An Improved Insulation System for the LHC Main 13 kA Interconnection Splices

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In 2013, a long shutdown of the Large Hadron Collider (LHC) at CERN will allow comprehensive maintenance plus consolidation of the machine components, in particular of the 13 kA circuits that feed the main superconducting magnets around the 27-km ring. This shutdown will prepare the accelerator for operation at nominal energy, 14 TeV, with adequate margin on the critical performance parameters. An essential part of the consolidation program consists of adding to the 13 kA splices of the magnet interconnects a copper shunt of high RRR (> 300) that will carry the current in the event of a busbar quench. An important R&D program was conducted in 2010 to design a sound solution for the shunt and for an improved insulation system. The development of the insulation system has required iterations aiming at adequate solution. The functional requirements for the insulation are a breakdown voltage of at least 3.1 kV in superfluid helium and sufficient mechanical strength to withstand stresses of the order of 50 MPa. The insulation system shall provide mechanical restraint for the shunted splices so that their transversal deflection is limited to 0.25 mm. This paper describes the final design of the insulation and the optimization process. The results from dielectric tests and numerical optimization of the insulation cover will be also presented. Finally the performance of the new insulation will be compared to the previous version.

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An Improved Insulation System for the LHC Main 13 kA Interconnection Splices

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Abstract—In 2013, a long shutdown of the Large Hadron Collider (LHC) at CERN will allow comprehensive maintenance plus consolidation of the machine components, in particular of the 13 kA circuits that feed the main superconducting magnets around the 27-km ring. This shutdown will prepare the accelerator for operation at nominal energy, 14 TeV, with adequate margin on the critical performance parameters. An essential part of the consolidation program consists of adding to the 13 kA splices of the magnet interconnects a copper shunt of high RRR (> 300) that will carry the current in the event of a busbar quench. An important R&D program was conducted in 2010 to design a sound solution for the shunt and for an improved insulation system. The development of the insulation system has required iterations aiming at adequate solution. The functional requirements for the insulation are a breakdown voltage of at least 3.1 kV in superfluid helium and sufficient mechanical strength to withstand stresses of the order of 50 MPa. The insulation system shall provide mechanical restraint for the shunted splices so that their transversal deflection is limited to 0.25 mm. This paper describes the final design of the insulation and the optimization process. The results from dielectric tests and numerical optimization of the insulation cover will be also presented. Finally the performance of the new insulation will be compared to the previous version.

Index Terms— LHC Interconnection, Dielectric insulation, Dielectric breakdown, Electromagnetic forces

I. INTRODUCTION

In 2013-14 a long shutdown of LHC [1] will be performed for consolidation of the main 13 kA interconnection splices and the related surrounding dielectric insulation. This intervention will allow safe increase towards the nominal LHC operational energy of 7 TeV per beam (14 TeV at the centre of mass). The critical aspects when developing an insulation system for the LHC high current superconductive accelerator magnet interconnections are not only given by the knowledge of electrical, mechanical, metallurgical and chemical aspects. The design phase also has to take account of the assembly aspects required to achieve the entire tunnel intervention within the foreseen time schedule of 16 months. Several design iterations were performed during the past three years to successively improve the design of the consolidated splice. This development work was based on four key tasks which were successively iterated according to the design status and the results obtained. The main steps of the development work were as follows:

- Definition of a functional specification;

- Writing of procedures for each consolidation step;
- Execution of mock-up and validation tests;
- Final design acceptance and further installation training based on mock-ups.

II. GENERAL CONSOLIDATION APPROACH

The main goal of the intervention is to ensure the copper to copper continuity across the joints by soldering shunts (Fig. 1) in parallel to the existing copper junctions [6].

Fig. 1. The shunt copper piece to be applied over the 13 kA splices

In 2010, tests were performed on spare quadrupole cold masses (Q8-Q9). They have demonstrated the single shunt capability to bear 14 kA continuous current through an 8 mm unsoldered gap between the interconnected busbar (Fig. 2). This is equivalent to a dissipated energy of 50 μ W over a time window larger than 1 s without thermal runaway [8].

Fig. 2. Test setup in 2010 with an 8 mm unsoldered gap

Quality control criteria concerning the splice resistance and the connection geometry will be applied to determine whether a splice has to be consolidated or completely re-soldered before application of the shunt [2]-[5]. The estimated amount of superconducting splices to be redone is about 15% while the shunts will be applied on all interconnections.

The work plan to apply the copper shunt across the busbar stabilizer consists of:

- The machining of the stabilizer copper surfaces to obtain planar surfaces. This should provide a suitable contact

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surface roughness for the shunt solder, and remove the oxidation layers.

- Soldering of the copper shunt to the machined stabilizer surfaces using proper qualified flux. The selected solder material is based on a Sn60Pb40 alloy with a melting temperature of 190°C. The soldering material which is used for the interconnection of the superconductive Nb-Ti cable is the Sn96Ag4 with a melting temperature of 221°C. The 13 kA dipole busbars will be equipped with redundant shunts on the top and bottom surface and on both sides of the splice interconnection. Two shunts will be soldered simultaneously. The dipole circuit (RB) is therefore equipped with four shunts per busbar interconnect. The spool busbars placed on the top of the quadrupole circuits (RQ) are limiting the space for the soldering operations. Due to the inherent difficulties and associated risks and because of larger margin in the operation, it has been decided to solder only two shunts to the bottom surface of the quadrupole splices.

III. INSULATION DESIGN CRITERIA

The standard insulation along the busbar is made out of polyimide layers with a 50% overlap. These tapes are wrapped in opposing orientation and surrounded by a layer of cured fiberglass epoxy tape. Additional elements are needed to insulate the regions of busbar interconnections. The original LHC design requirements regarding the breakdown voltage under maximum operation conditions are 3.1 kV for the dipole and 0.9 kV for the quadrupole circuit under helium gas atmosphere and under a pressure of 1 bar [7]. The redesign of the insulation system has to provide equivalent or higher arc resistance than the presently installed solution. Apart from the dielectric insulation, the implemented solution must meet the following requirements:

- The insulation system shall contain the Lorentz forces induced by the busbar current flow of 13 kA. The two busbars are separated by a distance of 12 mm. The longitudinal busbars supports are separated by a distance of up to 600 mm. The repulsive forces of about 750 N at maximum current are inducing a bending stress on the interconnect region. The number of load cycles on the shunts, estimated to be 20,000 during the entire machine life cycle, lead to fatigue of the solder interconnection [13]. The requirement is therefore to compensate the occurring bending stresses with the surrounding insulation system. Careful selection of materials is required not to induce bending stress at 1.9 K and 13 kA due to difference in thermal contraction and large change in mechanical characteristics.
- The assembly work should not induce additional stresses to the interconnection region.
- The design has to show same performance under the expected geometrical variations of the two parallel busbars. The required clearances between the insulation object and the busbar are ± 3 mm in horizontal and ± 5 mm in the vertical plane. These large geometrical variations are due to the busbar shape and assembly tolerances of the cold masses as well as the relative cold masses alignment in the tunnel. This estimation of geometrical imperfections and resulting

mechanical tolerances has been specified together with the expertise of technicians who took part to the previous installation and repair phases.

- The chosen material has to sustain a radiation dose of 1 MGy (using a safety factor of 10 respecting the worst computed case along an LHC arc) integrated over 20 years. Furthermore, the material should not fail due to fatigue after 20,000 current cycles.
- Due to the tight schedule and the amount of interconnections, the ease of installation is a key requirement for the final insulation system.
- All tooling required for the assembly of the insulation system should fit the limited space inside the LHC tunnel area.
- The dimension of the insulation shall minimize the helium pressure drop in the busbar lines as a continuous helium flow is preferable. Furthermore, the chosen material should not fail due to the operation under cryogenic temperature.
- In order to increase the robustness of the shunt implementation with respect to any relevant solder material degradation or incident scenario, it was decided that the shunt should be kept mechanically in place [5, 6].

IV. THE FINAL DESIGN OF THE INSULATION SYSTEM

In order to fulfil the design requirement for keeping the shunt in place mechanically, additional clamping parts were required in the previous design version [6, 9]. In new design iteration this function was implemented without need for additional pieces. This final design consists of two complementary translucent profiles made from PolyEtherImide (PEI) which was qualified to fulfil the stringent material characteristics in terms of mechanical, thermal and radiation requirements. This final design is presented in Fig. 3. The insulation consists of an inner layer of pre-folded polyimide foil.

Fig. 3. Final solution of the interconnection insulation based on the example of the quadrupole interconnection lines which includes the insulation of the spool cables via the comb piece.

In addition, an injection bag surrounding the top, bottom and transverse plane of the busbar is attached to the interconnection area. After installation of the insulation covers, this bag made from polyimide and equipped with an injection valve is filled with a two component room temperature curing epoxy resin. After a curing time of 24 hours, homogeneous form closure between the inner insulation surface and the busbar is achieved over the entire length of interconnection. Due to the translucent design of the insulation cover, a visual quality control during the injection process

allows the detection of related defects or areas insufficiently filled with the epoxy resin. Fig. 4 presents the integration of the insulation assembly in between the two spider support points. These supports are centring the interconnection inside the cryogenic tube and are allowing the thermal contraction during cooling to 1.9 K.

Fig. 4. Final solution of the interconnection insulation based on the example of the dipole interconnection showing the off-centric positioning of the insulation in between the two supporting spiders.

The cross section of the insulation for the dipole RB and RQ circuit are presented in Fig. 5.

Fig. 5. Left: Insulation of the RQ interconnection including the spool cables insulation based on a comb profile. Right: Insulation of the RB interconnection.

The iterative design process was performed based on 3D finite element analysis in order to minimize stresses induced during nominal operation conditions. As the interconnect region is located off-centred in between the two spider supports (see Fig. 4) the stress induced in the insulation cover is asymmetric and induces higher stresses on one extremity of the insulation cover. Fig. 6 presents the equivalent von Mises stress distribution on the insulation cover.

Fig. 6. Equivalent stress (von Mises) induced in the insulation cover at maximum current (13 kA and 1.9 K).

After verification of the mechanical properties of the PEI, the encountered stress levels show that there is a safety factor of

18 before failing due to flexural stress [10]. Available fatigue data for room temperature is demonstrating, that with the existing stress amplitude at nominal current the insulation system would withstand at least 10^7 cycles to failure [11]. The insulation system described in the subsequent order according to the assembly procedure:

Each busbar interconnection is surrounded by pre-folded polyimide foil. Its length is covering the insulated busbar extremities towards the closest support point (Spider).

Two complementary PEI profiles are covering the busbar creating the insulation along the busbar connection. This system will also compensate the magnetic forces. One of the main advantages of this approach is given by the possibility of inserting the insulation covers inside the cryogenic tubes (M-line) obliquely positioned which allows insulating closer to the supporting spiders. The length of the insulation covers is only limited by the angle of insertion and the position of the spider support. Two screws are used to assemble the insulation cover. The design is such that a clearance of 2 mm is remaining on all surfaces between the busbar and the insulation covers. This remaining space is filled with two component curing epoxy resin on the upper, lower and external faces. One assembly requirement is given by a fast disassembly of all involved parts during inspection or replacement interventions. This requirement is especially due to the increasing radiation dose during the machine life cycle. Therefore, it is necessary to avoid the resin to stick to the busbar profiles. In addition, the filling operation has to be repetitive. Therefore, it is proposed to use a C shape sealed pocket into which the epoxy resin is injected. This filling process was tested in several mock-up tests and was found to be fast with repeatable quality. The dielectric discharge tests to ground showed that the insulation performance of this second design proposal is between 6 and 10.3 kV and therefore higher than the one achieved by previous proposals. A drawback is given by the quasi adiabatic assembly which should however not degrade the interconnect performance during the entire life cycle.

The electrical breakdown tests were performed with a quadrupole insulation setup where the interconnection was symmetrically localized in between the two supporting spiders. This allows a global overview regarding the insulation of the different circuits and represents a worst case as in this configuration the main busbars was closer to the surrounding sleeves and the spider legs. Fig. 7 is provides the ranges of breakdown voltages measured at the described setup. The chart is categorized by the different electrical circuits and towards their close environments (represented by another circuit or ground). The dashed lines are representing the average values calculated among all the test results. The orange range bars without dashed lines are showing results for which the insulation setup of the non-interconnected spool extremities failed before the insulation of the interconnection. The values indicated in the graph are specification requirements within the organizational aspects and safety rules for successful electrical qualification of superconducting circuits [12]. As presented in the graph one can see that all specified safety margins are far below the measured values

observed during the measurements of the final insulation design.

Fig. 7. Results of the breakdown voltage tests in comparison to the indicated specified values.

V. THE FINAL VALIDATION OF THE DESIGN

The final insulation design was tested and validated on the same setup as the previous proposal in 2010 [8]. For the setup preparation all related procedures for the shut-down intervention were applied. In order to apply worst case conditions all the tests were performed at 4.3 K. Under this thermal condition quench cycles were performed up to 15 times per interconnection. In addition the specified 20,000 current cycles from 2 kA to 14 kA and one thermal cycle were performed. The quality control [4]-[5] after the test campaign has shown that this extensive test has not shown any measurable increase of the resistance of the shunted interconnections resistance. In addition no degradation or sign of fatigue was observed on the insulation hardware. The results clearly indicate that with these experimental conditions the shunted interconnections and the related insulation are not showing any degradation. Fig. 8 is showing the prepared setup before the final validation test.

Fig. 8. Left: The insulation of the RB interconnection in preparation of the final validation tests.

VI. CONCLUSION

The specification for the new LHC splice interconnection was described and the final solution for the insulation system presented. It is based on the assembly of two complementary covers. An injection bag located on the inner surface of these covers and filled with epoxy adhesive resin allows compensating the geometrical tolerances (misalignment and assembly) along the interconnection region. This paper shows

that all specified requirements were achieved successfully. This was demonstrated based on various mock-ups and during a final validation test on a real magnet to magnet interconnection. Electrical breakdown measurements were performed to improve consequently the arc resistance in between the busbars and their close environment. The achieved final performance was demonstrated to be at least 2.5 times higher than the specified values. Concerning the final validation all tests were performed above the specified conditions applied during the entire LHC life cycle. The applied quench and current cycles have not shown induced degradation to the resistance of the interconnection. An important further milestone before the shut-down 2013 will now be given by the training of personnel. This milestone will be achieved based on full scale mock-ups inside a representative tunnel environment.

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REFERENCES

- [1] The Large Hadron Collider; A Marvel of Technology, L. Evans, Ed., Lausanne/Boca Raton, FL: EPFL/CRC Press, 2009.
- [2] L. Belova, M. Genet, J.-L. Perinet-Marquet, P. Ivanov, and C. Urpin, "Design and manufacture of the superconducting bus-bars for the LHC main magnets," *IEEE Trans. Appl. Superconductivity*, vol. 12, no. 1, pp. 1305–1309, 2002.
- [3] A. Jacquemod, A. Poncet, F. Schauf, B. Skoczen, and J. P. Tock, Inductive soldering of the junctions of the main superconducting bus bars of the LHC CERN-LHC-Project-Report-698, 2004.
- [4] F. Bertinelli, *et al.*, "Production and quality assurance of main busbar interconnection splices during the LHC 2008–2009 shutdown," *IEEE Trans. Appl. Superconductivity*, 21 issue 3, pp. 1786 – 1790.
- [5] F. Bertinelli, *et al.*, "Towards a consolidation of LHC superconducting Splices for 7 TeV Operation," CERN/ATS 2010-144.
- [6] P. Fessia, "Splice Consolidation: What we will do: status of main technical solutions," LHC Performance Workshop - Chamonix 2010.
- [7] F. Rodriguez-Mateos, "Voltage withstands levels for electrical insulation tests on components and busbar cross sections for the different LHC machine circuits," *CERN Engineering Specification*, EDMS Nr. 90327.
- [8] G. Willering, "Electro-thermal and mechanical validation experiment on the LHC main busbar splice consolidation," *CERN Technical note*, EDMS Nr. 1160067.
- [9] F. Lackner, MT22, "Development of a New Insulation Approach for the LHC Main 13 kA Interconnection Splices," *IEEE Trans. Appl. Superconductivity*, vol. 22, no. 3.
- [10] A. Gerardin, "Mechanical Testing of Candidate Materials for the Splices Insulation -3-" *CERN Quality test*, EDMS Nr. 1209952.
- [11] Laurence W. McKeen, "Fatigue and Tribological Properties of Plastics and Elastomers, 2nd Edition" Butterworth-Heinemann 2009, ISBN 0080964508 pp. 153 – 160.
- [12] R. Mompo, N. Catalan-Lasheras, G. D'Angelo, M. Bednarek, J. Ludwin, "Qualification of the superconducting circuits during hardware commissioning" *CERN test procedure*, EDMS Nr. 788197.
- [13] P. Fessia, "Specification for the consolidation of the LHC 13 kA interconnections in the continuous cryostat" *CERN Technical report*, EDMS Nr. 1171853.