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MACHINE PROTECTION PERSPECTIVE ON THE RESTART OF THE LARGE HADRON COLLIDER AFTER LONG SHUTDOWN 2

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Abstract

In 2022, the Large Hadron Collider started its third operational run. Following the three-year Long Shutdown 2, a careful re-commissioning of the machine protection system (MPS) took place. The initial hardware and beam commissioning period was followed by a 30-day-long intensity ramp-up, during which the number of circulating bunches was successively increased to 2460 bunches per beam. After each pre-defined intensity step, a detailed analysis of the functionality of the MPS was performed before advancing to the next step. It paved the way to reach a record stored energy of 400 MJ per beam in 2022. This was achieved without observing any beam-induced damage, confirming the excellent performance of the MPS. The paper reviews the strategy for the LHC re-commissioning and intensity ramp-up from a machine-protection perspective.

INTRODUCTION

The second Long Shutdown (LS2) of the Large Hadron Collider (LHC) [1] took place between December 2018 and March 2021. During this period, the LHC underwent extensive maintenance, consolidation and upgrade works across all major accelerator systems. Simultaneously, the available bunch current and beam brightness was significantly increased following the successful completion of the LHC Injectors Upgrade (LIU) [2].

After the end of LS2, a comprehensive re-qualifying and recommissioning campaign was required. It started with the hardware commissioning and powering test campaigns, which allowed qualifying all superconducting circuits for operation at the new record beam energy of 6.8 TeV [3], compared to 6.5 TeV before LS2. The next step was the recommissioning of all accelerator systems, including the Machine Protection System (MPS), followed by the beam commissioning, and finally the intensity ramp-up to reestablish high-intensity operation of the LHC.

BEAM TEST

The hardware commissioning period was interleaved with a two-week-long beam test performed in October 2021 [4]. For the test, the beam intensity was limited to three nominal bunches and the beam was kept at the injection energy of 450 GeV, with the exception of one test ramp to an intermediate energy of 3.5 TeV. Besides providing valuable operational experience, the beam test allowed the early identification of several machine protection related issues [5]. Most notably, an unexpected beam aperture restriction was discovered on the left side of the Insertion Region 3 of the LHC. This was caused by a buckled Radio-Frequency (RF) finger, which ensure the electrical contact at the interconnect of two magnets. As this would have considerably affected beam operation in 2022, the decision was taken to warm up the corresponding LHC sector and repair the RF finger.

Overall, the LHC restart in 2022 profited significantly from the experience gained and the issues mitigated during the beam test. Therefore, the approach of performing a short beam test several months before the actual restart after a Long Shutdown proved to be highly valuable.

MPS RECOMMISSIONING

Following the hardware and software modifications implemented during LS2, a careful recommissioning and revalidation of the MPS was required. As a first step, all relevant commissioning procedures for the MPS were reviewed in the Machine Protection Panel (MPP) [6] and updated by the system experts. In total, 13 subsystems were covered, including the various interlock systems, collimation, injection protection and the beam dump system.

More than 700 commissioning tasks were then extracted from the updated procedures and incorporated into a new dedicated online machine-protection checklist. This centralised checklist approach allowed for an efficient tracking of the commissioning process and provided a transparent, easy-to-assess account of the commissioning status and documentation of the tests' outcome.

BEAM COMMISSIONING AND SCRUBBING

After the successful completion of the hardware and MPS commissioning, the beam commissioning period started. Low intensity probe bunches were injected on April 22, 2022, and successfully circulated in both LHC rings.

The following commissioning activities included, among others, the measurement and correction of the beam optics, the setup of the RF system, the transverse damper, and the beam instrumentation devices, as well as the alignment of the beam-intercepting devices, like collimators and injection and dump protection absorbers. The correct protection functionality of the latter was then validated with beam-based measurements, together with the validation of the machine aperture and the detailed verification of the proper functioning of the LHC Beam Dump System [1, Ch. 17].

To prepare the LHC for high-intensity physics operation, periods of so-called beam-induced scrubbing [7] were interleaved with the beam commissioning. During the scrubbing run, high-intensity beam at injection energy was employed

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to reduce the Secondary Electron Yield of the vacuum chambers and beam screens, thus diminishing the electron-cloud build-up process [8]. This way electron-cloud-driven instabilities were mitigated and the heat load for the cryogenic system was reduced.

INTENSITY RAMP-UP

After approximately 11 weeks of beam commissioning, the LHC intensity ramp-up started. On July 5, 2022, three nominal bunches in each of the two LHC rings were accelerated to an energy of 6.8 TeV and brought into collisions. It was the first time that the beam mode *Stable Beams*, which allows the detectors to be switched on and take physics data, was declared at the new record centre-of-mass collision energy of 13.6 TeV.

The general strategy for the intensity ramp-up, already successfully applied during Run 2 of the LHC (2015–2018), was based on the step-wise increase of the injected and the stored beam energy [9]. It aims to identify and mitigate issues in machine-protection-relevant systems that remain after the individual system tests and the hardware and beam commissioning with as low as possible stored beam energy. In addition, it allows the early identification of issues and limitations related to stored beam intensity and other beam-related parameters [9].

An overview of the intensity ramp-up in 2022 and the following high-intensity operation is shown in Fig. 1. During the ramp-up in 2022, intensity steps at 3/12, 75, 300, 600, 900, 1200, 1800, and 2400 bunches were used. The initially foreseen step to go to 2700 bunches was dropped because the maximum number of bunches in 2022 was restricted to around 2460 bunches due to electron-cloud limitations.

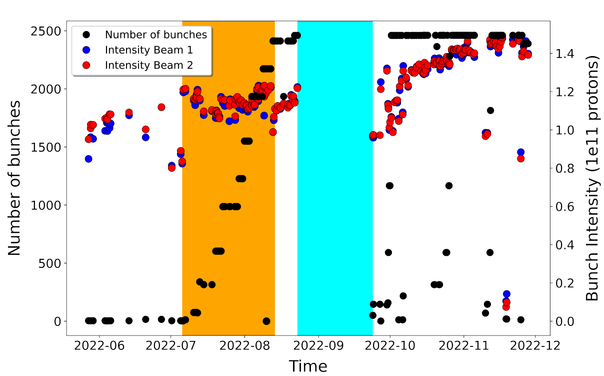

Figure 1: Number of bunches per beam (black) and bunch intensity at the beginning of *Stable Beams* (blue: Beam 1, red: Beam 2) during 2022. The intensity ramp-up period is highlighted in orange, and an unplanned stop caused by an incident at the RF cavities in cyan.

Intensity Checklists

For each step, the behaviour of the LHC was monitored during at least 3 fills and 20 hours in *Stable Beams* conditions. For each fill, the performance of the MPS was assessed by the different system experts. Besides this, the beam dump cause, the beam orbit changes before the dump event as well as the beam losses [10] before and during the dump were evaluated.

The readiness for the next intensity step was validated using a systematic and formalised check procedure based on a predefined checklist. The checklist included 100 check tasks for the following machine-protection-relevant systems: powering of the superconducting magnets, interlocks, RF, beam instrumentation, especially Beam Loss Monitors, collimation system, operation, orbit and feedback systems, beam dump system, injection system, and equipment heating.

At each intensity step, the checks were performed by the responsible system experts and the results filled into the checklist. Based on the checklist results, the restricted Machine Protection Panel [11] concluded on the readiness for advancing to the next step. The final checklist for each step, which included the corresponding fills and all observed issues during the period, was documented for reference.

Observations and Issues Encountered

Thanks to the diverse redundancy in the LHC Machine Protection System as well as the vigilant hardware and machine-protection experts and operation teams, no beam-induced damage occurred during the intensity ramp-up and the following high-intensity operation.

However, an important number of issues that degraded the protection functionality, or would have degraded it when left unnoticed, were identified and mitigated. At an early stage, unexpected high beam losses were noticed at one of the auxiliary injection protection collimators (TCLIA), requiring a re-positioning of the collimator jaw. Additional issues included a higher rate of erratic pre-firing of an injection kicker, as well as the sporadic missing of the beam-loss data in the Post Mortem System [12], which is required for the verification of the protection functionality after each beam dump. In addition, the protection thresholds of several Beam Loss Monitors had to be adapted at the intensity steps beyond 300 bunches to account for steady state losses during beam operation, which are difficult to predict in advance.

Bunch Intensity During the Ramp-up

As visible in Fig. 1, the bunch intensity during the ramp-up period was kept close to the nominal value of 1.15×10^{11} protons per bunch. After reaching the maximum number of bunches, it was gradually increased to around 1.4×10^{11} protons per bunch, profiting from the higher intensities available from the upgraded LHC injector chain [2]. During this period, beam-induced heating and the cryogenic load caused by electron-cloud effects [8] were carefully monitored. The achieved total intensity resulted in a new record stored energy of 400 MJ per beam, exceeding for the first time the LHC design value of 360 MJ.

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Ramp-up Duration

The first fill with more than 2400 bunches took place on August 13, 2022, less than six weeks after the first ramp-up fill with 3 nominal bunches. When excluding the time dedicated to other activities during this period, in particular to remaining commissioning activities and scrubbing, 1200 bunches were reached after about 18 days and the final step to more than 2400 bunches was reached after less than 30 days of intensity ramp-up.

This represents a very efficient performance considering that the LHC came out of a three-year long shutdown, which was marked by significant interventions on all major accelerator systems. For comparison, in 2015, the first year after Long Shutdown 1, almost 40 ramp-up days were needed to reach 1825 bunches, as shown in Fig. 2.

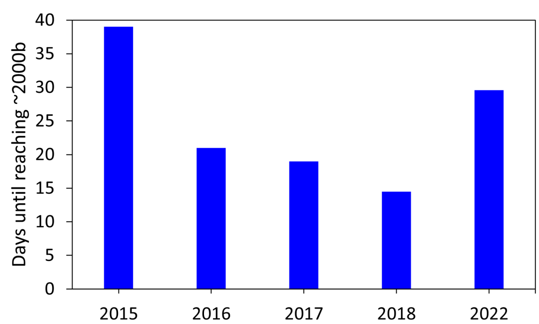

Figure 2: Comparison of the intensity ramp-up duration during LHC Run 2 (2015–2018) and in 2022.

Note that after the initial commissioning year 2015, the ramp-up duration during Run 2 decreased continuously until reaching approximately 15 days in 2018, demonstrating an increased maturity of the LHC and its main systems.

A breakdown of all performed ramp-up steps in 2022 is given in Fig. 3. It can be clearly seen, that the duration of the

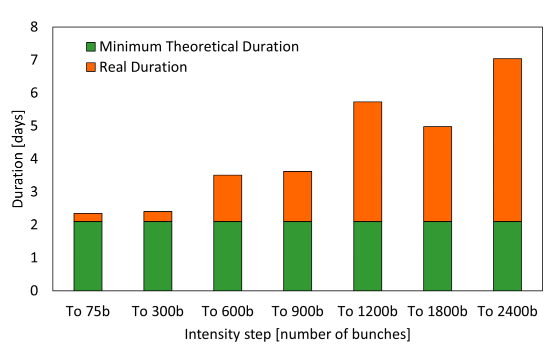

Figure 3: Duration of LHC intensity ramp-up 2022 per intensity step. The theoretical minimum achievable duration of 2.1 days per step is indicated in green.

seven steps differed considerably. The first two steps were completed in 2.4 days each. This is close to the theoretical minimum duration of 2.1 days, assuming a 60 % availability of the LHC, a 3 hours turn-around time between two fills in *Stable Beams*, and 10 hours to complete and validate the checklist after each step.

The following steps, in contrast, were marked by remaining commissioning activities and a high number of premature beam dumps caused by diverse faults. In addition, the interaction of the proton beam with dust particulates, called Unidentified Falling Objects (UFOs) [13, 14] at CERN, caused beam-loss events that triggered more than 20 protection dumps during the ramp-up period.

HIGH-INTENSITY OPERATION

After the successful ramp-up and after an unplanned stop between August 23 and September 19, 2022, due to an incident at the superconducting RF cavities, the operation of the LHC reached a remarkable stable phase. The number of faults decreased and the rate of UFO events dropped significantly. The fraction of time spent in *Stable Beams* increased from 31 % during the ramp-up period to 52 % during the operational periods in October and November 2022.

Similarly, the fraction of regular End-of-Fill beam dumps triggered by the operation crew almost doubled from 22 % during the ramp-up period to 40 % during the two last month of 2022 operation, indicating a reduced number of premature protection dumps due to an increased maturity of the accelerator system.

In 2022, the LHC delivered an integrated luminosity of more than 40 fb^{-1} to its two high-luminosity experiments ATLAS and CMS, which is a remarkable achievement for the first operational year after a Long Shutdown.

CONCLUSIONS

The restart of the LHC after its second Long Shutdown required the thorough and comprehensive recommissioning of the MPS, followed by the careful re-establishing of high-intensity beam operation. During 30 days of beam intensity ramp-up, the total stored beam intensity was increased following a systematic and well-established strategy. At each intensity step, the status of the MPS was evaluated through a pre-defined checklist. Centralising and formalising the check process reduced the risk to overlook a check task and provided a common holding point, where the state of all systems was evaluated simultaneously, allowing for an efficient decision taking on the readiness to advance to the next intensity step.

The successful intensity ramp-up paved the way to reach a total stored energy per beam of 400 MJ at the end of 2022, exceeding for the first time the LHC design value. This was achieved without observing any beam-induced damage, confirming the excellent performance of the LHC's MPS.

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