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OPERATIONAL PERFORMANCE OF THE MACHINE PROTECTION SYSTEMS OF THE LARGE HADRON COLLIDER DURING RUN 2 AND LESSONS LEARNT FOR THE LIU/HL-LHC ERA

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Abstract

The Large Hadron Collider (LHC) has successfully completed its second operational run in December 2018. To allow for the completion of the diverse physics program at 6.5 TeV, the machine has been routinely operating with stored beam energies up to 300 MJ per beam during high intensity proton runs as well as being frequently reconfigured to allow for special physics runs and important machine development studies.

No major damage has incurred to the accelerator equipment throughout the run thanks to the excellent performance of the various machine protection systems. However, a number of important observations and new failure scenarios have been identified, which have been studied experimentally as well as through detailed simulations. In this contribution we provide an overview of the operational performance of the machine protection systems throughout Run 2 as well as the important lessons learnt that will impact consolidation actions and future designs of the machine protection systems for the LIU/HL-LHC era.

MACHINE OPERATION AND LIMITATIONS DURING RUN 2

The second run of CERN's Large Hadron Collider was successfully completed in December 2018, producing 160 fb^{-1} of integrated luminosity over the 4 year long run. Following the consolidation of the magnet interconnections during Long Shutdown 1 (LS1) [1], the machine was operated throughout Run 2 at a beam energy of 6.5 TeV, allowing to routinely reach stored beam energies in each of the two beams of up to 300 MJ as depicted in Figure 1 [2].

The first operational year of 2015 was devoted to the recommissioning of the accelerator at the increased energy of 6.5 TeV, initially using a bunch-spacing of 50 ns in order to minimize the additional heat load induced on the cryogenic system by the e-cloud effect. As of July, the nominal bunch spacing of 25 ns was used, whereas the β^* at the interaction points of the main experiments ATLAS and CMS was conservatively set at 80 cm to ensure large aperture margins and allow for more relaxed collimator settings for this initial commission phase. A non-conformity was discovered in one of the injection protection absorbers (TDI), risking to induce cracks in the material in case of high energy deposition following injection failures [3]. As a result, the length of the bunch trains injected from the SPS was limited to 144 bunches per injection resulting in a limitation of the total number of stored bunches in the machine to 2244 bunches per beam, which is 20% less than the nominal 2808 bunches.

Following the exchange of the TDI during the following winter-shutdown, the LHC resumed operation in 2016 using the nominal 25 ns bunch scheme as well as a β^* for IP1 and IP5 of 40 cm. The machine was however again limited to use only bunch trains of 144b at injection due to a vacuum leak that developed in the internal SPS beam dump and that was likely to degrade further in case higher beam intensities would be continuously disposed on the dump block. Due to the absence of an appropriate spare element and the desire to maintain both the LHC as well as the SPS North Area fixed target physics program, the total accelerated intensity was limited in the SPS for the entire year. Additional software interlocks maintained the total intensity disposed on the leaking SPS dump block in a given interval of time within acceptable limits. Despite this limitation, the availability of a new high-brightness beam type called BCMS (Bunch Compressions, Merging and Splitting) [4] from the injectors allowed surpassing the design peak luminosity of $1x10^{34}$ $cm^{-2}s^{-1}$ with a maximum of 2076 bunches stored in each ring. The operational year was also marked by the discovery of a first dipole magnet in sector 12 of the LHC (A31L2) showing signs of an inter-turn short, causing a few quenches at fairly low current during the ramp-down of the magnet circuit. While operation could continue for the remainder of the year, several mitigation measures were implemented. This included increasing slightly the quench detection thresholds while lowering the beam loss monitor thresholds in the whole sector to avoid the likelihood of quenches and fast power aborts in the affected magnet, which could have led to a further degradation of the inter-turn short. The presence of the inter-turn short was confirmed in the SM18 test station after its removal during an extended winter-shutdown.

Following the exchange of the magnet during an extended winter-shutdown, the 2017 run was started with the same beam configuration as in 2016. With increasing intensity, more and more physics fills were however aborted as a result of a new beam loss phenomenon originating in cell 16L2 of sector 12 [5]. It manifested itself by causing fast beam instabilities with growth rates as fast as 10s of turns (~1 ms), ultimately exceeding the beam loss thresholds either in nearby beam loss monitors or in the collimation region of IR7. An air leak during the cool-down process of the sector, resulting in several litres of frozen gas in the two beam pipes around the interconnection of 16L2 was identified as the root cause of these events. Attempts

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to evaporate it by means of a local warm up of the beam screen were unsuccessful, and the machine performance could only be recovered using an alternative beam production scheme, called 8b4e, along with a limitation of the bunch intensity to ~1.1×10^{11} p/b, which considerably reduced the occurrence of the events.

For the final operational year in 2018, the 16L2 issue was mostly solved by a partial warm-up to around 90K during the winter-shutdown and the machine was operated very successfully with 2556 BCMS bunches, reaching a new peak luminosity record of 2.06×10^{34} cm^{-2}s^{-1}.

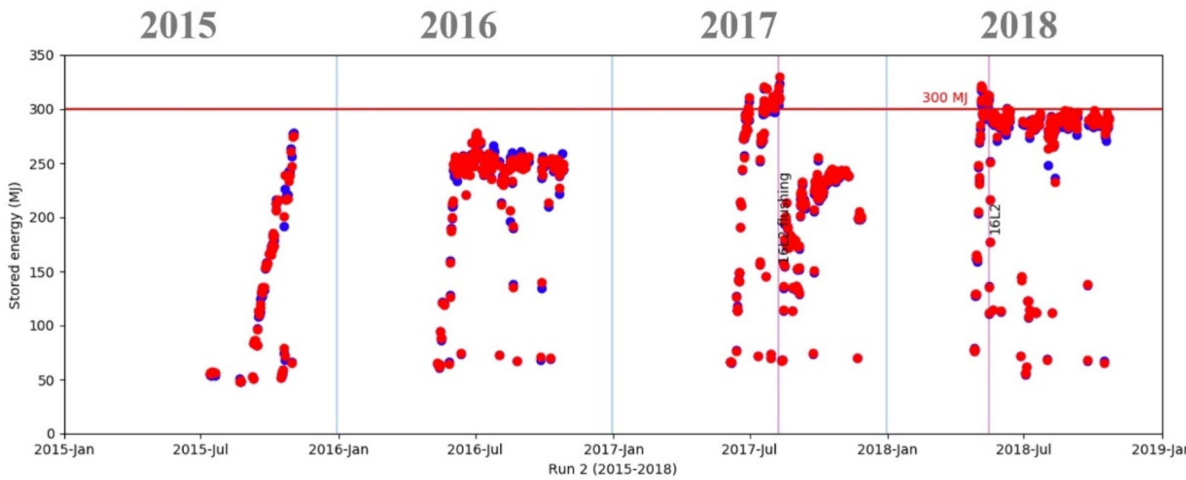

Figure 1: Stored energy of the two LHC beams during the 4 operational years of Run 2.

PERFORMANCE OF MACHINE PROTECION SYSTEMS DURING RUN 2

While the above-mentioned non-conformities were limiting machine operation all along Run 2, the flexibility of the injector complex, the LHC equipment systems and not at last the machine protection systems allowed for the implementation of appropriate mitigation measures to very successfully and safely operate the machine in presence of these unexpected boundary conditions. This is reflected by a steady increase of the number of LHC fills that reached the flat top energy of 6.5 TeV during Run 2 as detailed in Table 1. 2017 was an exception to this trend as the 16L2 beam loss events were predominantly triggered during the energy ramp, resulting in a more than 4-fold increase of beam aborts during this mode with respect to 2016 or 2018.

Table 1: Premature Beam Dumps as a Function of Beam Energy Including Commissioning, MDs and Special Runs

	2015	2016	2017	2018
Injection	611	384	327	509
Acceleration	28	12	57	13
Flat top	415	424	416	510

Considering only the beam dumps that occurred while in collision at 6.5 TeV (detailed in Table 2) one can clearly observe the increased mastering of the machine achieved over the years despite the tighter operational margins towards the end of the run. During the 3 last years primarily devoted to physics operation, the number of fills being deliberately dumped steadily increased from 37% in 2016 to 40% in 2017 and finally 56% in 2018. This is mainly leveraging on a considerable reduction of beam aborts following equipment failures, which is a direct consequence of the major efforts, conducted in the past years to increase the LHC machine availability through the implementation of fault tolerance strategies and targeted hardware consolidation programs. Despite their complexity involving many 10.000 interlock channels, the MPS systems themselves only contribute with around 2-4% of the premature dumps, a number that remained constant over time even considering the constant evolution of the system and the operational parameters throughout Run 2.

Table 2: Cause of Beam Dumps During Stable Beams

	2015	2016	2017	2018
Programmed dump	123	139	150	243
Equip monitoring	193	175	169	148
Beam monitoring	16	9	16	16
MP tests	65	42	29	15
False positives	18	8	14	8
Total	415	373	378	430

Changes to the MP System During Run 2

Similar to LHC Run 1, the second operational period saw a number of improvements and extensions made to the machine protection backbone, safely allowing for a further reduction of the operational margins or to mitigate newly discovered failure modes or shortcomings. A non-exhaustive list of the changes includes:

- A redundant triggering channel between the LHC beam interlock and beam dumping system was deployed, assuring an additional asynchronous dump request to be issued in case of failure of the trigger synchronization unit of the dump system.
- Modification of quench detection settings and beam loss thresholds for the majority of the individually powered

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quadrupoles to increase their tolerance against electromagnetic perturbations while assuring protection against aperture symmetric quenches.

- In addition to the beam energy and position limits used during Run 1 for interlocking the collimators, redundant gap limits as a function of β^* were used for tertiary collimators installed in experimental insertion regions.
- Tertiary collimators (TCTs) were equipped with button pickups and slowly used for orbit interlocks to assure their alignment throughout all operational phases.
- Additional software interlocks were implemented, e.g. for a redundant opening of the 13kA Energy Extraction (EE) systems, the surveillance of the inert gas pressure inside the beam dump volume or for distribution of the transfer line optics to assure correct settings of the injection protection devices.
- Adding diamond BLMs at selected locations for better understanding of beam loss phenomena [6].

These changes were typically introduced during LS or winter-shutdowns and, thus, validated for operation in the re-commissioning program following the operational stop.

Machine Protection During MDs and Special Physics Runs

Run 2 of the LHC also allowed for important early tests of future optics configurations, levelling tools and hardware that will be required for the HL-LHC era of the LHC after the next long shutdown LS3. Dedicated machine development periods (MD) served for an early validation of ATS optics variants [7], crystal collimation schemes, tests of low-impedance collimators, UFO and long-range beam-beam compensation studies. In addition, remaining limitations such as e-cloud and heat-loads or instability thresholds were explored during these MD periods, often stretching along with special physics runs (Van der Meer scans, high beta and intermediate energy runs) the validated machine configurations and requiring the discussion and implementation of special procedures for these runs [8].

RELEVANT EVENTS AND LEARNINGS FOR LIU/HL-LHC ERA

No beam induced damage has incurred to the accelerator equipment of the LHC throughout the entire run thanks to the excellent performance of the machine protection systems. Nevertheless, a number of important observations and new failure scenarios have been identified which have been studied experimentally as well as through detailed simulations. This resulted in the definition and implementation of appropriate mitigation measures for throughout the run, but more importantly represent vital input for future developments and machine configurations in view of the expected increased beam intensities following the LHC injector upgrade (LIU) and the HL-LHC upgrade project. A few of the Run 2 machine protection relevant events with the resulting follow-up are listed:

- Intermittent inter-turn short in main dipole magnet MB.A31L2 (August 2016). Machine operation paused for around 48h for investigation and deployment of mitigation measures. Magnet exchange during year-end technical stop.
- N_2 leaks at the windows of the beam dump block (2016). Paused machine operation initially, before adding pressure surveillance and a continuous nitrogen supply added, the windows are to be consolidated during LS2.
- Beam injection into beam abort gap (2017). Additional checks of consistency of injection scheme, train length and abort gap length added in sequencer and software interlock system. Improved procedure for changes.
- MKBV flashover (July 2018), resulting in loss of almost 50% of dilution kick strength in the last part of the sweep path. Consolidation of HV generators planned for LS2, implementation of re-triggering system towards dump extraction kickers in case of dilution kicker erratic.
- Symmetric triplet quench due to fast orbit drift (June 2018). [9]
- Spurious firing of quench heaters due to injection beam losses (June 2018) due to radiation induced misbehaviour of components of the quench detection system. Additional radiation qualification of components ongoing in addition to relocation and shielding efforts to minimise exposure of sensitive equipment.
- Erratic of injection kicker magnet inducing a quench of triplet magnets in IP2 (September 2016). Expected failure case but unusually high losses due to grazing impact of the beam on the TDI jaw. Detailed FLUKA simulations to increase understanding of quench limits at injection energies.
- Fast orbit changes due to missing beam-beam kick due to the non-simultaneous extraction of the two beams. Reduction of communication delays and automatic linking of beam abort requests for all high intensity fills under study. The use of a hollow electron lens to control the beam halo in the HL-LHC era is being studied [10].
- Fast orbit changes due to heater firings in the main dipole and quadrupole magnets. Proposed mitigation for HL-LHC through an optimised connection scheme of the quench heater strips, a timely detection of spurious hater firings and a preceding beam extraction [11].

CONCLUSION

The reliability as well as the flexibility of the LHC machine protection systems proved a major asset for the very successful operational Run 2 of the LHC. While no beam induced damage was observed, several unexpected events and new failure mechanisms were observed which have been studied in detail and are important input to the ongoing designs of equipment for the HL-LHC era. Special physics runs and machine development periods remain one of the major concerns as the machine and protection systems are operated outside the well-defined and validated configurations. The present machine protection architecture is deemed appropriate for the HL-LHC era, nevertheless a number of additional tools and system upgrades will be required to master the two-fold intensity increase expected as of Run 3.

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