

CONSOLIDATION OF THE 13 kA SPLICES IN THE ELECTRICAL FEEDBOXES OF THE LHC

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Abstract

In 2008 a defective connection in one of the 13 kA dipole circuits of the LHC caused an electric breakdown that resulted in extensive damage in a sector of the accelerator. The investigation performed after the accident showed the necessity to consolidate the electrical splices of the 13 kA dipole and quadrupole circuits in order to operate the LHC at its nominal energy of 7 TeV. These circuits are powered through electrical feedboxes located at each end of the 8 sectors of the LHC. In the feedboxes the current is routed from room temperature to the superconducting magnets busbars along current leads and superconducting busbars and flows through at least two internal splices. These splices are based on the same technology as the magnet-to-magnet ones but they are significantly different in terms of environment and configuration. As for the magnet to magnet splices, a consolidation will be necessary to operate them at nominal current. This paper presents an analysis of the properties of these splices and the technologies that will be used to consolidate them. The quality control and the workflow to perform this operation during the first long shutdown of the LHC are also presented.

INTRODUCTION

The magnets in the arcs of the 8 sectors of the LHC are powered by 16 electrical and cryogenic feedboxes (DFBA) located at each end of the 3.3 km long continuous cryostats [1]. The main dipole and quadrupole circuits, hereafter referred to as the "13 kA" circuits, are powered through current leads located in these feedboxes. Following the electrical breakdown of 2008 a detailed investigation showed that the cause of the incident was a faulty splice between magnets in the dipole busbar system [2]. Further simulation and measurements also identified weaknesses in the continuity of the copper stabilizer for both the quadrupole and dipole circuits of LHC. Following a campaign of assessment of the quality of the splices, the maximum current of the dipole and quadrupole magnets was limited to 5925 A, equivalent to a beam energy of 3.5 TeV (instead of 11850 A for 7 TeV) [3] which has recently been increased to 4 TeV [4].

In order to reach the 7 TeV nominal energy of LHC, the decision was taken to systematically consolidate all (>10'000) splices of the 13 kA circuits of the LHC [4], including the splices in the DFBA. The specifications, the technical solution and the consolidation plan for the magnet-magnet splices have been defined and thoroughly reviewed by external committees [5,6].

There are 136 splices in the DFBA, although similar in many aspects to the magnet-to-magnet ones, these splices are located in a very different environment and for 64 of them are of a significantly different design.

THE 13 kA SPLICES IN THE DFBA

The 16 DFBA of the LHC supply the electrical current to most magnets in the LHC arcs with current leads ranging from 120 A to 13 kA. The powering requirements of the arcs are different depending on the location and the DFBA have also corresponding different configurations. As concerns the 13 kA circuits, the main variations between the DFBA is their relative position with respect to the arc (left or right) and the absence of the main quadrupole current leads on one of the two extremities of the arc.

Fig. 1 shows the configuration of a DFBA that is located on the right side of an LHC arc, DFBA for a left side feed are essentially a mirror symmetry of the one shown in Fig. 1. As concerns the configuration of the 13 kA splices, most DFBA are similar, with two notable exceptions being the DFBA located in point 6 and point 8 of the LHC (see below).

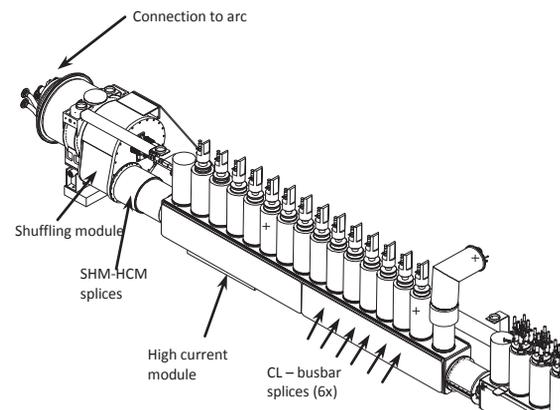


Figure 1: view of a DFBA with the main parts and position of the 13 kA splices.

The Two Types of 13 kA Splices in the DFBA

The DFBA are made of two main sub-assemblies: the Shuffling Module (SHM), connected to the LHC arc on one side and the High Current Module (HCM) that hosts the current leads. Because of assembly constraints, splices are present between the SHM and the HCM for all 13 kA busbars as shown in Figure 1. The SHM-HCM busbar-

busbar splices are essentially identical to the ones found between magnets [7], with a SnAg alloy soldered connection. In the SHM-HCM interconnections, there are either 6 splices (2 dipole busbars, 4 quadrupole busbars) in even points of LHC or 2 splices (2 dipole busbars) in odd points. These interconnections exist in two configurations, right and left, corresponding to the DFBA location.

The 13 kA current leads are connected to the busbars through a flexible connection, hereafter called “pigtail”, made of 72 individual NbTi strands and flexible copper stabilizer sheets bolted to the bottom of the current leads. Although sharing the same basic joining technology (low temperature SnAg brazing), the busbar-pigtail splices differ significantly from busbar-busbar ones: the geometry of the pigtail is very different from a busbar and the longitudinal space available for the connection is much smaller. The resulting design is shown in Figure 2: the length of the splice is reduced to 70 mm (120 mm in busbar-busbar ones) and the Rutherford cable of the busbar is sandwiched between two layers of 36 superconducting strands. The splices come also in two versions, left and right, corresponding to the DFBA configuration.

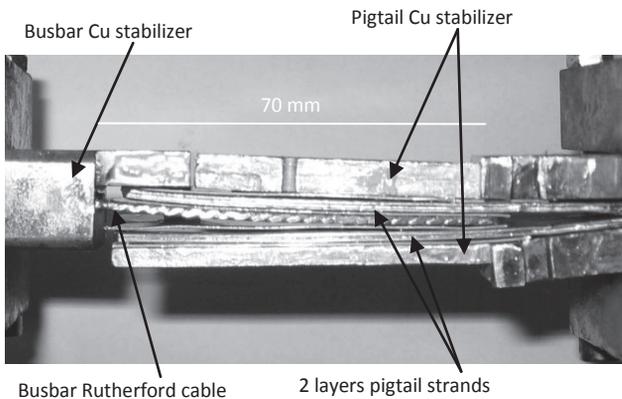


Figure 2: Geometry and components of the pigtail-to-busbar splice

In addition to the two splices for each busbar (total 128), there are two singularities: 1) in a DFBA located in sector 7-8 two additional splices were necessary to repair a damaged busbar in the HCM-SHM connection, 2) in sector 5-6, the presence of the beam dump required a specific geometrical configuration with 6 additional splices. The number and types of splices in the DFBA are summarized in Table 1.

The quality of the connection between the superconducting components of the DFBA splices was checked during an extensive measurement campaign that included all the splices of the LHC. At 1.9 K, the measured average resistance was 0.3 nΩ, very similar to the magnet-to-magnet splices. Since the start-up of the LHC in 2009 (more than two years), no degradation has been observed by the continuous monitoring system [8]. As concerns the continuity of the copper stabilizer, the

measuring techniques developed for the arcs [3,4] could not be used and therefore no measurement is available. The splices in the DFBA are of a similar design as the ones between the LHC magnets and are therefore affected by the same weaknesses concerning the resistance of the connection between the copper stabilizers.

Table 1: List of the 13 kA Splices in the DFBA

Type of splice	Dipole	quadrupole	total
SHM-HCM right	8 DFBA x 2	4 DFBA x 4	32
SHM-HCM left	8 DFBA x 2	8 DFBA x 4	32
CL-busbar right	8 x 2	4 x 4	32
CL-busbar left	8 x 2	4 x 4	32
Special DFBA P	-	2	2
Special DFBA K	2	4	6

Consolidation of the DFBA Splices

The consolidation technology will be very similar to the one that has been developed for the magnet interconnections [9], shown in Fig. 3 for the dipole busbar. It essentially consists of soldering copper shunts (4 on dipole busbars and 2 on quadrupole busbars) of with a cross section of 15 x 3 mm² at each position where the copper is discontinuous. This not only provides a low resistance electrical connection but also improves the mechanical characteristics of the splice.

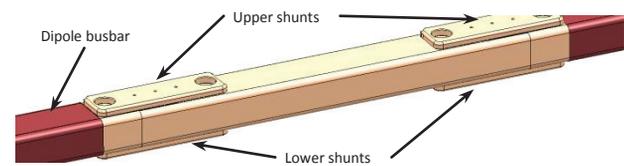


Figure 3: Design of the consolidated magnet-to-magnet splice in the dipole circuit showing in total four electrical shunts.

Development work is on-going to adapt the techniques already developed to the environment around the busbars and to the very limited accessibility. Fig. 4 shows the configuration of an SHM-HCM interconnection and shows the location of the splices. All 6 13 kA splices are located in a pipe of a diameter of less than 200 mm positioned closely behind the splices of 6 kA and 600 A busbars. Access to the splices and the subsequent re-welding are very difficult operations because of the very tight space constraint and the requirement to avoid the production of dust (because of the activation of the materials). The currently envisaged approach is to use orbital cutting machines and to perform the welding operations manually. The consolidation operation will

also include a new mechanical supporting system that will reduce the stresses in the splices.

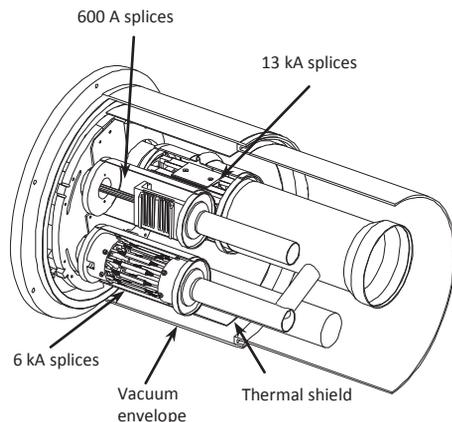


Figure 4: detailed view of a SHM-HCM interconnection showing the position of the 13 kA splices.

The busbar-pigtail splices are of a different design (cf. Fig. 3), but the same principle, namely adding copper shunts, will be used also for these splices. The access to the busbar-pigtail splices is easier than for the SHM-HCM splices because the possibility to replace the current leads was part of the design of the DFBA. An orbital cutting technique will be used to access the busbar and the re-welding will be performed manually.

PERFORMING THE CONSOLIDATION

Strategy

For 14 of the 16 DFBA, the consolidation of the splices will be performed in the LHC tunnel, without moving the feedboxes. This avoids an operation that would require the complete disconnection of all circuits and a delicate transport operation. For the two DFBA with splices located in non-standard positions, an in-situ consolidation is a much more complex and risky operation and the strategy to apply to these two DFBA is still under study.

Quality Control

Quality control will be applied to existing and to consolidated splices. Very little information is available today on the electrical quality of the copper continuity in the DFBA splices so they will be systematically measured. The acceptance criteria are being developed in analogy with the quality control provisions defined for the magnet-magnet splices [8].

Schedule and organisation

The consolidation of the 13 kA splices in the DFBA will be performed in parallel with the consolidation of the magnet-magnet splices during the long shutdown of the

LHC in 2013-2014. The development work necessary to adapt the existing technologies to the DFBA is on-going. The work will be organized in a similar way as for the magnet-to-magnet splices [9], with the sequential intervention of specialized teams. The duration of the consolidation work on one DFBA is estimated to be between 3 and 5 working weeks. The relatively short intervention times (compared to the consolidation of an LHC arc) allow the integration of this operation in the global long shutdown schedule. The two DFBA that need to be moved will require longer intervention times of 10 to 14 weeks and the organization of dedicated workshop areas.

CONCLUSIONS

The consolidation of the 13 kA splices in the 16 DFBA is currently under preparation at CERN. Although similar to the busbar splices between the magnet, the specificities of the splices of the DFBA require a significant development work that is currently being performed. The consolidation of the 136 splices in the DFBA will be performed during the first long shutdown of the LHC in 2013-2014, in parallel with the consolidation of the magnet-to-magnet splices.

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