

COMMISSIONING OF THE MACHINE PROTECTION SYSTEMS OF THE LARGE HADRON COLLIDER FOLLOWING ITS FIRST LONG SHUTDOWN

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Abstract

During the first long shutdown of the Large Hadron Collider (LHC) extending for more than 18 months, most Machine Protection Systems (MPS) have undergone significant changes, and upgrades. A full re-commissioning of the MPS was performed at the end of the shutdown and during the LHC beam commissioning in 2015. To verify the correct functioning of all protection-relevant systems with beam, a step-wise intensity ramp-up was performed, reaching at the end of 2015 a record stored beam energy of ~ 280 MJ per beam, nearly 80% of the value in the design report. This contribution summarizes the results of the MPS commissioning, the intensity ramp-up and the continuous follow-up during operation, focusing mainly on near misses and false triggers and their proposed mitigations. A strategy to minimize risks during machine development periods for future operation of the LHC, when the protection parameters are modified for several tests, is discussed. The machine protection strategy for the LHC run in 2016 is presented.

INTRODUCTION

Figure 1 shows the beam dump causes above injection energy (450 GeV) and their occurrence during the LHC runs 2015 in comparison to 2012. The run 2012 was dedicated to luminosity production [2]. The LHC was well known after two years of operation and the beam parameters were optimized to produce as much integrated luminosity as possible. In contrary the 2015 LHC run marks the first year after more than 18 months of shutdown, operating at higher energy and different bunch spacing with respect to 2012, which requires a thorough re-commissioning of all systems and gaining experience with this quasi new machine, applying generous safety margins and taking into account the increase of the maximum beam energy from 4 TeV to 6.5 TeV. Therefore, the share of machine protection tests has doubled and the beam dumps due to beam monitoring (beam losses, beam instabilities and orbit excursions) decreased slightly compared to 2012. In both years the percentage of false dumps due to failures in the machine protection systems and the percentage of fills dumped by the LHC operators were comparable. 2015 was the first year with so-called training and beam induced quenches during LHC operation, accounting for 3% of all dumps above injection energy. The LHC was operated with a particle energy of 6.5 TeV, which lead to significantly reduced margins in the superconducting magnets.

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In 2012 the beam energy and the thresholds of the ~ 3600 beam loss monitors were chosen such to avoid quenches in the LHC main magnet circuits during beam operation as far as possible, while maximising machine availability by avoiding unnecessary dumps, and, in case of a quench at top energy, to minimize the risk of damage due to known weaknesses in the 13 kA splices [4]. After the consolidation of the 13 kA splices in the interconnections of the LHC main dipole and quadrupole circuits during the long shutdown [5, 7], these pre-cautions are not required anymore and the strategy for the interlocking of beam losses was revised [6].

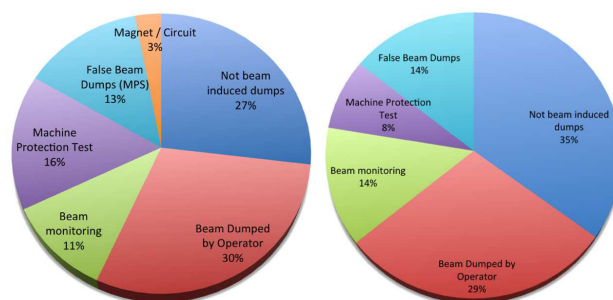


Figure 1: Beam dump causes and their occurrence during the LHC run 2015 (left) and 2012 (right). In total 442 beam dumps above injection energy of 450 GeV occurred in 2015 compared to 536 in 2012.

COMMISSIONING OF LHC MACHINE PROTECTION SYSTEMS

Following significant hardware changes during the first long shutdown of the LHC, the machine protection systems [1] have undergone a full re-commissioning first without and later with beam. To track the commissioning progress, most systems used shared lists. In the longterm the commissioning of all machine protection systems will be performed within the ACCTESTING framework [3], which has successfully been used during the powering test of the LHC superconducting circuits since 2013 and during the 2015 commissioning for a small subset of machine protection systems (Powering Interlock System, Warm Magnet Interlock System, Fast Magnet Current Change Monitor, partially Collimation).

At the end of the beam commissioning, thus, before increasing the energy stored in the LHC beams significantly above 1 MJ, which is equivalent to ~ 10 nominal bunches of 1.15×10^{11} p, the readiness of all MPSs has been reviewed and confirmed at a one day workshop at CERN.

INTENSITY RAMP-UP

The beam commissioning was followed by a step wise increase in the number of bunches, thus, stored beam energy, the so-called LHC intensity ramp-up. At each intensity step the accumulation of three successful fills with a total time in collision of 20 hours was required. Each of the fills and beam dumps was analysed in detail by the experts of the different machine protection systems to identify and mitigate non-conformities as early as possible. Only after the approval by all relevant system experts the number of stored bunches was increased. Fig. 2 shows the evolution of the stored beam intensity in the LHC during the 4th July and the 20th July and between 7th September and 3rd November 2015, respectively. This first period with intensities from three bunches to about 500 bunches per beam was performed in five individual steps. It was dominated by hard- and software issues in the LHC machine protection and related systems and can also be interpreted as debugging phase after a long shutdown. A non exhaustive list of discovered and, where possible mitigated, issues is given in the following: Timing mis-alignments in the Beam Interlock System; Communication problems between Beam Loss Monitor system and the Software Interlock System; Glitches of the beam intensity reading for the Setup Beam Flag; Glitches of position interlocks for moveable devices; Missing data in the Post Mortem database; Heating in a secondary collimator due to wrong connection of cooling pipes; False dumps by the Beam Current Change Monitor; Unbalanced ruptures of the interlock loop of the quench protection system; Problems with attenuation in some optical fibers of the Beam Interlock system.

The second period of the intensity ramp-up with intensities above ~ 500 bunches was dominated by intensity and beam related issues. Therefore the increase of the beam intensities was performed in small steps, with check-points every few hundred bunches, up to 2244 bunches at the end of the proton run. A non exhaustive list of issues is given in the following: Single event upsets on a radiation sensitive boards of the quench protection system causing beam dumps - the issue was solved by replacement of the boards in a planned technical stop of several days; Macroparticle induced beam losses causing beam dumps and beam induced quenches [8]; Beam induced RF Heating [9]; Beam instabilities [10, 11]; Heating of the LHC beam screen reaching the cryogenic limit due to build up of electron cloud [12, 13]; Injection losses reaching $> 60\%$ of the dump threshold [14]; Vacuum spikes at the B2 injection protection absorber (TDI) during high intensity operation [9].

In addition, issues not related to debugging or increasing stored beam intensity have been observed: erratic triggering of dump (MKD) and dilution kicker (MKB) generators, the first leading to the only asynchronous beam dump observed during 2015 beam operation - the respective generators were replaced; training quenches in the main dipole magnets at top energy (see below); earth faults in a main

dipole and a sextupole spool piece circuit, the latter had to be condemned.

At the end of the proton run 2015 a leak in the B2 beam dump was discovered. During normal operation the two carbon beam dump blocks (TDEs) of the LHC, housed in ~ 8 m long enclosures, are operated in a nitrogen atmosphere with a slight over pressure of 1.2 bar to avoid the intake of air in case of a leak. Fig. 3 shows the nitrogen pressure in the B1 and B2 TDE blocks between 1st and 5th November 2015. The saw tooth behaviour in the pressure reading of both beams is due to the increase of the average TDE temperature after a high intensity beam dump. After a beam dump on 2nd November the pressure in the beam 2 TDE dropped steadily. The leak was discovered two days later due to an interlock in the automatic checks of the beam dumping system, performed after each beam dump, when the pressure had dropped below 1.1 bar. As a safety precaution the allowed stored beam intensity at 6.5 TeV was immediately lowered to 12 nominal bunches, as a limit known to be safe even with a dump block entirely exposed to air. In addition an interlock was added to the SIS, dumping the beam, if the pressure would drop below 1.1 bar. After a few days the source of the pressure drop was identified and solved by tightening a flange.

PROTECTION DURING MAGNET QUENCHES AT 6.5 TeV

In 2015 seven so-called training and six beam induced quenches of main dipole magnets were recorded during operation with circulating beam at 6.5 TeV. In addition, four quench tests were performed as part of the Machine Development programme at the end of the 2015 run. In three out of four tests a beam induced quench was triggered. For all of these quenches, the voltages across the magnets, the loss pattern, the trajectory of the beams and the sequence of interlocks were analysed in detail and correlated. Fig. 4 shows, exemplarily, the voltage U_{diode} across a main dipole magnet during a beam induced quench on 13th December 2015. The quench protection systems (QPS) detects the quench of the magnet at the beginning of the voltage rise, when it reaches 100 mV. The beam dump was initiated ~ 10 ms after quench detection and the quench heaters were fired ~ 5 ms later. The by-pass diode, which protects the quenched magnet, opened, when the voltage reached ~ 6 V, ~ 30 ms after the detection of the quench. Thus, the LHC beam was already dumped ~ 20 ms before the magnetic field in the quenched magnet started to decay. No changes in the particle trajectory were observed due to the quench, which could have caused losses in the LHC collimation region in IR7. No orbit distortions were observed after any quench in the main dipoles at 6.5 TeV with circulating beam during the 2015 run. This shows, that the reaction time of the quench protection system in combination with the powering interlock system guarantees redundancy to the BLM system to dump the LHC beams in case of a quench in the

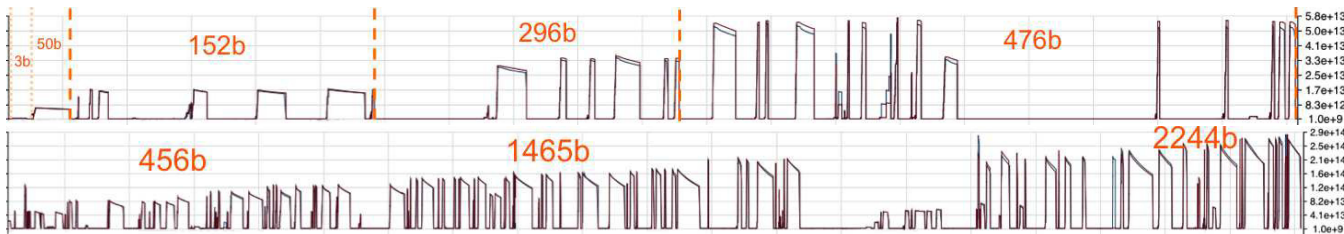


Figure 2: Evolution of the stored beam intensity (B1 - blue, B2 - red) in the LHC between 4th July and 20th July 2015 (top) and between 7th September and 3rd November 2015 (bottom).

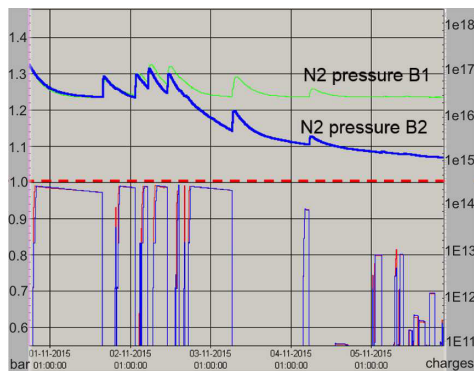


Figure 3: Nitrogen pressure in the beam dump blocks (TDE) of B1 (green) and B2 (blue) between 1st and 5th November 2015. The stored beam intensity in the LHC is shown in the lower part of the plot (B1 -blue, B2 - red).

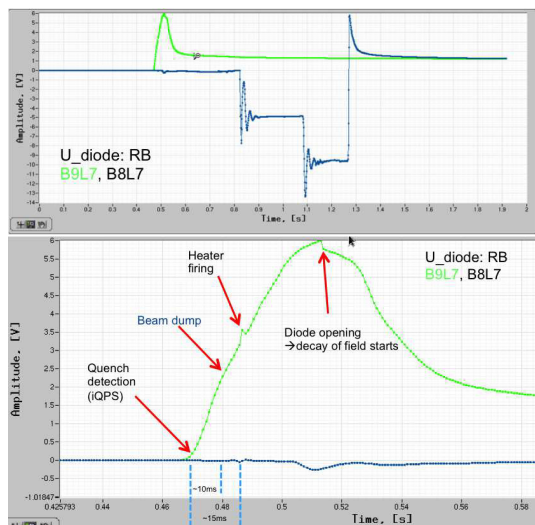


Figure 4: Voltages U_{diode} across a main dipole magnet (green) and its direct neighbour (blue) during a beam induced quench on 13th December 2015.

main dipoles, well before losses in the collimation region can reach a critical level.

MACHINE DEVELOPMENT AND MACHINE PROTECTION

In 2015 three five day blocks of machine time were assigned for machine developments (MD), with in total 50

scheduled MDs. For each MD a detailed procedure had to be written by the MD responsible. Each of these procedures was checked and classified by machine protection experts. Seventeen MDs were classified as machine protection critical MDs and, therefore, required an approval by the restricted Machine Protection Panel and the documentation of their procedures. In average the MD procedures were available about one week before the respective MD block. This time window has proven to be just sufficient to ensure a proper checking, necessary discussions and iterations for protection critical MDs. This approach improved the safety and efficiency of MDs. Therefore, for the future the same strategy will also be applied to MDs or MD like tests scheduled outside of dedicated MD blocks.

CONCLUSION

The machine protection systems ensured safe operation of the LHC with up to ~ 280 MJ energy stored per beam in 2015. The commissioning of the machine protection and related systems was followed by a step-wise intensity ramp-up, requiring the approval of system experts to go from one step to the next. A similar intensity-ramp up will be performed after the LHC beam commissioning in 2016. Only one asynchronous beam dump was recorded during the 2015 run of the LHC (with only three bunches in the LHC), which is significantly lower than the 2-3 per beam per year expected after intensive testing of the beam dumping system at the end of the long shutdown. Thirteen quenches in the LHC main dipole magnets occurred during standard operation and with circulating beams at 6.5 TeV. In all cases the beams were dumped well before any decay of the magnetic field in the quenched magnet could have caused a distortion of the particle trajectory. The preparation of detailed procedures for each MD eased significantly the identification of machine protection critical MDs and helped to improve efficiency during the MD.

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