TOWARDS A CONSOLIDATION OF LHC SUPERCONDUCTING SPLICES FOR 7 TeV OPERATION

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Abstract

Following the analysis of the September 2008 LHC incident, the assembly process and the quality assurance of the main 13 kA interconnection splices were improved, with new measurement and diagnostics methods introduced. During the 2008-2009 shutdown ~5% of these 10 000 splices were newly assembled with these improvements implemented, but essentially maintaining the original design.

It is known today that a limiting factor towards 7 TeV operation is the normal conducting resistance of ~15% of the original main 13 kA interconnection splices, associated to the electrical continuity of the copper stabiliser. A "Splices Task Force" has been set up at CERN to evaluate the need for, develop and test design improvements and prepare the implementation of a consolidation campaign. Important issues of splice design, process choice, resources and time requirements are considered.

INTRODUCTION

The analysis of the September 19, 2008 incident at the Large Hadron Collider (LHC) identified consolidation actions on many systems to improve safety and reliability [1, 2]. Many of these were implemented during the 2008-2009 shutdown ending with the successful restart of operation on November 20, 2009 limited to 3.5 TeV beam energy. Particular attention was clearly devoted to the superconducting splices, and specifically to the main 13 kA interconnection (IC) splices between magnets.

MAIN INTERCONNECTION SPLICES

The main IC splices are assembled by inductive soldering using lead free Sn96Ag4 alloy and non-activated rosin liquid flux Kester 135. This connects both the superconducting Rutherford cables with an overlapping joint and the stabilizing copper of the busbars. The assembly and the quality assurance of the process were improved for the 2008-2009 shutdown when ~5% of these 10 000 splices were redone [3]: gamma radiography was successfully introduced to visualise the internal volume of the splice and room temperature (RT) electrical resistance measurements to quantify the copper continuity (referred to as "R16" from the resistance of 16 cm length across the splice). These measurements are referred to as "invasive", since they require direct access to individual splices.

"Non-invasive" diagnostics were also performed: these are electrical resistance measurements performed from externally accessible magnet voltage taps, covering a segment of busbar length in series with interconnecting splices. These were performed at RT, 80 K, 25 K and 1.9 K [4] to measure both in normal conducting (NC) and superconducting (SC) states.

The main IC splice resistance in the SC state is typically 0.3 nΩ - average value of all splices measured using the new Quench Protection System - with only a few cases found as high as 2 nΩ: these cases will be further investigated for their mechanical strength, but are acceptable for cryogenics and machine protection.

The main IC splice resistance in the NC state is more difficult to determine with precision. Invasive measurements were made in the five sectors that were warmed up on ~230 splices: typical R16 values are 12 μΩ for dipole splices and 19 μΩ for quadrupole splices, but higher resistances were measured with an additional "excess" at RT up to ~60 μΩ. Physically this higher resistance is related to the combination within the same cross-section of gaps in the stabilizer copper continuity together with lack of contact between the SC cable and its copper stabilizer over a distance of a few centimetres. Unfortunately this second factor was not appreciated, either by analysis or diagnostics, at the installation phase.

Non-invasive measurements were made more extensively, but are less precise as they include the strong contribution from the RRR of the copper busbars: this affects in particular the three sectors that were maintained cold during the 2008-2009 shutdown. While all known splices with extreme resistance were repaired using the improved procedures, it was recognized that a full intervention requires significant time and further preparation and it was preferred to initially limit the operating energy to 3.5 TeV [4].

The further consolidation actions required for 7 TeV operation are being studied by a multi-disciplinary Splices Task Force set up in November 2009 with the mandate to review all superconducting splices of the machine: experience from collaborating Institutes and other SC machines is extremely valuable.

SPLICE CONSOLIDATION FOR 7 TeV

An important issue is whether all main IC splices will require consolidation. Based on the analysis of the R16 measurements, it was estimated that ~15% of the 10 000 splices in the machine will present an excess RT resistance of at least 10 μΩ, the typical limit for 7 TeV operation, and would therefore require consolidation. For 5 TeV operation, the equivalent figures are an excess of 40 μΩ and ~2% that require consolidation.

Unfortunately the currently available non-invasive diagnostics can at best localise resistive segments (containing typically 2 or 3 splices for dipoles, 8 for quadrupoles) but not specific individual resistive splices. Moreover, busbars included in the quadrupole segments have a large dispersion of resistances, larger than the IC splice values one is attempting to identify for 7 TeV. The only known solution is to cut open the sleeves for all the segment splices to allow a local invasive measurement.

In addition it was experienced that a consistent number of splices presented acceptably low R16 resistance values, but were repaired for considerations (e.g. gaps and misalignments) found during visual inspection.

The conclusion for 7 TeV operation is that it will be required to open all interconnects in order to access the splices to perform invasive, local resistance measurements. It is foreseen that ~15-20% of the splices will be improved by desoldering and resoldering according to the improved procedures. In addition it is foreseen to systematically add shunts and mechanical clamps to increase the overall long-term safety margin. The baseline strategy for a consolidation shutdown is based on this scenario.

An intermediate lighter consolidation for 5 TeV operation would require improvements in the precision of non-invasive diagnostics and interventions with partial warm-up of the concerned segments: while in principle possible, this is not the baseline.

CONSOLIDATED SPLICE DESIGN

The current design for consolidating the main IC splice is shown in Fig. 1.

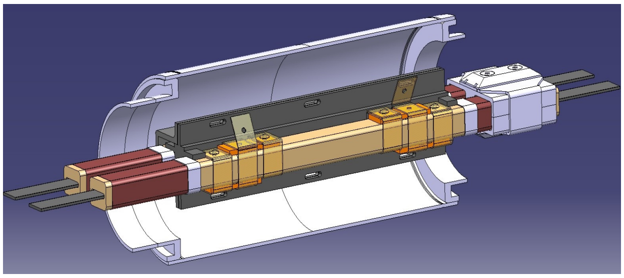

Figure 1: Main IC splice, consolidated design, showing additional shunts, clamps and insulation.

The design mechanical loads for this structure are specified at RT as 550 N longitudinally (from the stiffness of the lyra) and at 1.9 K as 1 100 Nm^{-1} transversally (from electromagnetic forces), with 20 000 powering cycles and 100 thermal cycles over 20 years' lifetime.

Additional copper shunts are soldered across the two end joints of the splice. These are dimensioned to carry the full 13 kA during the current extraction time $\tau\sim100$ s, requiring a shunt cross-section of 15 mm x 3 mm, a maximum unsoldered length of 10 mm and a minimum RRR of 200. Ideally the shunt would have a flexible geometry (with braid or lamellar construction) in order to adapt to existing geometrical imperfections and to maintain a stress-free solder interface. This is proving difficult in practice due to the short length, and may be replaced by a fully annealed plate. As a principle it is intended to avoid machining within the interconnection volume that is a potential source of dust, pollution and damage to the SC cable. A second parallel shunt is envisaged for redundancy on the opposite face of the joint.

The solder retained for the shunt is the near eutectic 60Sn40Pb: this has a significantly lower melting temperature than Sn96Ag4, which allows the shunt to be joined by soldering without affecting the existing connections. First tensile tests at 80 K show ultimate tensile force above 7 kN. Fatigue tests in tension are being conducted at 80 K to exclude the possibility of solder degradation, which to our knowledge has not been reported in similar applications. Alternative alloys will also be considered at a later development stage.

First prototype tests to validate the proof of principle at 1.9 K have been performed successfully [5], see Fig. 2, with further tests ongoing. The thermal runaway current of 7 to 10 kA is increased to 15 kA, well above operating conditions.

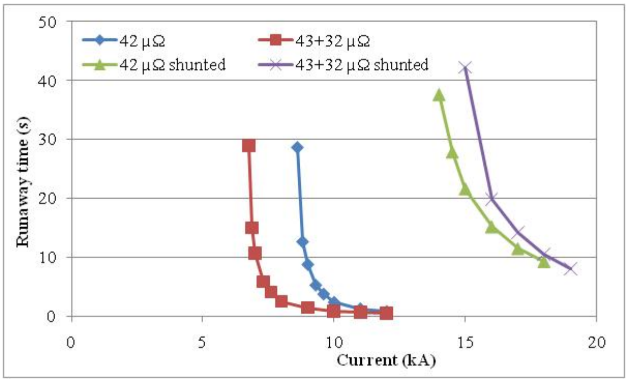

Figure 2: Proof of Principle test results.

Additional mechanical clamps are included. Their function is to maintain the splice together - transversally and longitudinally - in the event of a solder meltdown for at least the $\tau\sim100$ s time taken for a full current extraction. It is currently foreseen to stud-weld a stainless steel screw, and apply stainless steel bands with a Belleville washer ensuring sufficient compression at 1.9 K.

The splice insulation is provided by a structure that also restrains transversal deformation (typically ~0.1 mm). It is intended for this structure to be produced by injection moulding and be easy to assemble in-situ. The base candidate material is glass fibre reinforced Ryton (PPS), which is documented to have acceptable cryogenic and radiation-resistant properties. For redundancy a second, independent insulating layer is also included.

The overall increase in hydraulic impedance of the IC splice and insulation is within the acceptable limits of the cryogenic system.

During operation it is foreseen to include the automatic monitoring in the SC state of the segments resistance, and to perform regular measurements in the NC state at 25 K or 80 K.

Development work is progressing to select the soldering process between three potential candidates:

cartridge-oven heating, induction and fast resistive heating, where the effect of rapid heating on solder quality is being studied. An important point is the limited available space, and specifically that the main IC quadrupole splices are located close to the existing spool busbar splices which should not be disconnected or damaged, see Fig. 3.

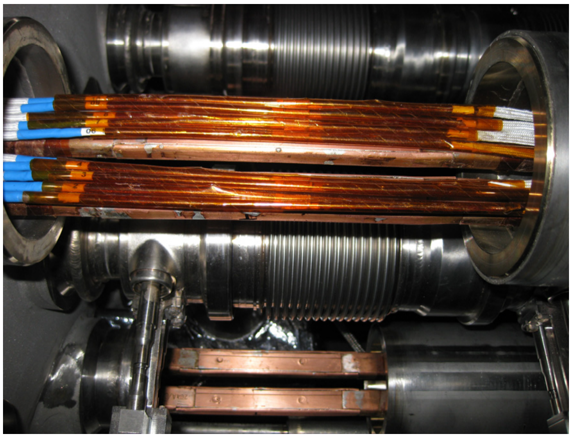

Figure 3: Environment of main IC splice, showing spool splices over the main quadrupole splices.

Quality Control techniques are being studied in collaboration with specialised Institutes. In consideration of the large number of shunts (~40 000), a simple, but quantifiable method is required. Potential candidates include electrical resistance, ultrasonics, thermal imagery and go-no go traction tests.

A final validation test of the complete solution is being prepared for Summer 2010. It consists of two MQM quadrupole magnets whose traversing busbars will be connected in series to a cold test station using the consolidated splice design on a purposely built defect to simulate the closest conditions to LHC.

SHUTDOWN SCENARIO

The splice consolidation intervention requires a chain of activities of different nature: assembly, machining, soldering, electrical insulation, quality control, electrical testing, welding, leak testing. It is planned to perform this work with a team of ~120 technicians, 50% already present at CERN and 50% to be integrated, possibly within Collaboration Agreements to be set up. On the basis of past experience it is planned to perform work at an average rate of ~50 IC activities per week, and dimension capacity for ~70 IC activities per week. Work is planned over 2 shifts per day, but not for the same activity. Each activity will progress from one sector to the adjacent one, with the overall chain extending over three adjacent sectors. In these conditions it is planned for 14 weeks to complete consolidation of the first sector, then 5 further weeks for each additional sector. It is currently planned to consolidate the 8 LHC sectors for 7 TeV in 49 weeks during the 2011-2012 shutdown. It could be possible to consolidate a single sector in an earlier shutdown depending on the motivation for testing before full implementation and the availability of the machine.

Maintenance interventions are also required on other magnet systems: these will use the same technologies and resources, hence imply a few additional months.

ANALYSIS OF OTHER SC SPLICES

The SC magnet system at LHC includes ~10^5 splices, both internal to equipment and as interconnections, in circuits with different current ratings and inductive energies. Aside from the consolidation of the main IC splices, the Task Force is also reviewing other splices aiming at an integrated approach across full circuits.

The 6 kA circuits for the individually powered quadrupoles and dipoles include splices with "praying hands" configuration, known to have failed in Tevatron and Hera. While the design was extensively analysed as acceptable, further actions are being undertaken: a laboratory fatigue test at 4.2 K, additional inspections, completion of the protection system and resistance mapping.

The integrated approach will allow performing an overall risk analysis and investigating alternative failure mechanisms, their potential consequences and possible mitigation actions.

CONCLUSIONS

The baseline design for the consolidation of the main IC splices for 7 TeV operation is being defined, and development work is proceeding for final validation by Summer 2010. Implementation issues being studied include choice of process, Quality Control, integration with other activities and necessary resources. The LHC intervention is planned for the shutdown 2011-2012.

REFERENCES

[1] P. Lebrun et al., "Report of the Task Force on the Incident of 19 September 2008 at the LHC", CERN LHC Project Report 1168, March 31, 2009.

[2] L. Rossi, "Superconductivity: its role, its success and its setbacks in the Large Hadron Collider of CERN", Superconductor Science and Technology 23 (2010).

[3] C. Scheuerlein et al., "Production and Quality Assurance of Main Busbar Splices during the LHC 2009 Shutdown", Applied Superconductivity Conference, ASC, Washington, USA, August 1-6, 2010 (to be presented).

[4] M. Koratzinos et al., "High-current Bus Splice Resistances and Implications for the Operating Energy of the LHC", First International Particle Accelerator Conference, IPAC10, Kyoto, Japan, 23-28 May 2010.

[5] G. Willering et al., "Thermal Runaways in LHC Interconnections: Experiments", Applied Superconductivity Conference, ASC, Washington, USA, August 1-6, 2010 (to be presented).