

INSTALLATION AND QUALITY ASSURANCE OF THE INTERCONNECTIONS BETWEEN CRYO-ASSEMBLIES OF THE LHC LONG STRAIGHT SECTIONS

C. Garion, I. Slits, J.P. Tock, CERN, Geneva, Switzerland

Abstract

The interconnections between the cryomagnets and cryogenic utilities in the LHC long Straight Sections constitute the last machine installation activity. They are ensuring continuity of the beam and insulation vacuum systems, cryogenic fluid and electrical circuits and thermal insulation. The assembly is carried out in a constraining tunnel environment with restricted space. Therefore, the assembly sequence has to be well defined and specific tests have to be performed during the interconnection work to secure the reliability of the system and thus to ensure the global accelerator availability. The LHC has 8 long straight insertion zones composed of special cryomagnets involving specific interconnection procedures and QA plans.

The aim of this paper is to present the installation and quality assurance procedures implemented for the LHC LSS interconnections. Technologies such as manual and automatic welding and resistive soldering will be described as well as the different quality controls, such as visual and radiographic inspection of welds, electrical checks and leak testing. An evaluation and statistical analysis of the results of the interconnection work will be presented.

INTRODUCTION

The LHC machine is composed of 8 sectors each consisting of a curved part (Arc + Dispersion suppressors) and a Long Straight Section (LSS), approximately 528m long, located close to the insertion point (IP). Four LSSs are dedicated to beam focusing for experiment (Point 1, 2, 5 & 8). At these points, the beams go from 2 apertures to 1 and collide in the experiment detector. The other four LSS contain beam cleaning (IP 3 & 7), RF systems (IP 4) and the beam dump (IP 6) [1].

This paper is focused on the interconnections of the LSS at IP 8 Left. Its layout is presented in Fig. 1.

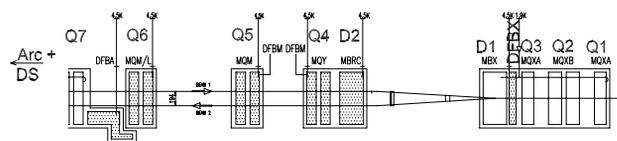


Figure 1: Layout of the LSS 8L.

The dipoles D2 and D1 are used for the separation/recombination of the beams. The inner triplet system provides the final focusing of the beam before the collision. The distribution feedbox DFBX provides electrical powering of the inner triplet as well as helium from the cryogenic distribution line (QRL). The inner

triplet (IT) is composed of D1, DFBX and Q3, Q2 and Q1 quadrupoles. Stand alone (Q5, Q6) and semi-standalone (Q4) quadrupoles are installed in the LSS. The nominal working temperature of the IT is 1.9 K against 4.5 K for the semi and standalone magnets. The inner triplet system and the separation dipoles are provided by a US collaboration [2].

The interconnection system has to ensure:

- Continuity of the beam transport system;
- Continuity of the beam and insulation vacuum;
- Continuity of the electrical powering system;
- Continuity of the cryogenic system;
- Continuity of thermal shielding;
- Compensation for the thermal contraction of the adjacent components;
- Transverse flexibility for the alignment and operation.

INTERCONNECTION TECHNOLOGIES

During the interconnection work two main technologies are used: soldering of electrical splices and TIG welding.

Soldering of Electrical Splices

In LSS8L, some 50 electrical junctions between superconducting cables have to be carried out: ~1/4 are main bus bars that power the main magnet (dipole or quadrupole), ~3/4 concern spool busbars powering the corrector magnets. All these splices are done with resistive soldering. The tooling consists of an oven in which cables and solder (Sn96Ag4) are placed in “sandwich”. A non-corrosive flux (Kester 135) is spread over all surfaces of cables and solder strips. The set is heated up to 230°C. The process is temperature controlled by a thermocouple (Fig. 2). After soldering, all splices are insulated with polyimide film and placed in a connection box in glass fiber reinforced epoxy resin (GFRE), see Figs. 2 and 3.

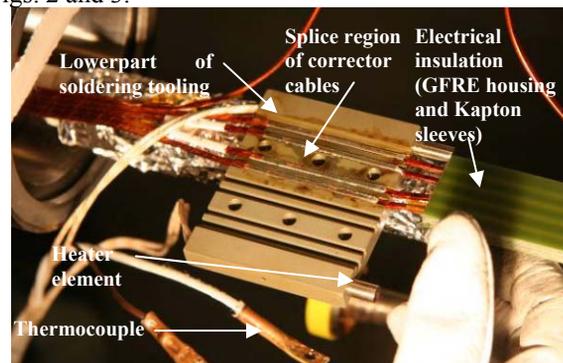


Figure 2: Soldering tooling during electrical junction.



Figure 3: Insulated splice in GFRE support.

TIG Welding

About 140 TIG welds are made in LSS8L. Three types are present: butt-, fillet-, and edge weld. In the baseline for the LHC interconnection welds, no internal inert gas is foreseen. A backing ring is installed inside the tube to avoid oxidation during welding. Whenever possible, automatic welding is preferred even if some additional tooling is required. Closed head welding machines are used for small diameter pipes ($OD \leq 33$ mm). A modular clamping system by interchangeable shells permits the adaptation to different diameters. Edge welds are carried out with open head welding machines, specially designed for minimum radial dimension.

QUALITY ASSURANCE

Sequence of Installation and Quality Control

Due to differences in design and test conditions, an installation sequence was made for the IT, semi-stand alone and standalone with a similar approach. The test sequence was mainly based on the following criteria:

- Electrical connections should be verified before closure of the cryogenic lines by TIG welding;
- All welds should be helium leak-tested (with minimum number of interventions) and remain accessible in case a repair is needed.

An example of the installation sequence for the IT is as follows. The preparation of the jumpers of the cryogenic distribution line, which implies cutting of the external envelope and internal lines, takes place before installation of the magnets or DFBX. In parallel kits of components are prepared on the surface, and mechanical and electrical interfaces on the magnets are prepared and checked for their conformity. Special attention is paid to vulnerable elements such as bellows expansion joints and superconducting cables. During installation and before alignment of the magnets, a 32 m copper tube is inserted in the heat exchanger tube of the Q3 magnet to supply helium from the DFBX upwards to the end of Q1.

Once the magnets are aligned, the splices between the superconducting Nb-Ti main busbars (13 kA, 8 kA and 5 kA) and corrector leads (600 A and 120 A) are performed. The instrumentation wires are connected through a connector or by soft soldering. The splices are insulated with a polyimide film (Kapton©) and a GFRE box to ensure the required insulation level. The quality of

the soldered connection is immediately checked by an electrical test that encompasses continuity and resistance measurements of superconducting and quench heater circuits, verification of the polarity of circuits, and verification of vacuum instrumentation cables. Then the cryogenic lines of the heat-exchanger and cold-mass are welded, followed by a second electrical test to verify that the welding did not affect the electric cables.

The beam-lines are then closed by welding the so-called plug-in module (a module that ensures beam-screen and cold-bore continuity). The beam-lines that operate in ultra high vacuum are visually inspected for cleanliness with an optical device. This is followed by welding of other cryogenic lines such as thermal shield (50-70 K), beam screen (4-20 K) lines. All the welds are visually inspected. Since 50% of the welds are done manually, about 90 welds are radio-graphed (γ -ray) to detect defects such as lack of penetration, root porosity, tungsten inclusion, and are evaluated according to welding class B (ISO 5817). The radiographic control is limited to butt- and fillet- welds with a tube thickness of approximately 2 mm. Each weld is leak tested under vacuum, clam-shell or accumulation. The two first methods are preferred because of the test rapidity and the good sensitivity in case of small volume to be evacuated.

To minimise heat in-leak to the cold-mass, the tubing is insulated by multi-layer insulation (MLI) and is enclosed in an aluminium thermal shield that is actively cooled at 50 K and covered with MLI. The cables for the Beam Position Monitor are installed and finally the outer envelope of the cryostat is closed with clamp-sealings and jumper connections by welding. A global leak-test including the QRL will evaluate the leak-tightness of the outer envelope.

Qualification of Processes

Before the interconnection work in the tunnel, a string of the complete IT (Q1 up to D1) was pre-assembled on the surface (see Fig. 4). Although connections were not welded, it was useful to validate the design of the different interconnection components and procedures, polarity of the electrical cables and displacement of the supports under vacuum.

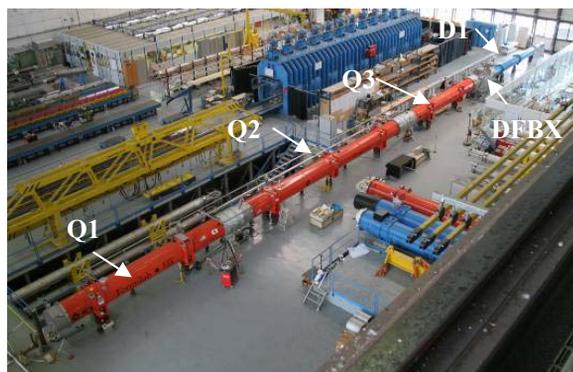


Figure 4: The string of the IT to validate design and installation procedures.

Due to their complexity and the space restrictions for the interconnection activities, several processes and operators were trained and qualified on the surface before implementation in the tunnel. For example the electrical connection between Q4 (CERN) and D2 (US-collaboration) was developed at CERN. Samples were made with the tooling on real cables in order to estimate the contact resistance ($\sim 1n\Omega$ for the splices of the semi-standalone magnets) and to define the overlap of the main bus-bars. High voltage tests have also been carried out to check the insulation with polyimide film and GFRE supports.

Automatic and manual welding of the different types of welding joints were qualified. Given the high number of different configurations (65 manual welds and 80 automatic welds per LSS), the number of qualifications has been reduced to 9 in accordance with ISO 15614-1. Samples were analysed by X-ray and macroscopies. Welders were qualified according to the norm EN287-1 on mock-ups simulating the configuration in the tunnel.

Interconnection Activities and Quality Control of the LSS at Point 8L

The interconnection activities at point 8L started in January 2006. For the first electrical interconnections, knowledge transfer took place between participants from Fermilab, BNL and CERN. At the moment, 90% of the interconnection activities in 8L are completed including around 140 welds, of which 73 were controlled using γ -rays. The type of defects as a function of type of weld is presented in Table 1.

Table 1: Welding defects in LSS 8L

Weld type	Manual / Auto.	OK	Not OK	Defect
Butt	A	16	4	Lack of penetration (3), Root porosity (1)
	M	9	4	Lack of penetration (1), Root porosity (3)
Fillet	A	10	0	
	M	12	4	Concave (1), Root porosity (1) Lack of penetration (2)
Edge	A	8	0	
	M	5	1	Tungsten inclusion (1)
		82%	18%	

The main causes for the defects were:

- Bad preparation of the tubes;
- Welding parameters that needed to be optimised for the real tube thicknesses (intensity);
- Insufficient backing protection of the welding ring for the manual butt-welds with persistent rings;
- Too much pressure for backing gas (Argon).

All non-conform welds were repaired and controlled again using γ -rays until the result was acceptable. This learning period led to the optimisation of the welding parameters and to the use of a backing gas (Argon) for all manual butt welds. In practice this means that for certain welds volumes up to 3-4 m³ (cold-mass circuit from Q1 up to D1) have to be filled with Argon. The interfaces of the interconnection components did not always match with the interfaces on the magnets. Also residual stresses after welding led to unacceptable transversal offset (± 1 cm) of compensating bellows on the cold-mass circuit. Both were corrected in situ with compensating welds using Argon backing protection to avoid root porosity. After welding, all welds were leak-tested using helium spectroscopy with a sensitivity between 10^{-9} and 10^{-7} mbar.l/s depending on the circuits. No leaks were found.

At each step of the assembly, the interconnection work is inspected. Visual inspections are carried out by CERN and by HNINP inspectors before and during the interconnection activities. Before interconnection, components and cryo-magnet extremities are inspected in particular sensitive elements such as bellows expansion joints or superconducting cables. A typical damage observed on bellows is a local bulk of the thin wall. To prevent this, protecting shells are installed around the bellows. During the interconnection activities, inspections consist mainly of visual control of the welds, electrical splices and their insulation, bellows and beam lines inspection with an optical device. Several non-conformities were opened and led to improvements. For example the electrical insulation of the corrector leads was changed to a demountable GFRE housing to facilitate brazing. Visual inspections of the beam-lines that operate under ultra high-vacuum revealed metallic dust (Cu, C, Pb, Sn) which led to additional cleaning operations in situ. Some of the tooling for automatic welding is being modified in order to match the actual components.

CONCLUSION

The first interconnections of the LHC LSS have been completed with the high required quality level. The experience acquired during this learning period will help to improve the installation sequence as well as to optimise the technologies for the next LSS interconnections.

The authors would like to express their gratitude to all people from US collaboration for their support, HNINP and CERN colleagues that are involved in the LSS interconnection work.

REFERENCES

- [1] "LHC design report", Volume 1 the LHC main ring, CERN-2004-003.
- [2] P. Pfund, "Inner triplet systems at IR 1, 2, 5 and 8", Functional specification, CERN & FNAL, EDMS 108981.