

# ELECTRO-MECHANICAL ASPECTS OF THE INTERCONNECTION OF THE LHC SUPERCONDUCTING CORRECTOR MAGNETS

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## Abstract

In addition to the main 1232 bending dipoles and 392 focusing and defocusing quadrupole assemblies 7772 superconducting magnets are included in the LHC machine. They are housed in the superfluid helium enclosures of the main cryomagnets. Among them, the lattice corrector magnets (i.e. tuning quadrupoles, sextupoles and octupoles) are integrated in the main quadrupole helium vessel and they are powered via an externally routed cryogenic line (line-N).

During machine assembly, these corrector magnets have to be connected according to a complex electrical scheme based on the optical requirements of the LHC. These correctors will be powered by means of a 42-wire auxiliary bus-bars cable. A total of 440 interconnection boxes, installed along the 27 km long LHC will allow to route the corresponding wires to the correctors inside the cold mass of the main quadrupoles. Stringent requirements in terms of volume, mechanical resistance, electrical conductance and insulation, reliability, and respect of the electrical schematics apply during the assembly and splicing of the junctions inside the line-N box. The activities and their sequence, aiming at ensuring the fulfilment of these requirements are presented. The planned activities (assembly, ultrasonic welding, general and electrical inspection, and electrical qualification) and the interactions between the various intervening teams are described.

## INTRODUCTION

The Large Hadron Collider (LHC), the next world facility for high energy physics, is presently under installation at CERN, Geneva. The LHC will bring into collision intense protons beams with a centre of mass energy of 14 TeV and a nominal luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ . At a later stage, heavy ions will be injected and circulated in the accelerator. To achieve this performance, about 1746 cryo-assemblies will be installed, including 7612 superconducting correctors to compensate for multipole errors and to adjust the proton and ion beams. The corrector magnet system consists of long and short trim quadrupoles, skew quadrupoles, sextupoles, skew sextupoles, decapoles, octupoles, dipole orbit correctors with a maximum current rating of 600 A. They are housed in the same helium enclosures as the main dipole and quadrupole magnets. This paper deals with the powering of the trim and skew quadrupoles, the sextupoles, the skew sextupoles and the octupoles integrated together with the main quadrupoles in the so-called Short Straight Sections (SSS). These corrector magnets are powered by superconducting cables

composed of NbTi strands embedded in a copper matrix and installed in an externally routed cryogenic line, the so-called line-N (Fig. 1).

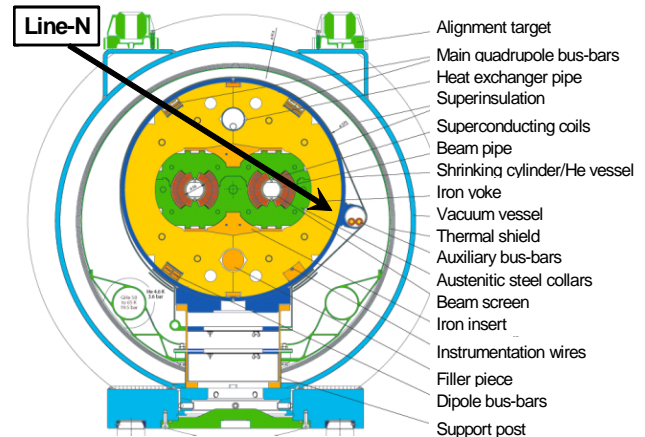


Figure 1: Standard cross section of the LHC cryodipole.

## ASSEMBLY IN THE LHC TUNNEL

### Overview of the sequence of activities

The electrical junction of the superconducting busbars powering the corrector magnets is part of the whole assembly process of the LHC interconnections [1] and involves different actors, responsible of tasks carried out according to the following chronological order:

- Preparation of the line-N cable segments in a surface workshop
- Insertion of the line-N cable segments in their housing along the cryomagnets in the tunnel
- Assembly of the interconnection board (Fig. 2)
- Verification of the electrical connection scheme [2]
- Ultrasonic joining (with quality monitoring samples) [3]
- Inspection of the junction (visual and electrical) [2]
- Conductor electrical insulation
- Verification of electrical insulation [2]
- Closure of the helium volume by TIG welding

### Electrical layout

The LHC machine is powered through 1712 superconducting electrical circuits [4]. Among them, 296 are powered via the 42-wire auxiliary bus-bars cable housed in the line-N. Each circuit is composed of up to 13 corrector magnets of the same type connected in series; it includes up to 116 junctions and has an extension of up to 2.7 km along the LHC machine. The confined and limited volume of the line-N box in which 46 junctions connect the two 42-wire auxiliary bus-bars cables and the

associated corrector magnets have required the design of a dedicated interconnection board to mechanically and electrically ensure the integrity of the circuits. The design fulfils the requirements in terms of accessibility and to allow for the electrical verifications (Fig. 2).

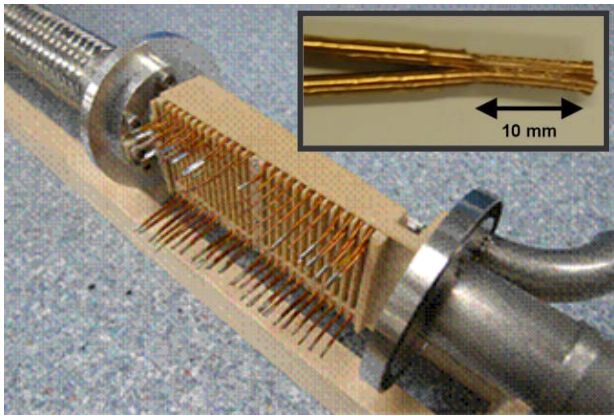


Figure 2: Line-N prototype interconnection box.

### Assembly technology

The main constraints defined for the junction of the auxiliary bus bars are:

- Maximum current intensity of up to 600 A
- Operating temperature of 1.9 K in superfluid helium with a design pressure of 2 MPa
- Electrical splice resistance lower than  $6 \text{ n}\Omega$  at operating temperature to meet the requirements of the cryogenic budget (even in case of repair)
- The increase of temperature and the duration of heating have to be limited to avoid degrading the superconducting characteristics of the cables
- The use of potentially corrosive materials has to be avoided in order to guarantee the tightness of very thin stainless steel sheets used in the manufacturing of the compensation system [5]
- Sufficient mechanical strength to sustain the assembly process, the thermal constraints during cool-down and warm-up and the electromechanical forces
- Strict process control for more than 50 000 joints
- High reliability level [6]: As for all the components and operations of the LHC interconnections, the junctions between the auxiliary superconducting cables have to reach a very high level of reliability. Failure of only one junction would jeopardise the correct operation of the LHC. The required reliability for the complete LHC interconnection system is 99.5%. After apportionment between the main systems, the electrical and mechanical failure probability has to be lower than  $2 \cdot 10^{-8}$ . To achieve this, the possible automation and on-line quality monitoring are considered mandatory in order to minimise the potential human errors.

- Limited space: longitudinally because the length allocated to the interconnections has been minimised to reach a ratio of non-magnetic to magnetic length close to 3.7% and transversally because the LHC is installed in a tunnel of given dimensions (Fig.3&6).
- Industrialisation including schedule and economical constraints to reach a mean rhythm of about 100 splices per day.

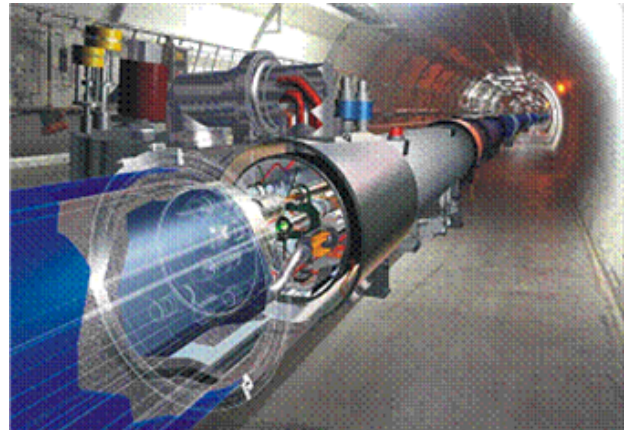


Figure 3: 3-D model of cryomagnet interconnections.

After a survey of the available technologies, the ultrasonic joining method has been selected, developed and qualified to carry out the splices of the 42-wire auxiliary bus-bars cable during the assembly of the LHC interconnections in the tunnel. It results in a low electrical contact resistance and a sufficient mechanical strength with an overlap of only 10 mm (Fig.2&4). The critical parameters are recorded on-line to ensure a high level of quality and reliability. To avoid long-term drift, samples are produced and extensively tested off-line in parallel with the assembly.

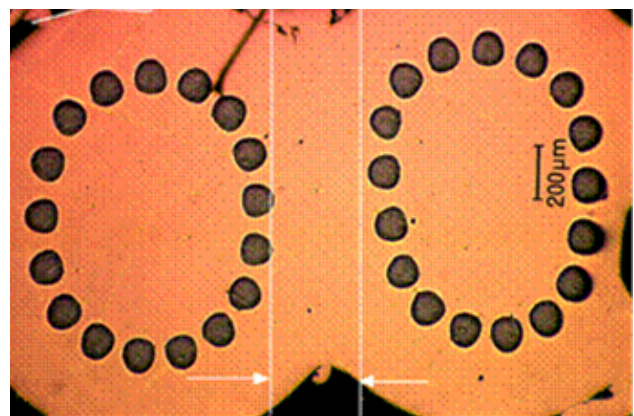


Figure 4: Splice cross-section

To qualify the process, measurements were performed on samples produced under series production conditions. The applied method is based on current decay time in a superconducting loop containing a splice. It allows the measurement of very small resistances of joints of superconducting wires [7]. The achieved average



electrical resistance is  $2.40 \text{ n}\Omega$  ( $\sigma = 0.32 \text{ n}\Omega$ ) (Fig. 5) and the mechanical strength is higher than 1050 N.

A full scale validation was carried out on the LHC test string, STRING2 [8] (prototype of a LHC full cell). It has been ensured that the stringent requirements applying to these junctions can be fulfilled.

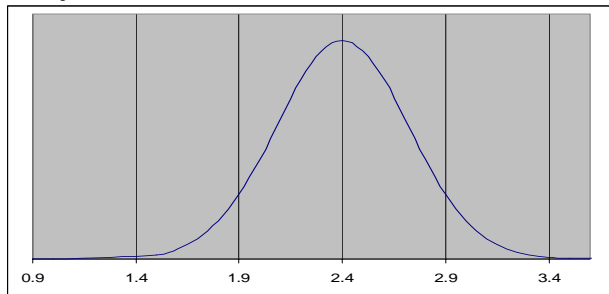


Figure 5: Distribution of splice electrical resistance [nΩ]

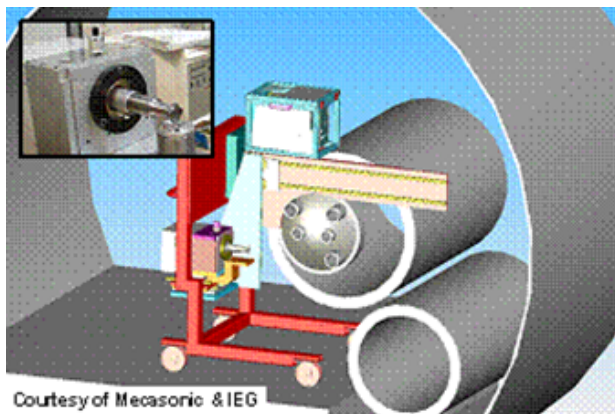


Figure 6: Ultrasonic joining machine in the LHC tunnel.

### Electrical Quality Assurance

Errors in the cabling of the electrical circuits, corrector magnets connected with the wrong polarities and electrical faults such as an electrical insulation resistance to ground will have an impact on the optics of the machine and can seriously degrade the performance of the LHC. To ensure the safe and correct functioning of all electrical circuits an electrical quality assurance plan (ELQAP) has been defined and will be applied during the assembly activities of line-N.

The verifications will be performed by an independent team at the different stages of assembly with a dedicated automatic system [2]. The following parameters will be systematically verified:

- Continuity of bus bars and corrector magnets interconnections.
- Authentication of magnet corrector type by means of ohmic resistance measurement.
- Corrector magnets polarity.
- Electrical insulation versus ground and other circuits.

At the end of the machine assembly each circuit will be qualified independently. The qualification will include the measurement of the total resistance and inductance, the insulation resistance with respect to ground and other electrical circuits and transfer functions.

## PLANNED TUNNEL ACTIVITIES

A contract has been signed with a consortium of firms for the assembly of the LHC interconnections, including the activities related to the electrical connection of bus-bars. As CERN is mastering this technology, a training programme and know-how transfer to the contractor is planned to ensure an efficient and reliable assembly. The machines for series production (Fig. 6) are under qualification. The procedures will be verified and validated during the assembly of the 10 first interconnections (pre-series).

## ACKNOWLEDGMENTS

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