Design of the consolidated LHC dipole diode busbar insulation system

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Abstract. During the second long shutdown of the LHC in 2019 and 2020, the electrical insulation of the 1232 dipole diodes and diode busbars is presently consolidated. The newly designed insulation system, mainly consisting of polyimide laminated fiber reinforced epoxy sheets and injection molded pure resin inserts, can be installed in the very constricted space of the LHC tunnel, without removing the presently installed insulation. The consolidated insulation will prevent shorts to ground caused by metal debris in the LHC cold masses and allow preparing the LHC for operation at 7 TeV.

1. Introduction

A large consolidation campaign of the Large Hadron Collider (LHC) [1] is presently taking place during its second long shutdown (LS2) [2]. At each of the 1232 main dipole magnet interconnections, the diode containers are opened and the busbar insulation system is inspected and consolidated. An overview of the dipole diode is presented in Figure 1.

Figure 1: Overview of the diode busbar half-moon splice insulation system (before consolidation). The insulation plates are only present in about 15% of the 1232 main dipole magnets (cold masses).
Before LS2, electrically conductive pieces in the cold masses remaining from production, could be transported by the helium flow and possibly cause contact of the diode busbars and their half-moon splices \[3\] with the grounded diode container and between both busbars. To date, the LHC experienced nine such short circuits \[4\]. Seven shorts were detected at ambient temperature and could be easily repaired. Two such shorts occurred at cold during magnet quenches \[5\].

In order to prepare the LHC for operation at its design energy of 7 TeV, it is estimated that hundreds of main dipole magnet training quenches are needed \[6\]. To avoid future shorts caused by metallic debris, the dielectric insulation is systematically improved: insulating pieces are added to the presently blank diode busbars and busbar half-moon splices.

2. Insulation System Main Requirements

The main goal of the consolidated insulation system is to prevent contact of the LHC diode busbars and their bolted splices (so-called half-moon splices) with the helium container that is grounded, in order to assure the voltage withstand levels as specified in \[7\].

The consolidated insulation system needs to be compatible with the existing insulation system (Figure 1), and its installation must be feasible without removing the diodes and without disconnecting the half-moon splices.

All insulation components must resist the mechanical forces that can be imposed by a differential helium pressure \[8\],[9], or by the mismatch of thermal contraction during cooling. The insulation system is designed to withstand a maximum pressure difference of up to 1 bar between both sides of the insert, and a hydrostatic pressure of up to 25 bar \[10\].

As the materials of the insulation system are inside the magnet cold mass and in the vicinity of the superconducting magnets, they have to be non-magnetic and compatible with superfluid helium at 1.9 K, and they must provide sufficient radiation hardness in order to withstand a total absorbed dose of 0.3 MGy over the entire LHC lifetime \[11\].

3. Consolidated Insulation System Components

The main components of the consolidated insulation system are shown in Figure 2. The insulation plates and sheets (a)-(d) are installed to provide additional insulation to the diode busbar half-moon splices. The modified connector block cover (e) and the insulation insert (f) insulate the presently blank diode busbars in the diode container.

![Figure 2: Insulation system main components. (a) Lower insulation sheets, (b) upper insulation sheets, (c) insulation plates, (d) spacer (optional), (e) modified connector block cover and (f) insulation insert.](image-url)
The new insulation components are designed such that they can adapt to dipole busbar manufacturing tolerances and geometrical imperfections, and they are compatible with the already existing insulation system, which can stay in place. Below the different insulation components are described in more detail.

3.1. Half-moon splice insulation system

Electrical insulation of the half-moon splices is provided by a lower and an upper insulation sheet (Figure 2 (a) and (b), respectively). These sheets are made out of a 0.5 mm thick fiber reinforced epoxy EPGC 203 sleeve (tradename ISOVAL®11) [12],[13], which provides the required mechanical strength, and onto which 50 µm thick polyimide foils are laminated on either side in order to improve electrical insulation. The flexible polyimide foils extending the fiber reinforced sleeves can adapt to the busbar geometry.

The different manufacturing steps of the insulation sheets are shown in Figure 3. The first step is the production of the EPGC 203 sleeves by water jet cutting. In the second step the polyimide film Krempel AKAFLEX KDF 0 50 25 is laminated onto the foils (compressed for 30 min at 30 bar at a peak temperature of 170 °C). Afterwards the laminated pieces are cut out to their final dimensions.

Figure 3: Insulation sheet manufacturing steps. (a) Cut out of 0.5 mm-thick fiber reinforced epoxy (EPGC 203) sheet. (b) Sheets laminated on either side with 50 µm thick polyimide film. (c) Insulation sheet with final dimensions cut out of the laminate.

So-called insulation plates are connected to the half-moon splices with dielectric fasteners in order to hold the insulation sheets in place (Figure 2 (c) and Figure 4). The insulation plates are machined out of glass fiber reinforced epoxy EPGC 203 (tradename ISOVAL®11) [12],[13], which is a commonly used material for cryomagnet applications.

In some cases, a 2 mm thick EPGC 203 spacer sheet is added between the lower and the upper insulation sheet in order to accommodate extending half-moon splice connecting screws (Figure 2 (d)).

Figure 4: (a) CAD model of the half-moon splice insulation system consisting of (b) insulation plate, upper and lower insulation sheets and an optional spacer. (c) Insulation components mounted with EPRS threaded rod and nut to a half moon splice.
3.2. **Insulation plate fasteners**

The new insulation plates are connected to the half-moon splices using electrically insulating M6 threaded rods and nuts (Figure 5(a)). Replacing the originally installed metallic screws by electrically insulating threaded rods and nuts gave more flexibility in the design of the insulation plates. The threaded rods are made of an epoxy-based glass fiber reinforced composite EPR S1, with a glass fiber content of 70 vol.% of mats and unidirectional fibers combined [14]. The hexagonal M6 nuts are made of EPR S7, which contains 67.5% layered fiber mats, corresponding to grade EPGM 203 [13].

As an alternative solution, socket head cap screws made of glass fiber reinforced polyamide (tradename Reny) [15] have been qualified. They are installed in cases where hexagonal nuts cannot be used because of limited space between insulation plate and busbar (Figure 5(b)).

![Figure 5: Insulation plates mounted with (a) threaded rods and nuts, and (b) with RENY hex socket screws.](image)

The maximum tightening torque at RT and at 77 K has been measured for M6 EPRS1/EPRS7 threaded rods and nuts, as well as for RENY screws. As shown in Table 1, the EPR S1 rod/EPR S7 nut combination can be safely tightened with a torque of 4 Nm. The tightening torque for the RENY screws should not exceed 2 Nm. Because of the relatively higher friction coefficient of the EPRS1/EPRS7 combination with respect to the Reny screw/Cu thread, a similar tightening force is achieved when the EPRS7 nut and the Reny screw are tightened with 4 Nm and 2 Nm, respectively.

| Temperature | Torque at rupture (Nm) | Number of tests |
|-------------|------------------------|-----------------|
|             | Average | Minimum |               |
| Reny        |         |         |               |
| RT          | 4.5±1.08 | 2.8     | 15             |
| 77 K        | 5.1±0.35 | 4.6     | 5              |
| Reny irradiated |     |         |               |
| RT          | 4.4±0.32 | 4.2     | 3              |
| EPRS1 rod/EPRS7 |   |         |               |
| RT          | 6.3±0.86 | 4.7     | 15             |
| 77 K        | 9.1±0.74 | 8.0     | 10             |

The torque at rupture was measured before and after irradiation. Irradiation of the RENY screws with 24 GeV protons with a fluence of $4\times10^{15}$ p/cm$^2$, corresponding with an absorbed dose of about 1 MGy, did not significantly degrade the mechanical properties.

The thermomechanical properties of different insulation materials determined at RT, 77 K and 4.2 K have been reported previously [19]. The RT stress-strain curves of the pure resins ULTEM 1000 and ULTEM FDM 9085, and the fiber reinforced composite EPR S1 (threaded rod material) are compared in Figure 7 (b). The fiber reinforced epoxy rods have comparatively high strength, while the pure resin ULTEM 1000 can be submitted to very high strains before rupture occurs. The CTEs of the glass fiber reinforced epoxies, used for the threaded rods and nuts for insulation plate fixation, are comparable to those of stainless steel (Figure 7 (a)).

Araldite 2011 two-component epoxy adhesive (pot life at 25°C is 2 hours) is used for locking of the glass fiber reinforced epoxy threaded rods and nuts, as well as for the Reny screws.
3.3. **Insulation insert**

An insulation insert installed in a LHC dipole magnet diode container is shown in Figure 6. The function of the insulation insert, in combination with the redesigned connector block cover, is to cover the presently blank diode busbars in the diode container, and to prevent large metal chips from entering the diode venting channel, which could cause a short to ground.

Different methods have been considered for the fabrication of 1300 inserts, including injection molding and sheet molding. The series inserts installed during LS2 were injection molded out of the amorphous polyetherimide thermoplastic ULTEM 1000 [16]. ULTEM 1000 was already qualified for use in cryogenic environment and is already used in the LHC [17]. The injection molding process allowed to produce the inserts with complex geometry in a cost-effective way. Machining the 1300 inserts needed out of fiber reinforced epoxy would have been much more expensive than the injection molding.

![Insulation insert made of ULTEM 1000 installed on a LHC dipole diode.](image)

Functional prototype inserts were made of the thermoplastic ULTEM FDM 9085 by fused deposition modelling. This allowed to install these inserts already before arrival of the series inserts in 22 spare magnets where the diode insulation system could be consolidated prior to LS2.

3.4. **Insulation insert connection and thermomechanical properties**

The insulation inserts are fixed to the diode pressure plate with two stainless steel M6 hex socket head cap screws, ISO 4762M6 A4-70. The 0.2% proof stress and the tensile strength of A4-70 stainless steel are $R_{p0.2}=450$ MPa and $R_m=700$ MPa, respectively.

The coefficients of thermal expansion (CTE) of the different insulation system materials are compared in Figure 7(a) with those of stainless steel 316LN [18]. Highest CTEs are observed for the pure epoxy ULTEM 1000. The thermal expansion mismatch of about 0.3 mm between the stainless steel screws and the ULTEM 1000 insert during cooling from RT to 1.9 K is compensated by the two CuBe2 (2.2147) Belleville washers. Torque tests at RT and subsequently in liquid nitrogen indicate that the tightening force in the stainless steel screws is reduced by about 20% when cooling the entire insert assembly to cryogenic temperatures.
Figure 7: (a) Comparison of coefficient of thermal expansion of ULTEM 1000 pure resin, glass fabric epoxy EPR S7 and EPR S1, and stainless steel 316L (insert connecting screw material). Reference temperature is 20 °C. (b) Comparison of the RT engineering stress-strain curves of EPR S1, ULTEM 1000 and ULTEM FDM 9085.

The stainless steel screw locking in the stainless steel pressure plate is achieved by a medium strength thread locking compound “ORAPI Freinage Moyen 303” (curing time of 24 h at 22 °C), which allows for screw disassembly with standard tools.

4. Discussion and Conclusion

An insulation system for the systematic consolidation of the dipole diode busbar insulation at the 1232 main dipole magnet interconnections has been designed, and all insulation components have been manufactured.

A main design challenge was to provide a robust insulation system that can be installed under the space constraints at the LHC interconnects onto the busbar system with relatively large geometrical variations. This has been achieved by combining the rigidity of fiber reinforced sheets and plates with a large busbar cutout, with flexible polyimide films providing excellent dielectric insulation, in combination with dielectric fasteners. By injection molding the diode busbar and venting-hole insulation could be realized with a single insulation insert that is easy to install.

The design process has largely profited from several design optimization steps that were possible thanks to the fast additive manufacturing of prototype components. Thermomechanical materials tests have confirmed the materials choices.

By February 2020 the installation of the consolidated insulation system on the 1232 LHC dipole diodes and diode busbars has been successfully completed.

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