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SUMMARY OF THE POST-LONG SHUTDOWN 2 LHC HARDWARE COMMISSIONING CAMPAIGN

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Abstract

In this contribution we provide a summary of the LHC hardware commissioning campaign following the second CERN Long Shutdown (LS2), initially targeting the nominal LHC energy of 7 TeV. A summary of the test procedures and tools used for testing the LHC superconducting circuits is given, together with statistics on the successful test execution. The paper then focuses on the experience and observations during the main dipole training campaign, describing the encountered problems, the related analysis and mitigation measures, ultimately leading to the decision to reduce the energy target to 6.8 TeV. The re-commissioning of two powering sectors, following the identified problems, is discussed in detail. The paper concludes with an outlook to the future hardware commissioning campaigns, discussing the lessons learnt and possible strategies moving forward.

INTRODUCTION

The LHC underwent an extensive period of maintenance in 2019-2021, the so-called Long-Shutdown 2 (LS2), in preparation for its third beam run (Run 3) in the years 2022-2025. This extensive maintenance involved many systems, related to both the accelerator and the particle detectors.

In particular, for what concerns the LHC superconducting circuits, a significant effort was devoted to the Diode Insulation and Superconducting MAgnet Consolidation (DISMAC) project [1]. Several other interventions took place, including the replacement of 19 LHC dipoles, due to known quench heater failures or high internal splice resistances [2].

Once interventions on the accelerator were finalized, a full re-commissioning of the LHC superconducting circuits for operation at the desired current levels was necessary. The initial energy target for the commissioning campaign was set to 7 TeV, which was then reduced to 6.8 TeV, as explained in detail later in the paper.

POWERING TESTS: STRATEGY

In order to fully qualify the LHC superconducting circuits for safe operation, a well defined sequence of tests needs to be performed. The tests aim at verifying the correct behaviour of the circuits, including both the warm and cold parts, from the powering scheme to the related interlock and protection systems and the ancillary systems. The LHC counts a total of 1572 superconducting circuits, including low-current circuits (60 A, 80-120 A, 600 A) and high-current circuits, i.e. Inner Triplets (ITs), Individually Powered Quadrupoles and Dipoles (IPQs and IPDs), main Dipole and main Quadrupoles (RBs and RQs), with nominal currents ranging from 4 kA to 11.6 kA.

The LHC is divided in 8 powering sectors and 28 powering sub-sectors [3], which can be independently powered and tested. Circuits within a powering sub-sector should in general not be tested in parallel, as interaction between tests may affect the efficiency of the testing process.

The following steps describe the general strategy for the commissioning of the LHC superconducting circuits:

1. Electrical Quality Assurance (ElQA): verification of the electrical integrity of the superconducting circuits before powering [4]
2. Quench Protection System (QPS) tests: verification of the correct detection and reaction to possible magnet quenches before powering
3. Powering Interlock System (PIC) tests: verification with limited or no circuit current of the correct propagation of interlock signals to all the required clients
4. Tests with increasing current levels, defined depending on the circuit type
5. Circuit powering to nominal current (including magnet training, if necessary)
6. Simultaneous powering of all circuits in a powering sub-sector, for validation of their collective behaviour in view of nominal operation
7. Tests of the connections of the PIC with the Beam Interlock System (BIS)

Tests are executed from the CERN Control Center (CCC). They are launched via the Accelerator Test Tracking framework (AccTesting) [5] and executed by the hardware commissioning sequencer.

SCHEDULE EVOLUTION

Based on the testing strategy outlined above, a baseline duration for the tests in each of the eight LHC powering

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sectors of the LHC was established as follows: two weeks for ElQA activities [4], one week for QPS Individual System Tests, five weeks for powering tests and eight weeks for the training campaign of the RB circuits. The latter were allocated based on the worst case estimates derived from the previous LHC training campaigns, in particular the one at the end of 2016 [1]. As a result of the complex combination of activities related to all LHC systems during LS2, the powering tests in each sector were scheduled to start at different times in the year (from January to April 2021).

In order to face the discovery of non-conformities during the ElQA and powering test campaigns, the hardware commissioning schedule had to be rapidly adapted in the course of 2021 due to the following major events:

- Short circuit at the level of the lyra [6] of magnet C22.R8 (sector 81). This is a known failure mode that can appear due to contraction during the cool-down of a sector and for which the mitigation procedures are well known. Such a non-conformity requires a sector warm-up, an intervention for repair and a sector cool-down, for a total duration of 10.5 weeks. Foreseen end of the commissioning: July 2021.
- Short circuit at the level of the lyra of magnet Q8.L7 (sector 67). Same as above, the total duration was 11 weeks, although it was the first time that this failure mode was observed on a quadrupole magnet. Foreseen end of the commissioning: September 2021.
- Inter-turn short circuit in a coil of magnet B28.L8 (sector 78), appeared on 25th April 2021, following a training quench at 11585 A. The event required a full thermal cycle and a magnet replacement, for a total duration of 20 weeks. This is a known failure mode that was already observed in the LHC and during tests in SM18 [7]. Foreseen end of the commissioning: December 2021.
- Cold bypass diode short circuit on magnet A23.R2 (sector 23), appeared on 26th May 2021, following a secondary quench during the training campaign at about 8 kA. The cold bypass diode was damaged due to insufficient helium venting in the diode press-pack [8], caused by an assembly defect. This was a newly discovered event of a known failure mode, which required a full thermal cycle and the replacement of the diode press-pack, for a total duration of 18 weeks. Foreseen end of the commissioning: December 2021.

Following the occurrence of the last two events during the training campaign, a risk analysis for continuing training to currents required for 7 TeV operation was conducted. Based on the result of this study, the CERN management decided to limit the nominal current of the main dipoles to reduce the number of training quenches, resulting in a reduced energy reach of the LHC in Run3 to 6.8 TeV. All activities were re-organized in order to be able to meet the deadline of a first test with beam in the LHC in October 2021, to be carried out at injection energy. This required the circuits to be only commissioned to injection current. The beam test was very successful and allowed for a thorough preparation of the machine for beam operation in 2022. Nevertheless, abnormal beam losses were observed in sector 23. These were caused by a faulty RF finger in a so-called plug-in module [9]. As operation with such a non-conformity could lead to significant beam intensity limitations in Run3, it was decided to warm-up sector 23 for a second time in 2021 and allow for the repair of the faulty RF finger. This required a full recommissioning of the sector from the powering point of view, which was ultimately finalized on 14th April 2022.

POWERING TESTS: STATISTICS

A full powering test campaign comprises about 21000 tests, covering the 1572 LHC superconducting circuits. While a subset of tests for low-current circuits is analysed automatically by dedicated software tools, most tests on high-current circuits are manually analysed by magnet protection experts. If the outcome of a given test is positive, experts acknowledge the successful completion of the test with a digital signature, which is required to launch the next commissioning step from the AccTesting. This ensures a safe execution of the tests and a full traceability of the results for future reference and comparison. A test can fail in case of hardware failures, observed deviations from nominal test parameters or circuit quenches.

Following the adaptation of the schedule, the thermal cycle of sectors 78 and 23 (twice) and the tests performed after the Year-End technical stop, about 17000 tests had to be repeated. Considering all executed tests in the campaign (successful and failed), a total of 41165 tests was launched.

Fig. 1 shows the statistics on the test execution for the full 2021-2022 powering test campaign. The test distribution among different circuit types shows that most tests are performed on low-current circuits, due to their higher number as compared to high-current circuits. Nevertheless, tests on low-current circuits are typically shorter, with most of the testing time effectively spent for powering high-current circuits to nominal current.

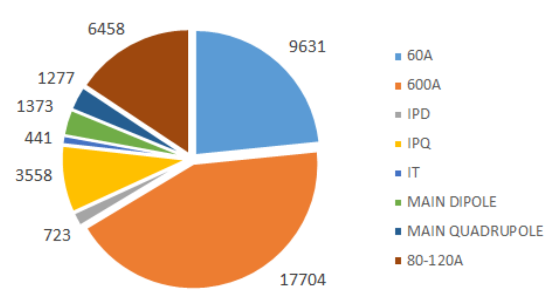

Figure 1: Number of LHC powering tests in 2021-2022.

TRAINING OF LHC MAIN DIPOLES

Most of the uncertainty for the duration of the LHC powering tests is associated to the difficulty of predicting the

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Table 1: Results from the 2021-2022 LHC Main Dipoles Training Campaign (*) Number of Quenches Experienced Following the Last Thermal Cycle

Sector	**12**	**23**	**34**	**45**	**56**	**67**	**78**	**81**
# Quenches	77	54*	70	87	76	62	22*	56
Max. E [TeV]	7	6.8	7	7	6.8	6.8	6.8	6.8

total number of circuit quenches that the dipole circuits will require in order to reach their target current. The target was initially set to 11950 A (accounting for 100 A of margin with respect to the current required to operate at 7 TeV - 11850 A). The margin increases reliability and limits the number of flat-top quenches that could be experienced during operation with beam. As previously discussed, the target was revised in September 2021 and reduced to 11600 A (6.8 TeV-equivalent current, including 100 A of margin).

A summary of the training performance of the eight LHC dipole circuits is reported in Table 1 and Fig. 2. Note that the table lists the number of circuit quenches (each RB circuit contains 154 dipole magnets). For each circuit quench, several individual magnets may quench due to helium propagation or by electro-magnetic coupling seen by the QPS. In the first case, quenches occur when the current in the circuit has already significantly decayed (e.g. to 8-9 kA). In the latter case instead, magnets quench within 1-2 seconds, i.e. secondary quenches occur at high current. This has a significant impact on the load on the cryogenic system and the quench recovery time. The distribution of quench recovery times as a function of the energy released during the quench can be seen in Fig. 3. Most of the quench recoveries took 6-8 hours, allowing to perform on average two training quenches per day and per sector. In order to reduce the number of high-current secondary quenches, it was decided to equip all sectors with a modified version of the quench detection system, using 200 mV quench detection thresholds (instead of 100 mV [10]), which still ensure full quench protection.

While the interpretation of the data collected during the training campaign is still ongoing, the following observations can already be made at this stage:

- The three main dipole circuits in sectors 12, 34, 45 reached the target current for 7 TeV. In all other sectors, the RB circuits were commissioned to 6.8 TeV-equivalent current.
- The chosen strategy of employing 200 mV quench detection thresholds allowed significantly reducing the number of high-current secondary quenches.
- A significant sector-by-sector variability in the quench behaviour can be observed.
- Compared to other magnet types in the LHC (e.g. IPQs), the LHC dipoles exhibit a very good quench performance, with most magnets never quenching before reaching the target current.

CONCLUSIONS

The 2021-2022 powering test campaign allowed fully qualifying all LHC superconducting circuits for operation at 6.8 TeV. The initial energy target of 7 TeV was revised in September 2021, following two major events that occurred during the training campaign of the LHC dipoles, which led to the a coil short circuit and a cold bypass diode short circuit. These two events had very significant implications on the schedule, which was redefined to accommodate the necessary sector warm-up, repair actions and cool-down. Despite the required changes, a first test with beam was successfully performed at injection energy in October 2021 (although revealing an aperture restriction and requiring an additional warm-up of sector 23). No further non-conformities for operation at 6.8 TeV were identified in the following powering tests.

A detailed analysis of the training campaign results is presently ongoing and will provide new insights and updated estimates for the number of quenches required to train the LHC dipoles to 7 TeV. This is an essential element for the risk assessment to define the strategy and energy reach of the LHC in the coming years.

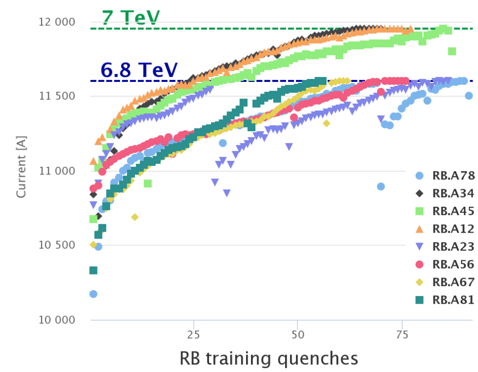

Figure 2: Training of the LHC main dipoles in 2021-2022, showing the number of circuit quenches occurred in each of the eight LHC sectors (sector 23: two additional thermal cycles; sector 78: one additional thermal cycle).

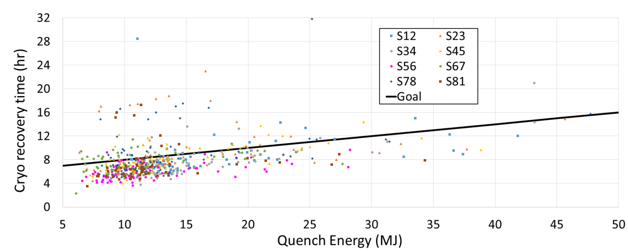

Figure 3: Quench recovery time as a function of the energy released in the cryogenic system during a quench event.

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