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AN AUTOMATIC ULTRASONIC WELDING PROCESS FOR INTERCONNECTING SUPERCONDUCTING WIRES OF THE CERN LARGE HADRON COLLIDER (LHC)

J.C. Brunet, A. Chatelain*, A. Jacquemod, I. Monteiro*

Abstract

The Large Hadron Collider (LHC), the next research tool for particle physics at CERN, is due to start operation in 2005. The main components of the LHC are the superconducting twin-aperture magnets, operating at a temperature of 1.9 K.

A large number of auxiliary superconducting wires have to be interconnected in series to electrically feed, at 600 A, the main dipole and quadrupole corrector magnets. To interconnect these wires, an ultrasonic welding process has been developed and compared to the former soft-soldering technique.

An industrial ultrasonic welding machine has been adapted and automated to satisfy the reliability and reproducibility. A high strength mechanical junction between wires has been obtained over the operating range from 293 K to 1.9 K.

Results of mechanical and electrical validation tests are presented.

LHC Division
*LAPP, Chemin de Bellevue, 74941 Annecy-le-Vieux, France

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CERN
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Jean-Claude Brunet, Alexandre Chatelain*, André Jacquemod, Inocencio Monteiro*

LHC Division, CERN, 1211 Geneva 23, Switzerland
*LAPP, Chemin de Bellevue, 74941 Annecy-le-Vieux, France

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1. INTRODUCTION

The 1650 main LHC cryomagnets (Figure 1), comprising more than 6000 superconducting corrector magnets, are connected in series and housed in 8 arc cryostat strings along the circumference. The corrector magnets are powered in series via 600 A superconducting wires, housed either in the main magnet 1.9 K superfluid helium filled cold mass or in cables, contained in a tube running along the magnets' side and operating at 4.5 K or 1.9 K.

The magnets are subjected to temperatures ranging from 300 K to 4 K and operating pressures of 0.13 MPa, with a maximum value of 1.2 MPa, during cool-down and warm-up transients.

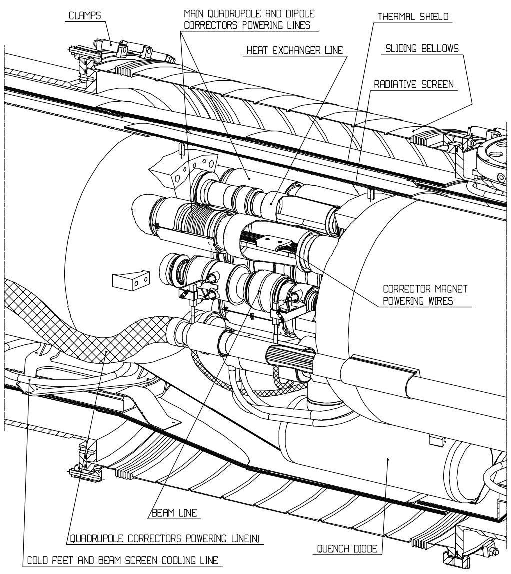

Figure 1 LHC Standard Interconnection

The corrector magnet powering wires are composed of NbTi filaments, embedded in a copper matrix. The dipole corrector magnets are powered via 20 rectangular wires, positioned above the main bus-bar current lines.

Concerning the quadrupole corrector magnets, the powering cables are composed of 42 circular wires. These cables are placed in a separate pipe (N line), which is coupled to the main magnet cold mass.

The mechanical strength of electrical connections must be sufficient to endure the assembly process and the thermal constraints induced by the thermal transients during cool-down and warm-up. To limit the ohmic power deposited in the superfluid helium to reasonable values, each connection must present an electrical contact resistance lower than 10^{-8} Ω.

There are a total of about 32000 junctions for the dipole corrector magnets and 18000 for the quadrupole corrector magnets. The consequent high number of connections requires a particularly strict quality control during the execution and verification phases.

2. TESTS AND PERFORMANCE OF DIFFERENT JOINING TECHNIQUES

Different methods were considered to provide the electrical continuity of the LHC auxiliary superconducting lines. Identical mechanical and electrical tests have been conducted for each technique considered.

The choice is guided by the following main requirements: electrical contact resistance at 4.2 K, mechanical resistance at 4.2 K, at least equal to that of the wire. The main parameters are: reproducibility of the two above requirements, continuity and integrity of electrical contacts and insulations, possibility of applying the joining method in a restricted space, possible automation of the method and field robustness of the joining process.

Most of the junction techniques studied required a special preparation of wires, especially for the circular ones. The methods tested on the two types of cables are indicated in Table 1, together with their characteristics and results of electrical resistance measurements.

METHOD	COMMENTS	Electrical contact resistance at 4.2 K (10^{-9} Ω)
BRAZING	Well-known method, easy to perform. Possibility of disassembling and reassembling. Etching flux necessary. Oxides are not completely removed. High values of electrical contact resistance. Overlap must be at least 50mm.	5 to 35
SLEEVE CRIMPING	Possibility of using a special material for the sleeve (Cu or Nb). Not easy to perform, big devices necessary. Oxides are not removed, high electrical contact resistance (not measurable). Visual control not possible.	> 1000
COLD PRESSURE WELDING	Clean method, except burrs that must be removed. No specific preparation necessary. Poor repeatability. High value of electrical contact resistance.	>1000
ULTRASONIC WELDING	Self-cleaning of the oxide layers due to friction between cables. No heat produced high repeatability (automatic machine). Very high mechanical resistance, very low electrical contact resistance. Special development necessary due to poor experience (recent technology).	3 to 6

Table 1 Joining method candidates

3. THE CHOICE OF ULTRASONIC WELDING

As apparent in Table 1, the ultrasonic welding method is the most efficient.

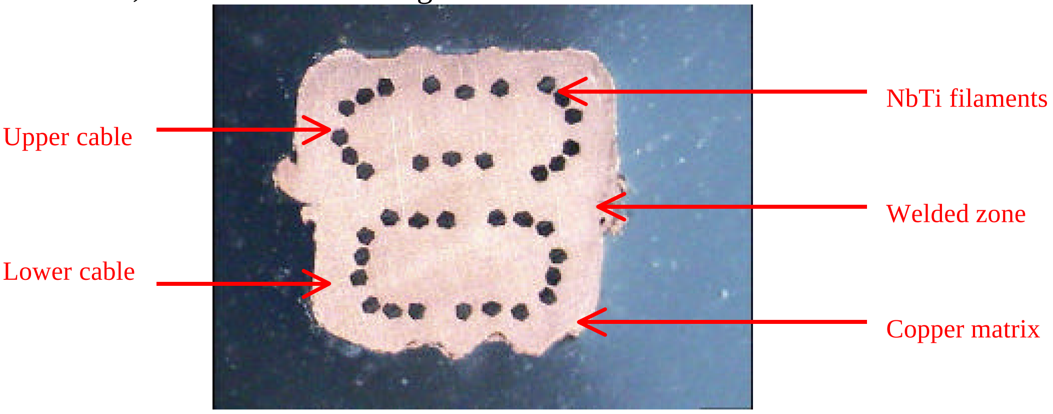

Figure 2 Ultrasonic weld on LHC auxiliary cables

Its main advantages are:

- no special preliminary cleaning (except insulation removal) is required to apply the process; oxide layers on the wires are completely removed during the application of the ultrasonic motion and force,
- clean technology (no detachable burrs), no additional material required (filler or flux),
- very short welding time (fraction of second),
- excellent electrical conductivity in the weld area,
- good mechanical strength,
- possibility to automate and industrialise the process, the human factor thus being minimised,
- good reliability and reproducibility after optimisation of the process parameters.

The only drawback of the ultrasonic welding method is the necessity to develop a special machine for the LHC application. In addition, the welding tool is heavy and bulky.

Some parameters, not directly linked to the process, have to be controlled in order to obtain a high reliability. These parameters concern the cable and its insulation: cleanliness, surface roughness and dimensions.

The process parameters have been studied and optimised by LAPP, through a collaboration contract with CERN. These parameters are essentially: the power applied during the weld, the applied compression to the wires to be welded (driving-in), the total energy applied, other mechanical and geometrical parameters (length, etc.) and copper cleanliness and surface roughness.

4. ULTRASONIC WELD PERFORMANCE

4.1 Electrical Contact Resistance at 4.2 K

The measurement of a very low electrical resistance between two superconducting wires is not a trivial matter.

The electrical contact resistance is only relevant at the temperature of liquid helium at which the NbTi material is superconducting, i.e. 8 K and below. A simple, usable, correlation between electrical properties at room temperature and at 4.2 K does not exist.

The electrical resistance of the junction was measured on a special bench designed at CERN [1,2].

The method is based on the measurement of the current decay time constant in a loop of known inductance incorporating the superconducting wire and the soldered junction.

The ultrasonic welding technique gave the lowest values of electrical contact resistance of all methods tested. The values were systematically situated between 5 and 9 x 10^{-9} Ω, thus allowing to consider a semi-industrial procedure, to be considered.

The driving-in parameter was identified as a fundamental one. If this parameter is within the limits defined in the procedure (0.75 to 0.95 mm), a good electrical contact resistance value (2 to 9 x 10^{-9} Ω) can be guaranteed, and the weld is qualified for its working temperature (1.9 K) (Figure 3).

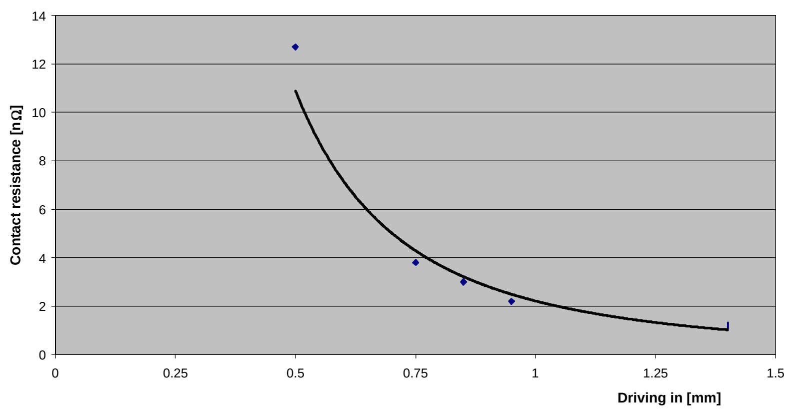

Figure 3 Electrical contact resistance as a function of driving-in

4.2 Mechanical Performance at 4.2 K

The manipulations that will be applied on the wire, during the preparation and insulation, require good mechanical properties to be obtained at room temperature. The mechanical resistance must also be excellent at the working temperature, to cope safely with electromechanical forces and thermal strains. During cool-down and warm-up of the LHC, and during the magnet quenches, high mass flow rates of liquid helium could cause some mechanical deformations to the wires.

During tensile test at 4.2 K and at room temperature, two rupture cases appeared: rupture in the wire (far from the weld, rupture normal stress 428 MPa) and rupture in the weld (rupture normal stress 478 MPa).

The best that one can expect is to obtain a rupture in the base material far from the weld. A rupture in the weld could shed suspicion on its quality.

However, all the rupture values were found to be acceptable, the minimum allowed value being 750 N (corresponding to the rupture stress of pure annealed copper, 250 MPa).

Voluntarily damaged samples have been measured to confirm the optimisation of the relevant welding parameters. Their mechanical resistance was very low at room temperature, but acceptable at 4.2 K. The electrical contact resistance was higher than $15 \times 10^{-9}\ \Omega$.

5. CONCLUSIONS

The ultrasonic welding technique produces welds that meet the requirements of reliability and reproducibility of the LHC superconducting electrical circuits feeding the 600 A corrector magnets.

The mean value of $3 \times 10^{-9}\ \Omega$ electrical contact resistance in the junction welds of all the 600 A auxiliary bus bars limits the parasitic ohmic power dissipated into the superfluid helium to less than 10 % of the total dissipated power; the main source being the 13 kA electrical junctions between the main magnet bus bars.

A good correlation is obtained between the driving-in parameter value and the contact resistance at 4.2 K. This will permit to estimate the weld performance just after its execution.

Most of the tested samples broke in the base material (at 293 K and 4.2 K) with a force largely higher than the 750 N requested.

6. ACKNOWLEDGMENTS

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REFERENCES

1. Herzog, R. and Hagedorn, D. Inductive Method to Measure Very Small Joint Resistances of Superconducting Wires Proceeding of ICEC 17 (1998), 495-498
2. Hagedorn, D. CERN Internal Project Note, SPS/EMA/note 78-22, unpublished