beam commissioning phase.

Additional developments to improve the tracking of relevant changes to the MPS systems should be defined and put in place, as 2011 has seen not less than 100 considerable changes to hardware and software components of the machine protection systems. Changes in machine protection systems require more than any others an appropriate culture and level of responsibility of the equipment expert to assure the dependability of the deliverables. Additional controls tools for intelligent rollbacks, centralized information on deployments/server reboots and RBAC like protections against changes on operational machines would further facilitate this effort.

This also applied to some extend to machine development periods, which by definition explore new machine and machine protection territory, often requiring numerous changes to the machine and machine protection systems to allow for the MDs to be performed. It has to be said that the MD requestors have demonstrated a high level of responsibility by proactively providing the required MP documents. More than 20 documents have been approved in EDMS for the MD periods in 2011 [6], and the preparation phase has proven very useful for the MD and MPS teams and often helped to increase the efficiency of the MDs. Certain flexibility with respect to the agreed procedure has shown to be useful on a few occasions, but must not become the standard procedure.

CONCLUSIONS AND OUTLOOK

The LHC Machine Protection and Equipment Systems have been working extremely well during the 2011 run thanks to a lot of commitment and rigor of operation crews and machine protection experts. Ever more failures are captured before effects on the particle beams are seen (i.e. no beam losses or orbit changes are observed). Therefore 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, which is 10 orders of magnitude more than the 10 mJ needed to quench a magnet. No evidence of a major loophole or uncovered risk in the protection architecture has been identified. At the same time additional active protection measures should be investigated and deployed for future runs. Maintaining the current level of good orbit stability will be of primary importance in view of future evolutions of the beam parameters towards higher energies and operation with lower β*. Despite the high dependability of the machine protection systems during the past two operational years we have to remain vigilant also in the following years when more emphasis will be given to increase the overall machine availability.

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