Industrial tooling and methods for the junctions of the superconducting busbars in the interconnections between the LHC cryomagnets

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Abstract. The Large Hadron Collider (LHC) is the next world-facility for the high energy physics community, presently under installation at CERN, Geneva. The main components of the LHC are the twin-aperture high-field superconducting cryomagnets that are powered in series by superconducting Nb-Ti busbars. Along the machine, about 60 000 splices between the superconducting busbars have to be performed in-situ during the interconnection activities. They are carrying a nominal current varying from 600 A to 13 kA depending upon the magnets, at an operating temperature of 1.9 K. Three specific techniques have been developed and optimised for the splicing of the three main types of cables: inductive and resistive soldering, ultrasonic welding. After a brief presentation of the constraints and requirements applying to these junctions, the tooling is described, highlighting the industrialisation aspects. Before their use to interconnect actual cryomagnets in the LHC tunnel, the equipments and procedures follow rigorous qualification to ensure that all the characteristics of the junctions (electrical, mechanical, reliability,…) are within the specifications. The assessment of the tooling performance is obtained via sample testing of superconducting busbars. Initial results are presented.

1. Introduction
The Large Hadron Collider (LHC) will bring into collisions intense proton beams with a centre of mass energy of 14 TeV and a nominal luminosity of \(10^{34}\) cm\(^{-2}\)s\(^{-1}\). This unprecedented performance will be achieved with the use of high-field superconducting magnets operating in superfluid helium below 2 K. The main components, i.e. cryodipoles and Short Straight Sections, are under installation in the LHC tunnel. Once positioned on their supports (jacks) and precisely aligned by the survey team, they have to be interconnected. The more than 8000 superconducting magnets are powered via about 1700 different electrical circuits. The layout comprises eighth independent sectors. The current is generally fed from room temperature to superfluid helium temperature through electrical feed boxes. Most of the cryomagnets are powered in series, by family. This paper focuses on the junction of the superconducting busbars between the main cryomagnets. For all of them, the technologies were developed and qualified by CERN. A full scale validation was carried out on the LHC test string called STRING2 (a 110 m-long prototype of a LHC full cell) assembled at the ground level [1].
Subsequently, a contract was signed with an industrial consortium of firms (IEG) for the assembly of the approximately 1700 LHC interconnections in the tunnel, also including the industrialization and the procurement and qualification of the tooling. A training programme and transfer of know-how are presently on-going to ensure an efficient and reliable assembly. All these activities have to be performed in a limited space (picture 1). The constraints come from the 3.8-m diameter tunnel environment but also from the fact that the longitudinal space allocated to the interconnections between cryomagnets has been minimized to preserve as much as possible the useful magnetic length.

2. Splices of the main dipoles and quadrupoles (13 kA)
The main dipoles and quadrupoles are powered via superconducting Nb-Ti cables carrying a nominal current of 11.85 kA and 11.87 kA respectively for dipoles and quadrupoles. Because of the high current rating, the constraint on the electrical resistance of the splices is very severe to limit the heat dissipation in the superfluid helium bath; it has to be lower than 0.6 n. An inductive soldering technique has been developed for the realization of these splices [2]. The machine developed to perform the approximately 10 000 splices around the LHC machine can be seen in pictures 2 and 3.
The soldering is performed under controlled pressure and temperature. The two cables overlap on 120 mm and are soldered simultaneously with stabilizing copper bars required to carry the current during the discharge after magnet quench. The tin/silver ribbons used for this junction have a melting temperature of 223°C, which is obtained in about 2 minutes, thus avoiding overheating and subsequent degradation of the superconducting characteristics of the cable and of the stabilizing copper. To ensure reproducibility, temperature and pressure are controlled in closed-loop. For each machine, 10 samples are performed before starting actual work in the tunnel. The splice resistance of the samples is measured at 4.2 K using an inductive method [3]. All values measured were found below 0.3 n, so well within the specification. In-process inspection is also implemented with regular manufacturing and testing of production samples to ensure the quality during the whole assembly of the LHC interconnections.

3. Splices of the corrector magnet system (600 A)
The corrector magnet system consists of families of long and short trim quadrupoles, skew quadrupoles, sextupoles, skew sextupoles, decapoles, octupoles, and dipole orbit correctors. They are powered in series via superconducting monolithic wires composed of NbTi strands embedded in a copper matrix with a maximum current rating of 600 A. Although the space allocated to the splices is very limited (10 mm overlap); the electrical resistance has to be lower than 6 n. The 50 000 junctions are performed by applying the ultrasonic joining technology [4][5]. The results are very satisfactory and well within specification. As example, table 1 gives the results of the electrical measurements made during the qualification of the first machine, shown in pictures 4 and 5.

| # | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | Average |
|---|----|----|----|----|----|----|----|----|----|----|---------|
| R [nOhm] | 4.74 | 5.68 | 6.36 | 5.06 | 5.42 | 5.35 | 4.78 | 3.91 | 5.89 | 4.84 | 5.20 |

Table 1: Qualification sample of the ultrasonic joining machine # 1

![Pictures 4&5: The specifically developed ultrasonic welding machine and a view of the sonotrode between two cryomagnets](image)

4. Specific splices (6 kA).
Insertion quadrupoles located in the dispersion suppressor zones are powered independently by 6 kA superconducting cables. About 200 splices on these cables have to be carried out in-situ. As this number is small with respect to the two other types of splices and therefore less stringent in terms of the limitation on the electrical resistance, it was decided to implement a standard joining solution: the resistive soldering. The space allocated to these connections is also very limited; consequently the resistive oven has to be tailor-made for this specific application. Superconducting cable extremities have to be specifically prepared to achieve a rectangular shape, starting from a circular cable. (Picture 6).
As this method is less automatic, reproducibility tests were performed on a representative geometry. Four samples were assembled and the electrical resistance measured at cryogenic temperature [3]. Table 2 gives the relative value of the splice electrical resistance. It can be seen that the reproducibility is better than 2 %, which is an acceptable value.

| #   | 1    | 2    | 3    | 4    |
|-----|------|------|------|------|
| Relative Elec. Resistance wrt to average [%] | 98.9 | 99.4 | 101.7 | 99.9 |

Table 2: Relative splice electrical resistance

Other tests were performed to define the overlapping length, using as a first input the experience acquired with the induction soldering of the main cables. A scaling with respect to the contact surface area was found to be a good starting point, even if cable and junction characteristics were different. The final value is 70 mm length on a width of 10 mm. A splice resistance of less than 0.7 n has been reached, therefore well within the specification of 1.5 n. The repair (unsoldering/re-soldering) procedure was also tested and no increase of the contact resistance was noticed.

5. Conclusion
The interconnection work in the tunnel started in May 2005 in collaboration between CERN and the selected Contractor (IEG). Despite numerous tests on mock-ups and in-situ verification of the space constraints, the tooling and procedures had to be adapted to the actual cryomagnets and to the tunnel environment. During this period, the inspection and quality assurance processes (actors, procedures, reporting, interfaces,...) were finalized. Some more optimization will be required to cope with the ramping-up of the interconnection activities and the industrial aspect of this huge endeavour.

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