Status of the Consolidation of the LHC Superconducting Magnets and Circuits

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Abstract. The first LHC long shutdown (LS1) started in February 2013. It was triggered by the need to consolidate the 13 kA splices between the superconducting magnets to allow the LHC to reach safely its design energy of 14 TeV center of mass. The final design of the consolidated splices is recalled. 1695 interconnections containing 10 170 splices have to be opened. In addition to the work on the 13 kA splices, the other interventions performed during the first long shut-down on all the superconducting circuits are described. All this work has been structured in a project, gathering about 280 persons. The opening of the interconnections started in April 2013 and consolidation works are planned to be completed by August 2014. This paper describes first the preparation phase with the building of the teams and the detailed planning of the operation. Then, it gives feedback from the worksite, namely lessons learnt and adaptations that were implemented, both from the technical and organizational points of view. Finally, perspectives for the completion of this consolidation campaign are given.

1. Introduction

The LHC started regular operations in 2009 at an energy of 3.5 TeV per beam. With the experience acquired over two years of operation, the energy was increased to 4 TeV at the beginning of 2012. These beam energies were chosen on the basis of careful analysis of the machine safety following the incident in 2008 that occurred in the main dipole circuit of sector 3-4 [1]. Its origin is basically hih resistance in the superconducting circuits that initiated a quench associated with a poor connection of the copper stabilizer that should have carried the current during the current decay. The goal of the first long shutdown (LS1) of the LHC is to consolidate the 13 kA splices of the main superconducting circuits to allow safe and reliable operation of the LHC up to its design energy of 14 TeV center of mass. The CERN's plan and consolidation actions were successfully reviewed by an international committee of experts. It is also an opportunity to carry out repairs, maintenance and consolidation in the whole accelerators complex [2]. The LS1 started on 16th February 2013 with powering tests aiming to identify other possible limitations of the superconducting magnet circuits that could be repaired during LS1. About 540 circuits were tested in 10 days, with a total of 1300 powering cycles; only a few minor issues, which neither jeopardize the LS1 schedule nor the capability of LHC to operate at the design energy, were discovered.

Before and after warming-up (figure 1) of the LHC from 1.9 K to room temperature, electrical quality assurance tests were carried out to check the integrity of the superconducting circuits. They revealed a few weaknesses and defects that will be corrected during LS1. Leak tests were also carried out at different temperature levels to identify, measure and localise existing air and helium leaks prior to the consolidation interventions. Operation had coped with all of these leaks, but LS1 provides an opportunity to understand their origins and eliminate them. So far, 14 of the 20 known helium-to-insulation vacuum leaks have been localized to the component level.

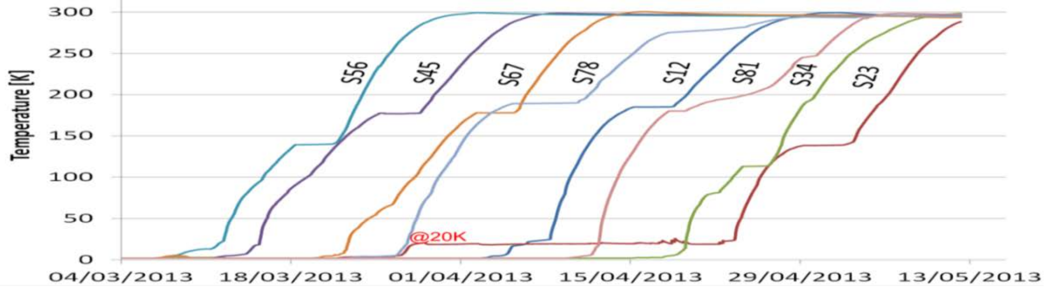

Figure 1. Warm-up of the 8 LHC sectors over 10 weeks

2. Consolidation of the 13 kA main splices

2.1. Design of the consolidated splices

The consolidation of the 13 kA splices [3] consists mainly of:

- Soldering a shunt on the existing splices to ensure the electrical continuity of the copper stabiliser of the busbars in all conditions as shown in figure 2. Tin/lead alloy is used for soldering to avoid unsoldering the underlying splices that were carried out with tin/silver-
- Installing an improved electrical insulation system that, in addition to providing dielectric strength, is also a mechanical restraint that limits stresses and deformations of the busbars and splices under the Lorentz forces as shown in figure 3.

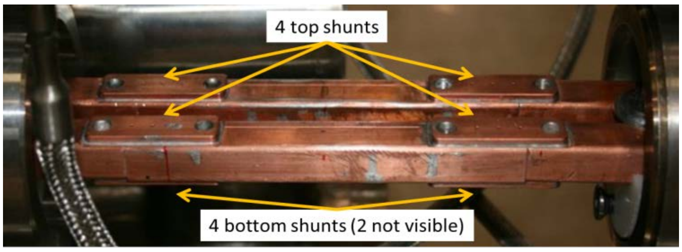

Figure 2. Shunts installed on the 13 kA splices.

Figure 3. Electrical insulation system

Strict quality controls (electrical and geometrical) are applied to existing splices. The on-going verification of more than 40 % of the 10 000 existing splices shows that about 30 % of splices have to be redone. This proportion, based on the repairs and measurements carried out in 2009, had been estimated at about 15 % [3]. This increase is mainly due to the need for appropriate geometry to allow installation of the shunts in optimum conditions. No compromise is made on the quality: the defined criteria in terms of resistance of the copper stabilizer and of geometry are not relaxed. To cope with the resulting extra work, the team has been reinforced with extra technicians, now trained and fully operational. Extra tooling and components were also procured.

2.2. Sequence of operations

Although the delicate operations on the splices are at the heart of the superconducting circuits consolidation, they occupy only about 15 % of the entire project team of 280 persons. Most of the resources are used to provide access to the splices and then reclosure after the consolidation interventions: each envelope of the interconnections (insulation vacuum external bellows, thermal shielding, superfluid helium enclosure, electrical insulation system) have to be opened and finally reclosed. A simplified sequence is shown in figure 4. These operations, together with other specific interventions, are part of the Superconducting Magnets And Circuits Consolidation (SMACC) project.

The external bellows and thermal shields of the first interconnection were opened on the 8th of April 2013 and about 75 % were open by the end of August 2013. This task is entrusted to two teams of collaborators from the National Technical University of Athens (Greece) and from the Wroclaw University of Technology (Poland).

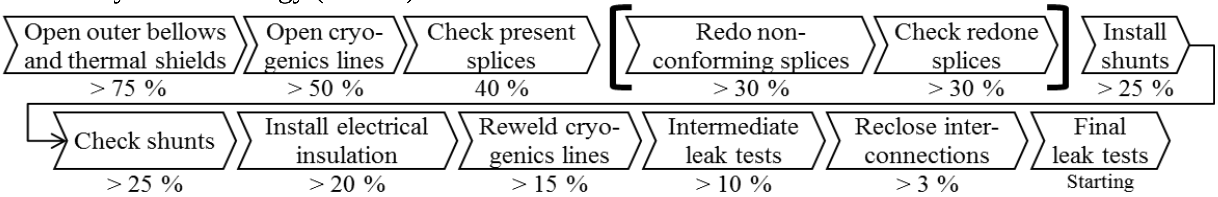

Figure 4. Simplified workflow and status updated on 9.09.2013.

Opening of the cryogenics lines enclosing the busbars gives access to the splices. During LS1, 5 000 welded stainless steel sleeves will be cut using orbital cutting machines designed and produced at CERN. This operation is particularly important because the quality of the orbital TIG weld used for re-closing the lines strongly depends on the geometry. This task is carried out by a team of collaborators from the National Center for Physics (Pakistan Atomic Energy Commission) [NCP(PAEC)].

After removal of the electrical insulation, the quality of the existing splices, mainly electrical and geometrical, is systematically checked. So far, about 30 % of the splices are not meeting the criteria and must be completely remade as shown in table 1.

Table 1. Preliminary results of existing splices quality control (9.09.2013).

Sector	Sector 56	Sector 67	Sector 78	Sector 81	LHC
Measured [%]	100	100	100	25	40
To redo [%]	28	32	29	31	30

Splices not satisfying the acceptance criteria are first de-soldered. The superconducting cables are then carefully inspected to identify all defects that could jeopardize the quality of the future splices. The splices are then re-soldered with improved procedures and induction soldering machines.

The installation of the shunt is the main activity: more than 27 000 shunts have to be installed. To meet the schedule, 20 shunts should be installed every working hour. The shunts are soldered across the splices with resistive ovens after preparing the interface by a careful milling operation. This surface quality and the integrity of the splice are validated by mechanical and electrical checks.

The next step is the installation of the electrical insulation systems: 5 000 units have to be assembled and validated by the QC team during LS1. Most of the QC steps are carried out by a team of engineers and technicians normally in charge of the operation of the CERN accelerators. They have been trained on mock-ups and are overseen by system experts for deeper analysis and handling of problematic cases.

The previously cut sleeves are re-welded. This task is carried out by a team constituted of collaborators from NCP(PAEC) and of experienced CERN welders (staff and industrial support). Rigorous quality assurance is also applied to this activity: pre-qualification of the welding procedures, equipment and personnel associated with recording of the actual welding parameters, visual endoscopic inspection by certified inspectors and local leak tests. Specific tooling was developed to allow testing of 2 welds simultaneously. On the first 2 000 welds, 2 leaks were discovered. Careful off-line analysis localised them in the vicinity of the welding area but not in the welds themselves.

After verification that all non-conformities have been closed, the interconnections are finally reclosed. At the end of August, 45 interconnections have been reclosed. This is according to the baseline schedule defined in March 2013. The opportunity is also taken to improve the thermal screens design [4]. The last operation, the final leak testing of the insulation vacuum, has just started.

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3. Other consolidations of the superconducting magnets and circuits

Eighteen main superconducting magnets with different non-conformities will be replaced during LS1: 8 presenting a high internal resistance that could be the sign of a lack of mechanical strength, 5 being affected by minor electric integrity issues and 5 for other reasons. They have all been disconnected and replaced by spare ones. This operation is part of the mandate of the Special Intervention Team, composed of polyvalent and experienced technicians who also intervene on major non-conformities.

Following the incident of 19th of September 2008 [1], pressure relief devices were installed on the LHC cryostats. Their aim is to limit the extent of damages should the helium enclosure be punctured. At that time, for schedule reasons, only part of the machine was equipped. During LS1, 612 new pressure relief devices will be installed, bringing the total to 1344 units.

Sixteen electrical feed boxes power the main LHC superconducting circuits. As the 135 main circuit splices in the electrical feedboxes need to fulfill the same functionality as the ones between the magnets, they will be consolidated to the same standards [5].

4. Quality Assurance (QA)

The quality of the work has priority over schedule. To achieve the necessary high level of quality, about one third of the project team is assigned to QA tasks. Meetings are held several times a week to systematically review arising non-conformities, to agree on the action plan, to decide on the updates of the procedures and hence rapidly deal with open issues. An independent QA manager is nominated, reporting directly to the LS1 coordinator.

5. Conclusions

Starting new activities as early as possible to allow time to debug them has proven to be a profitable strategy. The CERN priorities are strictly followed: safety, quality, schedule, budget. Only one minor accident related to the work in the LHC tunnel occurred. The motivation of all the participants and the control of the routine risk are the present focus of the management team.

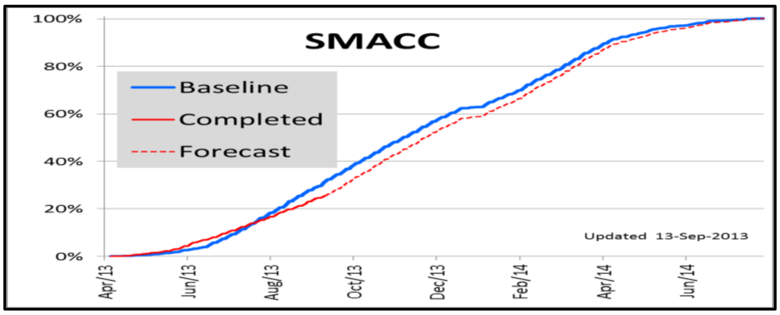

Figure 5. .SMACC main progress dashboard

Thanks to a good preparation, the end date of the SMACC project is still summer 2014, according to the baseline. Regular updates are available at: http://lhcdashboard.web.cern.ch/lhcdashboard/ls1/

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