THE SECOND LHC LONG SHUTDOWN (LS2) FOR THE SUPERCONDUCTING MAGNETS

J. Ph. Tock†, M. Bednarek, L. Bottura, E. Karentzos[1], F. Meuter, S. Le Naour, M. Pojer,
C. Scheuerlein, E. Todesco, D. Tommasini, L. Van Den Boogaard, G. Willering,
CERN, Geneva, Switzerland
[1]also at the National Technical University of Athens, Greece

Abstract

The Large Hadron Collider (LHC) has been delivering data to the physics experiments since 2009. It first operated at a centre of mass energy of 7 TeV and 8 TeV up to the first long shutdown (LS1) in 2013-14. The 13 kA splices between the main LHC cryomagnets were consolidated during LS1. Then, it was possible to increase safely the centre of mass energy to 13 TeV. During the training campaigns, metallic debris caused short circuits in the dipole diode containers, leading to an unacceptable risk. Major interventions can only take place during multiyear shutdowns. To ensure safe operation at higher energies, hence requiring further magnets training, the electrical insulation of the 1232 dipole diodes bus-bars will be consolidated during the second LHC long shutdown (LS2) in 2019-20. The design of the reinforced electrical insulation of the dipole cold diodes and the associated project organisation are presented, including the validation tests, especially at cryogenics temperature. During LS2, maintenance interventions on the LHC cryomagnets will also be performed, following the plan based on a statistical analysis of the electrical faults. It is inscribed in the overall strategy to produce collisions at 14 TeV, the LHC design energy, and to push it further towards 15 TeV. We give a first guess on the impact on the LHC failure rate.

INTRODUCTION

The Large Hadron Collider (LHC) has been delivering data to the physics experiments since 2009. It has been operating at a reduced centre of mass (CoM) energy of 7 TeV and 8 TeV up to the first long shutdown (LS1) in 2013-14 [1]. The LS1 was the first multiyear shutdown allowing to consolidate the 13 kA splices between the main LHC superconducting magnets [2, 3]. It was then possible to increase safely the CoM energy to 13 TeV [4].

In addition to long shutdowns typically every 5/6 years, there are yearly short stops at the end of each year, the so-called (Extended) Year-End Technical Stops (E)YETS that are lasting a few months allowing only to carry out limited interventions. They are followed by a recommissioning of the 1572 LHC superconducting circuits.

At the end of 2016, two sectors, namely 34 and 45, representing, one quarter of the LHC, were pushed towards 7 TeV per beam, i.e. 14 TeV CoM with the aim to gather more information on the training behaviour at an energy higher than 6.5 TeV, i.e. 11.1 kA [5, 6]. The training in sector 45 was stopped after 24 quenches for time reasons at 11.54 kA, equivalent to a beam energy of 6.82 TeV. In sector 34, it was stopped after 8 quenches at 11.42 kA, i.e. 6.75 TeV, following the detection of a short circuit to ground [7]. The data acquired so far is compatible with the fact that the main dipoles have to be retrained after each warm-up and cool-down cycle [5, 6].

THE NEED FOR A CONSOLIDATION

Since 2006, nine short circuits to ground localised in the LHC dipole diode containers, visible in Fig. 1, already occurred. In the seven first cases, the LHC was at, or very close to, room temperature. They were solved by accessing the short circuit and removing the metal debris at the origin of the short to ground, shown in Fig. 2, with a slight impact on the schedule, a few days maximum, often in masked time. It allowed to identify the mechanism at the origin of these failures: metal debris, present in the cold masses since the manufacturing of the magnets in the years 2001-08, can be transported by large helium flows occurring during cool-down and warm-up phases and also in case of quenches, especially at high current, and eventually create short circuits.

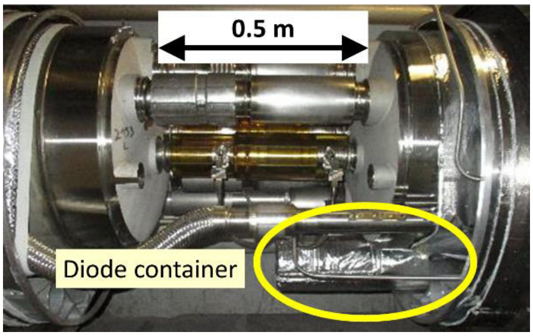

Figure 1: LHC interconnection.

The 8th case occurred after a high current quench at 11 kA; it had suspended the recommissioning to 6.5 TeV of sector 34 after the LS1 in March 2015. It was cured by discharging a capacitor bank, the so-called Earth Fault Burner (EFB), through the piece creating the short and vaporising it [7]. As the EFB is usable while keeping the machine cold, the impact on the schedule was limited to about a week. Otherwise, if the previous procedure had to be used, i.e. opening of the diode container and removal of the metal debris, this would have required to warm-up one 3 km-long LHC sector for the intervention that would have been followed by a cool-down and recommissioning (including possible retraining) period. This would have taken at least three months. The EFB method was also used to cure the 9th event that stopped the training in sector 34 at 11 415 kA as mentioned above.

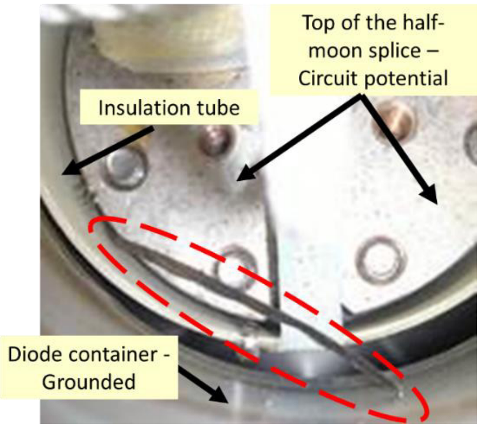

Figure 2: Bare half-moon splices and metal shaving creating an earth fault.

Despite the efficiency of the EFB, it is not risk-free even if mitigation measures are applied to avoid possible damages to the magnet chain components. Moreover, it is not a protection against double short circuits to ground that could generate major damages in the LHC machine – note that the stored energy in one of the eight main dipole circuits is about 1 GJ. Following a risk analysis of the potential problems caused by short circuits to ground, we have studied a method to remove the accessible debris and mainly to consolidate the electrical insulation of the bypass diodes bus-bars.

THE CONSOLIDATION

The consolidation consists in three main activities detailed below:

Half-Moon Splices Insulation Consolidation

The half-moon splice is a bolted connection between the main bus-bars and the LHC bypass diodes. Most of them are not completely insulated as shown in Fig. 2. This is not an issue during normal operation but an earth failure can occur when metal debris are transported by helium flows on this splice and are in contact with the grounded helium enclosure. We have designed and validated a consolidated insulation system shown in Fig. 3 that has mainly to:

- Be compatible with the existing configuration, especially the present insulation system,
- Preserve the half-moon splices electrical resistances that were validated by the so-called Copper Stabiliser Continuity Measurement [8], i.e. being as little invasive as possible,
- Withstand a voltage to ground in liquid helium of 3.1 kV with a sufficient margin. It will be tested at least up to 5 kV,
- Withstand a maximum pressure difference of 0.1 MPa and a hydrostatic pressure of up to 2.5 MPa,
- Have a minimal impact on the hydraulic impedance,
- Withstand a radiation dose of 0.3 MGy.

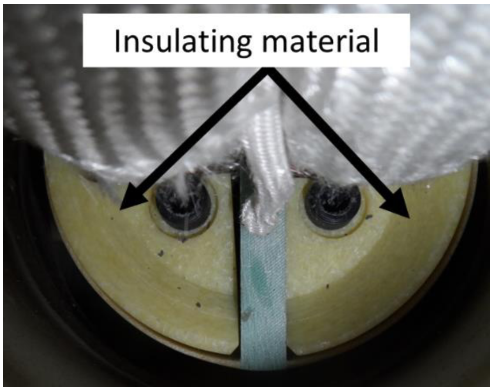

Figure 3: Half-moon splice equipped with the optimised consolidated electrical insulation.

The most delicate point is the development and optimisation of the installation procedures: the work has to be carried out about 1 200 times, in a very constrained location, in the interconnections [9, 10] as shown in Fig. 1.

Despite careful checks, the efficiency of the consolidated insulation cannot be tested and this makes the procedure even more critical; hence, a high level of quality assurance (QA) is implemented.

New Insulation Insert

Below the half-moon splices, parts of the bus-bars connecting the bypass diodes are not insulated as shown in Fig. 4. Even if no earth failure occurred at this location, we decided to add an insulation insert as this is a potential source of short circuit. The insert to be installed, shown in Fig. 5 has to meet the same requirements as the consolidated half-moon splice insulation given above.

Figure 4: Non-insulated bus-bars.

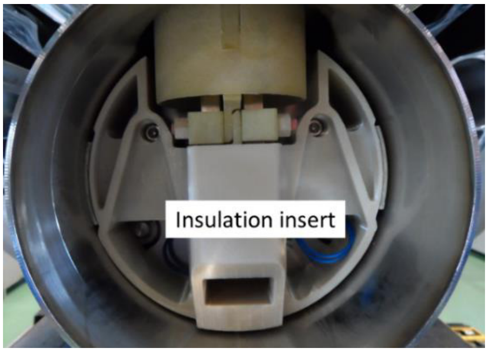

Figure 5: Insulation insert installed, covering the bare bus-bars and protecting the diode venting channel.

Removal of Debris

It is not possible to remove all debris present inside the cold masses that are about 15 m long. Nevertheless, as the helium enclosure will be opened to give access to reinforce the electrical insulation, all accessible debris will be removed using specifically developed tooling and a vacuum cleaner coupled with an endoscope and compatible with the radiological conditions encountered.

CRYOGENICS TESTS

In addition to components and assembly tests, we have carried out two main tests of the consolidated system at cryogenics temperature. In the first tests, the pressure and pressure difference over a consolidated diode insulation were measured following a quench in a spare main dipole up to ultimate current of 12.85 kA with 7 MJ deposited in the magnet in 0.4 s. The second test was performed in a special test setup using only the diode, the insulation and the diode container, measuring the pressure difference over the insulation piece during the 13 kA, 120 s time constant current decay in the diode, depositing 1 MJ in about 300 s. During all testing, the maximum pressure difference was 60 mbar, indicating that the hydraulic impedance added by the pieces is low. Visual inspection revealed no damage to the insulation following the cool-downs and tests.

OTHER INTERVENTIONS

As during LS1 [2-3], preventive and curative interventions will take place during LS2 on the LHC superconducting magnets. Twenty two cryomagnets with non-conformities will be replaced by spare magnets; few of them being repaired ones that were removed during LS1. Similarly to LS1, sixteen superconducting main magnets with inner splices resistance between poles or between apertures higher than the average values will be replaced, three other ones because of a redundant quench heater failure and the last three are affected by other non-conformities.

In the frame of the HL-LHC project, two Nb-Ti main dipoles of the LHC continuous cryostat, each of 14.3 m magnetic length and 8.3 T bore field, will be replaced by a pair of shorter magnets made of Nb_3Sn, i.e. the 11 T dipoles, forming a 15-m long 11 T Dipole Full Assembly when associated with a by-pass cryostat and a new collimator placed in between [11,12]. Two connection cryostats will be replaced by shorter ones and new collimators.

Five corrector circuits (sextupole, octupole) cannot be used due to permanent or intermittent faults to ground (the effect of these circuits have been compensated by other corrector circuits). No magnet exchange is planned to recover the complete integrity of these circuits, but, as they are composed of magnets powered in series, the faulty ones will be bypassed, minimising the impact of the faults.

Additional instrumentation will be installed to measure accurately the heat loads induced by the proton beams.

PROJECT ORGANISATION

The LS2 schedule was defined before the need for consolidating the diodes insulation was known. The LS2 will start end of 2018 for two years. To fit this intervention in the LS2 period, 10 dipole diode insulations have to be consolidated every working day.

Using heavily the experienced acquired during LS1, especially for the SMACC [Superconducting Magnet And Circuits Consolidation] project, a team of about 150 persons (CERN staff, collaborators and industrial support) is being built and organised in a CERN wide project: DISMAC [Diodes Insulation and Superconducting MAgnets Consolidation]. As this is a key, more than one third of the workforce is dedicated to QA activities.

NEXT STEPS

The consolidation described in this paper is a mandatory step before performing massive training campaigns necessary to increase the LHC energy and produce collisions at 14 TeV. This will take place after the LS2. The possibility to push it towards 15 TeV is also studied; especially estimating the number of quenches and the time necessary to reach this unprecedented level.

A first statistical analysis of the electrical faults in the LHC superconducting magnets and circuits was presented in 2017 [13]. Though preliminary, we are giving here a guess of the failure rate associated with the above risks that can be encountered during operation at 7.5 TeV per beam, assuming a scaling based on the increase of mechanical and electric stress of the type:

$$\mathrm{MTTF(7.5TeV)} = \mathrm{MTTF(6.5TeV)} / \mathrm{AF} \qquad (1)$$

where MTTF is the Mean Time To Failure and AF is the Acceleration Factor. To give orders of magnitude, we make the assumption that the MTTF will be dominated by electrical faults, and take a scaling for AF based on a power function of the ratio of maximum voltage at the present operation energy vs. the ultimate value. As the maximum voltage will be proportional to the energy, AF can be estimated as follows:

$$\mathrm{AF} = [7.5\ \mathrm{TeV} / 6.5\ \mathrm{TeV}]^{\alpha} \qquad (2)$$

where α is a power exponent that is customarily taken equal to 2 for electrical machines. The resulting AF is 1.33, and the MTTF is expected to decrease from the observed value of 1764 yrs (at 6.5 TeV) to 1324 yrs (at 7.5 TeV), i.e. an increase of 25 % in the expected number of failures.

CONCLUSIONS

The mandatory consolidation of the dipole diodes busbars insulation allowing to increase safely the LHC energy and produce collisions at more than 13 TeV has been presented. This will be carried out during LS2, together with the other maintenance interventions on the LHC superconducting magnets.

ACKNOWLEDGEMENT

The authors thank all the DISMAC project members for the detailed development of this consolidation.

REFERENCES

[1] F. Bordry, S. Baird, K. Foraz, A.L. Perrot, R Saban, J.Ph. Tock, "The First Long Shutdown (LS1) for the LHC", in *Proc. 4tht Int. Particle Accelerator Conf. (IPAC'13)*, Shangai, China, May 2013, paper MOZB202.

[2] J. Ph. Tock et al., "The Consolidation of the LHC Superconducting Magnets And Circuits: "Magnet Technology conference MT24, IEEE Trans. Appl. Supercond. 26 (2016) 4002706.

[3] J. Ph. Tock et al., "Consolidation of the LHC superconducting circuits: a major step towards 14 TeV collisions", IPAC'12, New Orleans, 2012, Proceedings of IPAC2012, New Orleans, Louisiana, USA, pp. 3575-3577.

[4] A. Verweij et al., "Retraining of the 1232 Main Dipole Magnets in the LHC" IEEE Trans. Appl. Supercond., vol. 26, no. 4, Jun. 2016.

[5] E. Todesco et al., "Training Behaviour of the Main Dipoles in the Large Hadron Collider", ASC2016, Denver, 2016, IEEE Trans. Appl. Supercond., vol. 27, Issue: 4, June 2017.

[6] E. Todesco et al. "Training of the Main Dipoles Magnets in the Large Hadron Collider towards 7 TeV Operation", IEEE Trans. Appl. Supercond., vol. 28, Issue: 3, April 2018.

[7] M. Bednarek et al., "Design, Assembly and Use of a Device to Eliminate Earth Faults Caused by Metallic Debris in the LHC Main Dipole Circuit", IEEE Trans. Appl. Supercond., vol. 28, Issue: 3, April 2018.

[8] S Rowan et al., "CSCM: Experimental and Simulation Results", 5th International Particle Accelerator Conference, Dresden, Germany, Jun 2014, pp. 3988.

[9] J. Ph. Tock et al, "The Interconnections of the LHC Cryomagnets", *in Proc. 2001 Particle Accelerator Conf. (PAC 2001), Chicago, pp 616-618.*

[10] J. Ph. Tock et al, "The Interconnections of the LHC Cryomagnets at CERN: Strategy Applied and Results of the Industrialization Process", *IEEE Trans. Appl. Supercond. 18(2), 116–120 (2008).*

[11] F. Savary et al., "Design and Construction of the Full-Length Prototype of the 11-T Dipole Magnet for the High Luminosity LHC Project at CERN", IEEE Trans. Appl. Supercond., vol. 28, Issue: 3, April 2018.

[12] A. Vande Craen et al., "The design of the new LHC connection cryostats", IOP Conf. Ser.: Mater. Sci. Eng. 278 012181.

[13] L. Bottura, J.Ph. Tock et al., "A Statistical Analysis of Electrical Faults in the LHC Superconducting Magnets and Circuits", IEEE Trans. Appl. Supercond., vol. 28, no. 3, Apr. 2018.