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**Development of a New Insulation Approach
for the LHC Main 13 kA Interconnection Splices**

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Abstract

In the long LHC (Large Hadron Collider) shutdown in 2013 it is foreseen to intervene on all the 13 kA interconnections in order to guarantee the necessary margin and redundancy to provide safe LHC operation at 7 TeV per beam. This implies reinforcement of the present interconnection configuration including a new insulation scheme of the busbars. The purpose of the new insulation model is to provide dielectric insulation with at least the same performance as its predecessor currently installed in the LHC machine, but in addition to contain the Lorentz forces. This paper describes the analytic and empirical approach of development to reach a new insulation concept based on state of the art materials and manufacturing techniques.

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

I. INTRODUCTION

The 2013-14 long shutdown of LHC includes consolidation of the present main 13 kA interconnection splices as well as the surrounding dielectric insulation to be performed in order to safely increase the operational energy to 7 TeV per beam (14 TeV center of mass). The required tooling and procedures were successively revised and improved in order to satisfy the stringent expected physical performance. Furthermore the entire consolidation work will have to be completed within an LHC shut down schedule of 16 months. This period does not only comprise the consolidation work itself but also an extensive quality control and works on the experiments and technical services [1].

This paper provides a summary on the overall approach of preparation for the foreseen 13 kA splice consolidation with the aim to focus on the electrical insulation aspects. The requirements for the busbar insulation are presented and furthermore two proposals concerning its design are introduced.

II. GENERAL CONSOLIDATION APPROACH

The main goal of the intervention is to reinforce the copper to copper continuity in the joints by soldering shunts (Fig. 1) in parallel to the existing junctions [2]. Tests driven on spare

quadrupole cold masses (Q8-Q9) demonstrate the single shunt capability to bear 14 kA continuous current through an 8 mm unsoldered gap between the interconnected busbar. This is equivalent to a 50 μ W over a time window larger than 1s without thermal runaway.

Criteria concerning the splice resistance and the connection geometry will be applied first to determine whether a splice has to be consolidated or completely redone [3]. It was estimated that about 15 % of all splices will have to be redone.

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

- Machining of the stabilizer copper surfaces to obtain planar surface. This should provide a suitable contact surface for the shunt solder and remove the oxide layer.
- Soldering of the copper shunt to the machined stabilizer surfaces using proper qualified flux. The selected solder material is based on a Sn60Pb40 alloy using a controlled temperature of 190 °C. This temperature is below the melting temperature of the Sn96Ag4 soldering material which is used for the interconnection of the superconductive NbTi wire.

Fig. 1. The shunts copper piece to be applied over the 13 kA connections

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 (see Fig. 2). Two shunts will be soldered simultaneously. The dipole circuit (RB) is therefore equipped with four shunts per busbar interconnect. The spool pieces 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 REDESIGN

The standard busbar insulation is made out of polyimide layers with a 50% overlap. These foils are wrapped in opposing orientation and surrounded by a layer of cured fiberglass epoxy tape. Additional elements are needed to insulate the region of busbar interconnection. The original

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design requirement is 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 [4]. The redesign of the insulation concept should provide equivalent or better arc resistance than the one presently installed. Apart from the dielectric insulation, the implemented solution must meet the following list of requirements:

- The insulation concept 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 repulsive forces are inducing a bending stress on the interconnect region. The estimated load cycles of 2000 during the entire machine life cycle lead to fatigue of the solder interconnection. The challenge is to preload the interconnect region during the installation minimizing the induced normal stress. After cooling the system to 1.9 K and applying a current of 13 kA the induced normal stress should not exceed the stress applied by the preloading system.
- The concept should show the same performance under the expected geometrical variations. The required clearances on an insulation object are ± 3 mm in horizontal and ± 5 mm in the vertical plane. These large geometrical variations are due to the busbar shape and alignment tolerances of the cold masses as well as the relative cold mass alignment in the tunnel. They have been integrated with the expertise of technicians who took part to the previous installation and repair phases.
- The chosen material has to sustain the radiation dose of 1 MGy (using a safety factor of 10 respecting the worst computed case along an LHC arc) integrated over 20 years.
- Due to the time schedule and the amount of interconnections the ease of installation is a stringent requirement for the new insulation concept. In this context it is important to mention the space limitations of the environment.
- The dimension of the insulation shall minimize the helium pressure drop in the busbar lines as a continuous helium flow is preferable.
- In order to increase the safety relevant aspects of the shunt implementation with respect to any relevant solder material degradation or incident scenario it was decided to implement an additional mechanical clamp to the soldered shunts.
- Provide, if possible, a better cooling with respect to the previous interconnect solution. Better cooling would provide larger margin vs. thermal runaway.

IV. INSULATION CONCEPTS

Two different approaches have been taken into consideration in order to block this variable geometry:

1. Providing an insulation shell clamped with controlled force
2. Providing an insulation shell and injecting a resin into the inner volume. This would provide a form fit between the insulation system and the busbar respecting the interconnection misalignment and geometrical imperfection.

A. Insulation clamped with controlled force

The first concept relies on the force control in order to put the busbar in a mechanically defined state of stress and strain. This system has the advantage of supplying space around the

busbar and is therefore providing the possibility to increase the busbar cooling. This can be optimized by providing the maximum possible direct contact between the busbar and the helium bath. This insulation assembly is based on the following steps:

• Insulation of the shunts and busbar extremities

Four identical subassemblies are surrounding the shunts and the busbars extremities. A polyimide insulation layer is wrapped around the subassemblies up to the closest support point (so called spider).

The four subassemblies (Fig. 2) are based on high density polyethylene profiles. They are inserted from the sides, fitting and providing an extra insulation to the insulated busbar extremities. This extra insulation is necessary to cover the original insulation that is by construction exposed to the contact with operators tooling and therefore can present defects. The profiles are based on a “C” profile with two longitudinal flexible extensions in the top and bottom plane. This allows an adaptation to small variations in the shunt geometry.

Fig. 2. Sequence of the insulation sub-assembly. 1: Subassemblies; 2: Polyimide foil; 3: Flexural part; 4: Steel binder

Once in place, two layers of 50 μm polyimide foils are wrapped around and maintained with coated stainless steel cables ties. The cable ties are fixing the subassemblies and are applying the requested vertical clamping force to the shunt.

In this approach the copper part between the two subassemblies is left without insulation. This leads to an improved cooling performance due to direct contact with the surrounding helium bath. The dielectric insulation is guaranteed by the components to be assembled in the subsequent steps.

• Insulation of the busbars

The subassembly has furthermore to be insulated with respect to the surrounding stainless steel environment. In addition, as mentioned above the two busbars have to be insulated with respect to each other.

Fig. 3. Interconnection insulation assembly. 1: Intermediate piece; 2: Polyimide foil; 3: External covers; 4: Clamping system;

An intermediate wall made of glass fiber reinforced polymer is inserted between the two busbars and two shells inserted from both sides (Fig. 3) are providing the insulation to the surrounding objects. Each shell is in contact with the busbar at the extremity. The most optimized location for the restrained contacts would have been in the overlap between the busbar and the connection piece on each side.

Unfortunately experience shows that some connection pieces were substantially deformed through the connection process used during the installation and therefore this location would not provide a clean reproducible contact area. The entire insulation is covered by an extra 75 μm polyimide foil. The assembly is fixed with cable binders (shown in Fig. 4) providing the adequate horizontal pre-load to the busbars using screws with controlled torque.

Fig. 4. Left: Proposed cable binder ($\phi 60$ mm), M4 screw and pin joints; Right: Measurement support and strain gage specimen

• Dielectric insulation test series

A test program based on 10 samples was launched to qualify the insulation concept. The samples were connected to electrodes in gaseous helium, tested under room temperature and a pressure of 1 bar. The results are showing that the breakdown voltage to ground varies between 5.6 and 8 kV.

In comparison the results obtained for the present installed insulation varied between 5.4 and 7.6 kV. A standard busbar with its various insulation layers shows a breakdown voltage variation between 5.4 and 17.4 kV.

The test vessel was assembled with a transparent flange on one side. This allowed observing the arc initialization at the copper surface of the interconnection piece. The majority of observations showed an arc towards the sharp edge of the M-line flange. Further arcs were observed towards the so called “spider legs” of the busbar support (metallic supports visible in Fig. 3).

• FEA computations

In addition to the insulation test a series of FEA simulation were performed in order to determine the amount of stresses and displacements in the interconnect region. Main objective was to define the optimum pre-stress in the binder. The normal stress in the busbar is presented in Fig. 5.

Fig. 5. Busbar stresses in function of the operating condition for an insulation assembled with 200 N total preload (equally distributed between the 2 binders)

It shows the stress conditions after the assembly and the applied pre-strain from the binders at room temperature. In addition it presents the pre-stress loss after the cooling to 1.9 K and furthermore the increasing stress due to the current flow

of 1 kA up to the nominal value of 13 kA.

Fig. 6. Stresses in the busbar innermost and outermost fibers at room temperature, in function of the total binders preload (2 binders force equally distributed) applied, and at 1.9 K 13 kA and no busbar restrain

The stress conditions shown in Fig. 5 are representing the preferred and ideal load case in which the chosen installation pre-stress of 20 MPa is reproduced when operating at nominal current of 13 kA and under a temperature of 1.9 K. The normal compression and tensile stress on the most outer and inner busbar fibers are presented in Fig. 6. The max. bending stress of 58 MPa is applied to the busbar when no insulation system and therefore no force compensation is applied. For the described optimal load case this stress is lowered by a factor of 3 to 20 MPa. This stress is located on the contact point between insulation cover and the busbar.

• Clamping force control during the assembly

Having set the desired force value at 100 N on each binder it is necessary to demonstrate that this force can be applied in a repeatable and time efficient way, achievable during the tunnel intervention. The proposed solution is to control the torque used to close the binder screws. The preferred commercially available binder is made from stainless steel. On the extremities two threaded pin joints are attached in order to close the binder with the preferred torque.

Fig. 7. Measurement series compression force induced by the binder

Repeatability measurements were performed based on a cross-section sample of the insulation cover. The measurements were performed using an aluminum based specimen supported inside the sample (see Fig. 4). A strain gage Wheatstone full bridge connection applied to the specimen provided the level of compression force. Fig. 7 shows the results of a measurement series. The results show that the preferred pre-load force can be controlled within $\pm 20\%$. The preferred force of 100 N per binder corresponds to a torque of 0.15 Nm on the M4 screw.

• Material selection

In parallel to the described approach, an extensive material selection study and qualification was performed. Polyphenylsulfid (PPS) fiber reinforced polymer was found to be an adequate candidate for producing the insulation object according the following characteristics: radiation hardness, insulation performance, flammability resistance, stability under cryogenic conditions, non magnetic behavior and ability to be used in an injection molding process.

B. Insulation complying to the natural busbar shape

The conceptual design of the second proposal is shown in Fig. 8, aiming also at minimizing the number of components. This proposal allows compensating the busbars misalignments, filling the void in between the shells. As the insulation objects are in direct contact with the busbars and the shunts over the entire length a higher stiffness of the assembly can be achieved.

Fig. 8. Second proposal of interconnection insulation. 1: Polyimide foils along the busbars connection shown orange; 2: Epoxy injected filler in a pocket between insulated busbars and insulation; 3: Complementary profiles retaining the shunts and the Lorentz forces shown in gray

Each busbars interconnection is surrounded by pre-folded polyimide foil. Its length is such to cover the insulated busbar extremities towards the closest spider. Two complementary profiles are covering the busbars 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 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 on the upper, lower and external faces. One assembly requirement is given by a fast disassembly of all involved parts during inspections or replacements. This requirement is especially due to the increasing radioactivity 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 polyimide pocket into which the resin is injected. According to the first tests of the filling process it appears fast and repeatable. The dielectric discharge tests 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 the first proposal. A drawback of the presented solution is given by the quasi adiabatic assembly which should however not influence the interconnect performance during the entire life cycle.

V. CONCLUSION

The chain of activities for the consolidation intervention was described. The further steps include validating all activities. This process includes the writing of procedures, purchasing of tooling and materials. An important task is given by the development of the quality control procedures. In addition the training of the personal will be performed based on full scale mock-ups inside a representative tunnel environment.

Two solutions are proposed for the dipole circuit interconnection insulation. The first one demonstrated capacity to fulfill the specification. The dielectric performances are comparable to the present insulation used in LHC. Tested models showed that their performance is well above the minimum design requirements. The concept provides lateral mechanical restraint with a controlled force, easy to assemble and fitting the possible geometric defects. The geometry is acceptable from the cryogenics impedance and enhances significantly the cooling of the interconnection. A second proposal was introduced and is based on a different approach. Tests and a FEA computation are currently in progress to assess the performance in comparison to the first proposal. After the final selection the solution will be adapted to the quadrupole circuit interconnections.

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