CONSOLIDATION OF THE LHC SUPERCONDUCTING CIRCUITS: A MAJOR STEP TOWARDS 14 TeV COLLISIONS

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Abstract

Following the incident in one of the main dipole circuits of the Large Hadron Collider (LHC) in September 2008, a detailed analysis of all magnet circuits has been performed by a dedicated task force. This analysis has revealed critical issues in the design of the 13 kA splices between the superconducting dipole and quadrupole magnets. These splices have to be consolidated before increasing the beam energy above 4 TeV and operating the LHC at 6.5-7 TeV per beam. The design of the consolidated 13 kA splices is complete and has been reviewed by an international committee of experts. Also, all other types of superconducting circuits have been thoroughly screened for potential safety issues and several important recommendations were established. They were critically assessed and the resulting actions are presented. In addition to the work on the 13 kA splices, other interventions will be performed during the first long shut-down of the LHC to consolidate globally all superconducting circuits. The associated quality control has been defined. Schedule constraints, repair production rate, available space and resources are presented as well.

INTRODUCTION

Following the incident in one of the main dipole magnet circuits of the Large Hadron Collider (LHC) in September 2008, a detailed analysis of all the magnet circuits has been performed by a dedicated task force [1]. A “Splices Task Force” was set up to review the status of all superconducting splices in the LHC machine and prepare the necessary consolidation actions [2]. This paper gives an update on the interventions planned during the first LHC long shutdown (LS1) in 2013-14 on the superconducting magnets and circuits. They are necessary to ensure that the LHC operating energy can be safely increased from the present 4 TeV per beam towards the nominal value of 7 TeV per beam.

MAIN 13 kA SPLICES

The assembly procedure of the 13 kA splices in the interconnections is extensively described elsewhere [2,3]. The electrical resistance of all splices was measured in superconducting state at 1.9 K operating temperature and an average resistance of 0.3 nΩ was found for all splices (i.e. 10 170 splices). Following an upgrade of the quench detection system, these values can now be monitored on-line for each current ramp. As of 2012, no degradation or significant change has been detected after more than two years of operation [4].

Another important parameter is the electrical resistance of the splice at room temperature (RT). To reach the adequate accuracy, only local invasive measurements are presently feasible. They require the warm-up of the accelerator and the opening of the interconnections up to the bus bar splices, quite a heavy operation.

Design of the Consolidated Splice

Reviewed by an international committee on two occasions, respectively in October 2010 and November 2011 [5], the specification of the consolidated splices [6] and the subsequent design were finalised. It essentially consists in adding a shunt across the splice interfaces and a new electrical insulation system, see Fig. 1, 2 and 3. The design has to be compatible with the existing splice environment with minimum impact and to meet requirements regarding electrical resistance, mechanical stress, radiation resistance and hydraulic impedance:

- The shunts applied to the present splices (without renewing them) have to ensure the electrical continuity of the copper stabiliser of the bus bars in all conditions.
- The electrical insulation system, in addition to providing sufficient dielectric strength between the circuits and to ground, also has to provide a mechanical restraint that limits stresses and deformations of the bus bars and splices due to Lorentz forces.

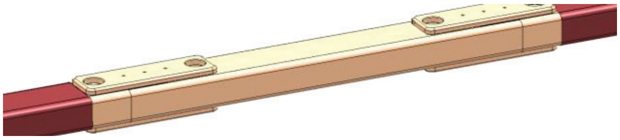

Figure 1: Design of the consolidated dipole magnets bus splice showing in total four electrical shunts.

In the dipole magnet bus splices, top and bottom pairs of shunts are installed, providing a twofold redundancy. In the quadrupole magnets bus splices, the presence of the superconducting busbars powering the spool pieces renders a similar operation more complex, risky and time consuming.

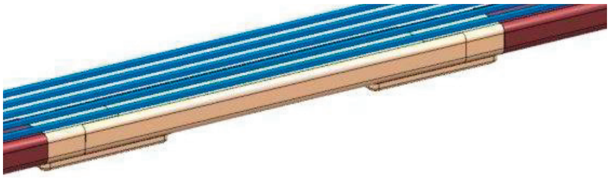

Figure 2: Design of the consolidated quadrupole magnets bus splice showing two electrical shunts and spool pieces bus bars.

Considering that the margin on the quadrupole circuit is higher and will even be increased by a reduction of the dump time constant from the present 37 s to less than 20 s, and also the fact that the energy stored in the main

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quadrupole magnets circuit is about 50 times less than in the dipole magnets one, the installation of a single pair of shunts on these splices has been considered sufficient.

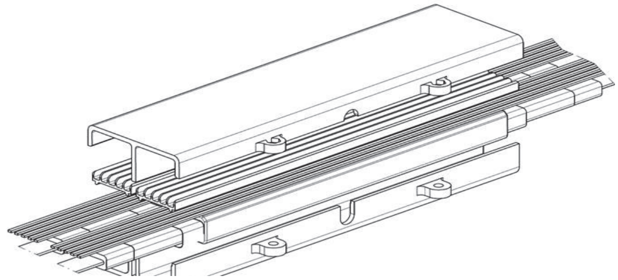

Figure 3: The new electrical insulation and mechanical support box enclosing two parallel bus line splices.

Quality Control

The quality controls are applied both to existing and consolidated splices. The new shunts and the new insulation boxes will be installed on all 13 kA bus bar splices. In addition, it is expected that about 15 % of the splices have to be completely opened and done again. The decision to redo a splice completely will be based on the following four criteria:

1. Excess of electrical resistance at 1.9 K of the junction between the superconducting cables higher than 0.8 nΩ and 2.0 nΩ for the dipole and quadrupole circuits respectively (This concerns about 1 % of the total 13 kA splices),
2. Excess of resistance of the copper stabiliser junctions higher than 5.0 µΩ at room temperature,
3. Poor geometry, locally preventing the installation of the shunts and/or the new electrical insulation boxes in optimum conditions,
4. Evident visual defects or obvious lack of mechanical strength.

Redoing a splice is a risky operation since it implies delicate work on the already soldered Rutherford superconducting cables. Moreover, it requires extra-time and resources. It will be done only if strictly necessary.

Quality checks based on detailed procedures shall be performed thoroughly and are interleaved within the production steps. They are of utmost importance because the final validation by a powering test of the 13 kA circuits to the nominal current can only be performed very late in the schedule, which excludes the possibility of corrective actions within a reasonable time.

OTHER SUPERCONDUCTING CIRCUITS

All superconducting circuits were screened by a team of experts. The higher risks concern mainly the 13 kA splices; hence the consolidation of such splices in the electrical feedboxes [7] is mandatory as they are part of the same electrical circuit.

Other weaknesses were identified in correction coils and stand alone magnets circuits with lower current ratings and lower stored energy. This first LHC long shutdown is a possibility for a massive consolidation on these circuits as well but on the other hand, the risks generated, the eventual reliability improvement, the repair time and resources involved have to be assessed carefully for a well balanced decision.

REPLACEMENT OF MAGNETS

In addition to the splices consolidation, LS1 is the opportunity to resolve non-conformities and, especially the ones that could be a limitation for an operation at 7 TeV per beam. In total, 19 main superconducting magnets: 15 dipoles and 4 Short Straight Sections (SSS) will be replaced.

Nine superconducting magnets will be replaced because they show a high inner splice resistance that could, in the worst case, be a sign of a potential mechanical weakness not acceptable for a long duration operation at 7 TeV per beam. Five more will be replaced for electrical weaknesses. For example, some quench heaters circuits have a weak electrical insulation. These circuits are presently condemned. This solution is viable at the present energy but is not acceptable at 7 TeV. The LHC is currently operating with a few non-nominal correction circuits; the replacement of three SSSs is necessary to restore their nominal performance. Two dipoles have to be replaced for a non-conformity on the beam screens orientation.

OTHER INTERVENTIONS

LS1 will last about two years during which there will be no physics data acquisition in the LHC experiments. It is so an opportunity also to solve known issues or to improve some subsystems in parallel with the main activities described here above:

- Improvement of reliability of some helium level gauges;
- Reinforcement of the electrical insulation in specific locations;
- Repair of present vacuum and helium leaks, even if they are acceptable for operation today;
- Fixing various other minor non-conformities.

This list is not exhaustive and unfortunately may become longer if new issues arise during the present LHC operation at 4 TeV in 2012 or discovered during the consolidation works. In fact, this constitutes a smaller volume of work but is much more difficult to plan as the scope of work cannot be defined in details yet and it will be necessary to react on the spot. These works require another dedicated team with very experienced and polyvalent staff.

SCHEDULE AND ORGANISATION

After stopping the physics run at the end of 2012, but prior to warming-up and opening the system, the following activities will take place:

- Specific powering tests on certain circuits;
- Electrical Quality Assurance checks (including electrical insulation);
- Leak tests.

The aim of the tests is first to identify other weaknesses or limitations that have to be solved during LS1 and then to help in the localisation of known non-conformities.

After warming-up and venting to atmospheric pressure, the first interconnection will be opened in January 2013 and the last one will be reclosed 14 months later.

To keep this ambitious schedule corresponding to an intervention rate of 53 interconnections per week for critical activities (twice the rate achieved during the initial assembly of the LHC), about 220 trained technicians and engineers are necessary, organised in three main intervention teams as illustrated in Fig. 4:

1. A production team of 128 persons, divided in sub-teams, covering both main splices consolidation and special interventions;
2. A Quality Assurance team of 81 persons, divided in sub-teams, covering all the production activities
3. A project support office of 11 persons, taking care of ad-hoc engineering support, safety, general coordination and logistics.

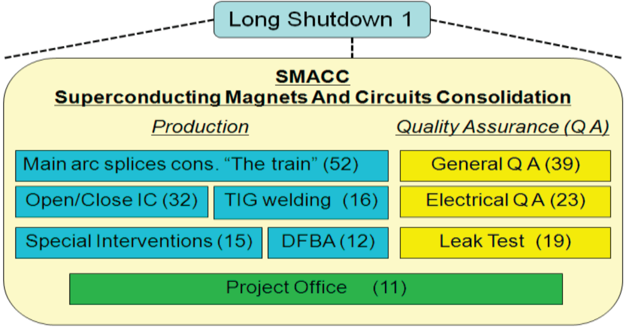

Figure 4: Simplified organisation chart.

The work will be carried out in the LHC tunnel, about 100 m underground and the worksite will extend over more than 13 km in the 27 km tunnel, making supervision and coordination a challenge.

Only one third of the staff involved has presently relevant experience to carry out the work. It implies that the other two thirds have to receive a proper training in the course of 2012. Also, in case of rotation, re-training will be needed in parallel with the work in the LHC. This ratio is considered critical and constrains the acceptable workload, risk level and the duration of the LS1.

OTHER ACCELERATORS

So far, such an extensive and extreme consolidation programme within a relatively short period was never carried out on a superconducting accelerator. For example, HERA at DESY-Hamburg experienced only a few smaller issues on the superconducting magnets: a few short circuits in cold diodes and one damaged splice. In the case of RHIC, there were several interventions that have required the opening of the vacuum vessel in the interconnection regions to allow interventions inside. In both cases, the amount of work was considerably less than what is planned for the so-called SMACC (Superconducting Magnet And Circuits Consolidation) project for this first long LHC shutdown in 2013-14. Consequently, application of lessons learnt from large scale interventions in other accelerators is rather limited; the relevant experience used in the SMACC preparation phase (budget and schedule) was the initial installation of the LHC itself [8] and the repair work carried out on 600 m of the machine after the September 08 incident [9].

CONCLUSIONS

The consolidation of the splices in the various electrical circuits of the LHC superconducting magnets and circuits was finally reviewed by an international committee of experts in November 2011. The final design of the consolidated 13 kA bus bar splices meets all requirements and recommendations of the review and is now being implemented for production.

The consolidation of the 13 kA splices, the replacement of 19 superconducting magnets and the special interventions are the main priorities of LS1. This work will require 14 months and a combined effort of about 220 persons. The planned production rate of 53 interconnections per week is very ambitious, with a minimal contingency in resources and time.

ACKNOWLEDGMENT

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