EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 883

Qualification and Start of Production of the Ultrasonic Welding Machines for the LHC Interconnections

A. Jacquemod[1], J.Ph. Tock[1]
J.M. Balaguer[2], F. Laurent[2], L. Vaudaux[2]

Abstract

The Large Hadron Collider (LHC) is presently under installation at CERN, Geneva. The approximately 4000 superconducting corrector magnets required by the machine are powered through copper-stabilized Nb-Ti busbars. To interconnect the magnets along the machine, about 50 000 joints between superconducting cables rated at 600 A have to be performed in-situ during the interconnection activities. An ultrasonic welding technique has been developed and optimised by CERN which led to the development of a dedicated machine which was qualified during the assembly of the STRING II, a 110-m chain of cryomagnets assembled as a prototype of the LHC.
The realization of the "series" interconnections together with the procurement of the tooling based on functional specifications have been contracted to a consortium of firms. Qualification tests and acceptance criteria in terms of electrical contact resistance, mechanical resistance, reliability and reproducibility have been defined by CERN. This paper presents the tests and some results of the qualification process relevant to the industrialized tooling provided by the contractor. Results of pre-series junctions done in the LHC tunnel are presented together with the perspective for the continuation of the work.

1 CERN, Accelerator Technology Department, Geneva, Switzerland
2 IEG, Villeurbanne, France

Presented at the 19th International Conference on Magnet Technology (MT19)
18-23 September 2005, Genova, Italy

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 19 May 2006

Qualification and Start of Production of the Ultrasonic Welding Machines for the LHC Interconnections.

A. Jacquemod, J.Ph. Tock, JM. Balaguer, F. Laurent, L. Vaudaux

Abstract— **The Large Hadron Collider (LHC) is presently under installation at CERN, Geneva. The approximately 4000 superconducting corrector magnets required by the machine are powered through copper-stabilized Nb-Ti busbars. To interconnect the magnets along the machine, about 50 000 joints between superconducting cables rated at 600 A have to be performed in-situ during the interconnection activities. An ultrasonic welding technique has been developed and optimised by CERN which led to the development of a dedicated machine which was qualified during the assembly of the STRING II, a 110-m chain of cryomagnets assembled as a prototype of the LHC.**

The realization of the "series" interconnections together with the procurement of the tooling based on functional specifications have been contracted to a consortium of firms. Qualification tests and acceptance criteria in terms of electrical contact resistance, mechanical resistance, reliability and reproducibility have been defined by CERN. This paper presents the tests and some results of the qualification process relevant to the industrialized tooling provided by the contractor. Results of pre-series junctions done in the LHC tunnel are presented together with the perspective for the continuation of the work.

***Index Terms*— LHC, Mechanical tests, Superconductor, Ultrasonic welding.**

I. Introduction

THE LHC machine optical layout includes some 4000 superconducting corrector magnets to ensure the perfect guiding and focusing of the two proton beams. These magnets are powered in series through two different types of superconducting busbars rated at a maximum current of 600 A. These so-called "auxiliary busbars" run parallel to the main busbars powering the main magnets (13 kA). To ensure the powering of the magnets, about 50'000 joints have to be performed around the LHC [1]. In order to limit the heat dissipation in the superfluid helium bath (1.9 K) and to power the corrector magnets with minimum losses, each joint must have an electrical contact resistance lower than 18 nΩ at the operating temperature.

After a study of the available joining technologies, the ultrasonic welding process was selected on the basis of its superior performance [2].

The first ultrasonic welds realized on samples and later on for the prototype of a LHC cell (String II) showed that this technology allowed to obtain reliably contact resistance values in the range of 2-6 nΩ. The mechanical and fatigue resistance was also tested on this prototype bench.

The decision was then taken to adapt standard industrial machines to meet the specific LHC requirements and to fit within the LHC interconnections geometry and space constraints.

Installation work is presently on-going and the results obtained are within expectation.

II. The LHC Superconducting Auxiliary Busbars

There are two types of auxiliary busbars. The first one is used to power the so-called "spoolpieces" which are superconducting corrector magnets located in the main dipole magnets helium enclosure (cold mass). Busbars consist of a rectangular shape (2.17 x 1.45mm) monolithic conductor with Nb-Ti filaments in a copper matrix (Fig. 1).

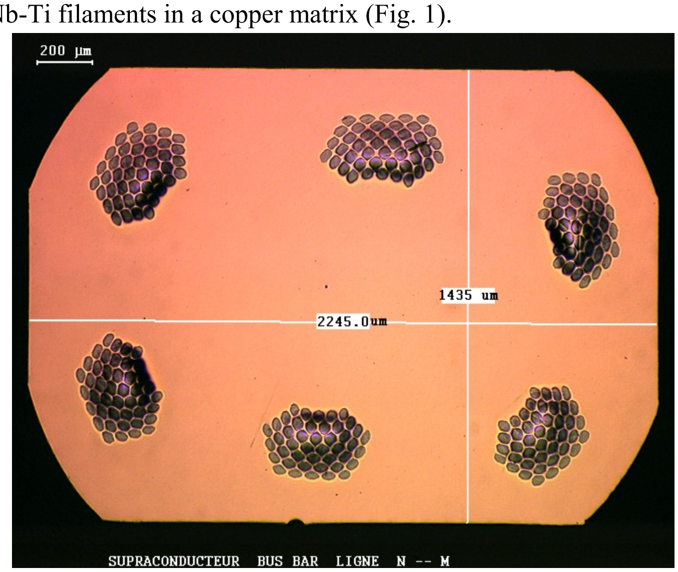

Fig. 1. Spoolpiece corrector magnet busbar section

Twenty busbars of this type are routed through the main cryomagnets. They have to be interconnected between each of the 1,700 cryomagnets, totalizing about 34,000 splices located in lines M1 and M2.

The second type is dedicated to the powering of the

Manuscript received September 20, 2005.

A. Jacquemod and J.Ph. Tock are CERN staff members, belonging to AT-CRI-CI section, responsible for the LHC Interconnections. J.M. Ballaguer, F. Laurent and L. Vaudaux are with the IEG consortium in charge of the interconnections of the LHC cryomagnets.

corrector magnets situated in the main quadrupole magnets.

It consists of cylindrical wires of diameter 1.6 mm made of Nb-Ti filaments in a copper matrix (Fig.2). 42 such wires are twisted together to form a 16mm diameter cable sheathed with a stainless steel braid (Fig. 3). This cable is inserted in a pipe running parallel to the cold masses, the so-called line N, and must be interconnected at the level of each quadrupole, i.e. every half cell. For the LHC machine, this represents a total of 16,000 joints.

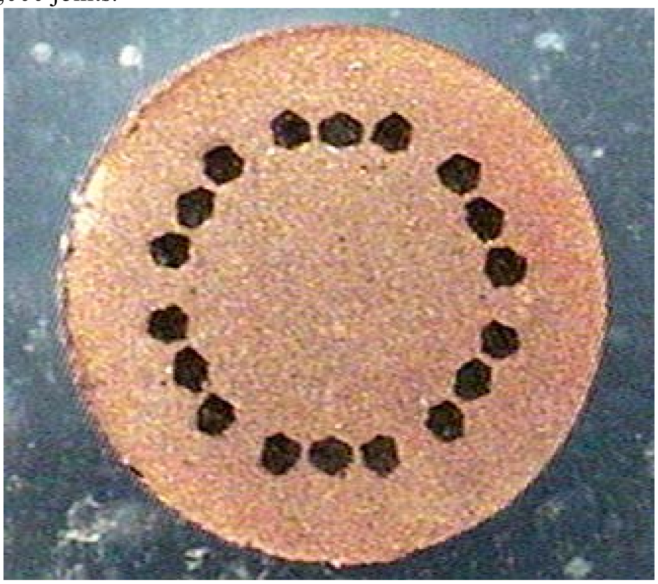

Fig. 2. Line N busbar section

Fig. 3. Line N cable

III. The Ultrasonic Welding Process

The ultrasonic welding technology is based on the principle of friction weld. It has been chosen to join the LHC superconducting auxiliary busbars because of several advantages compared to “standard” electrical joining methods.

- Clean method, no use of brazing flux or soldering material
- High mechanical resistance
- Low electrical resistance
- High level of repeatability and reliability [3]
- Automatic process control

A ultrasonic welding machine for metallic materials is made of two major elements: the anvil and the horn. The anvil is the base where the samples to be welded must be gripped. The horn (also called sonotrode) is the active part which presses on the two cable extremities to be joined (Fig. 4) and transmits the friction energy. The geometry of horn and anvil contact surfaces are machined in order to obtain a gripping surface penetrating in the copper matrix of the superconducting cables, thus preventing them from sliding. During the welding process, the horn is activated with a transverse ultrasonic movement (20 kHz) of a few hundreths of millimeter amplitude, while pressing the cables at a pressure of about 5 bar. Friction between cables removes the oxide layers and produces a weld (Fig. 5).

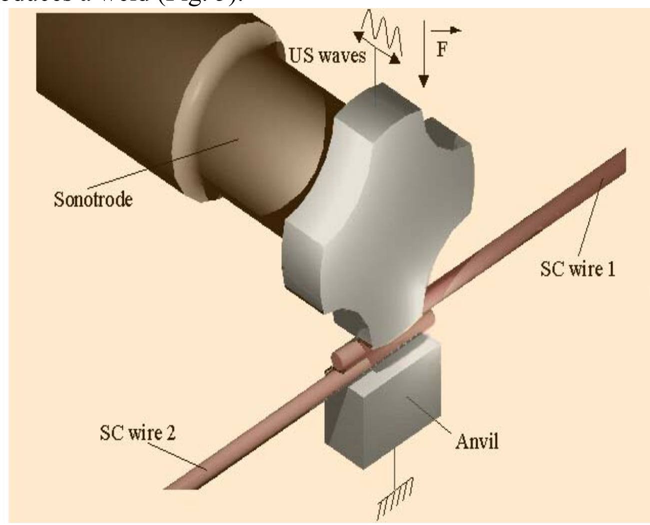

Fig. 4. Ultrasonic welding process

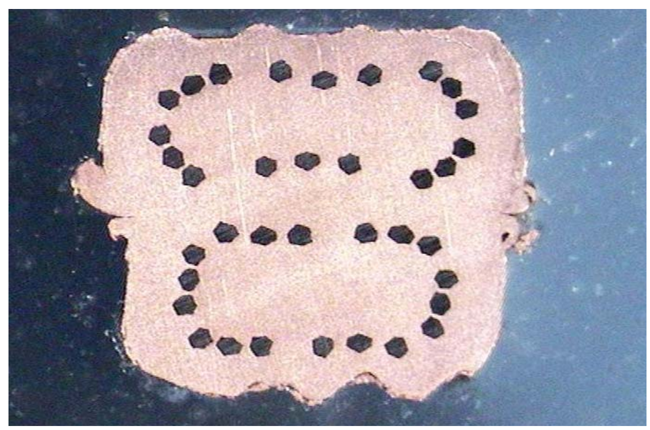

Fig. 5. Spoolpiece joint made with ultrasonic welding (radial section)

Some important parameters have to be properly optimised and controlled in order to achieve the required performance:

- Welding pressure
- Drive in (movement of horn after contact)
- Energy
- Welding time
- Weld final thickness

All these parameters are automatically controlled in closed loop by the machine itself. A laptop PC acts as operator interface. On-screen information is given for each weld concerning the output parameters and if any important defect in the process is clearly identified and the weld is rejected (Fig. 6). The parameters are automatically recorded in a database.

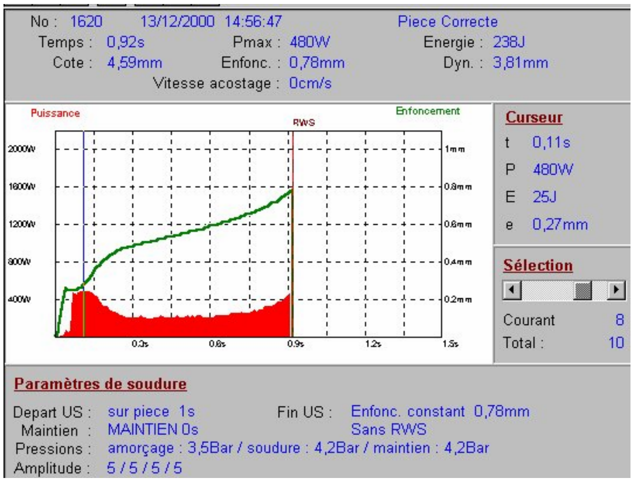

Fig. 6. Example of "on screen" process control

IV. Industrial Integration of Ultrasonic Welding Machine

The industrial standard welding machine had to be integrated in a special device to fit within the LHC magnet interconnections geometry and space available. The machine is assembled into a special frame which provides displacements along 4 axis to reach the 3 operating positions (respectively lines M1, M2 and N) (Fig. 2) where the ultrasonic welds have to be performed (Fig. 7). These 3 positions can be reached without disassembling the frame from the interconnection, thus minimising the handling operations.

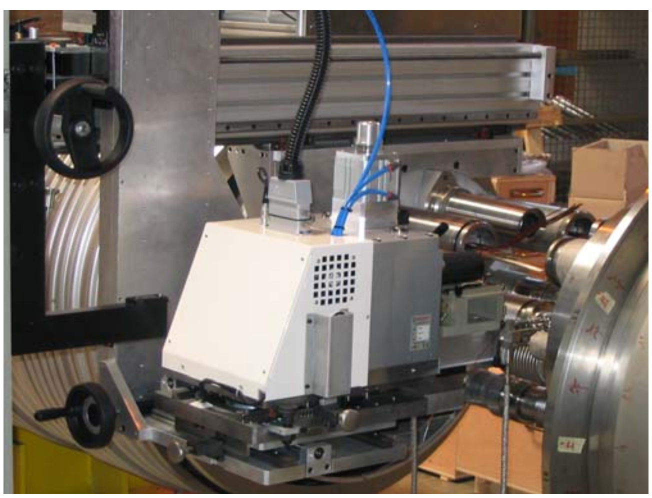
Fig. 7. Ultrasonic welding machine during operation

V. Qualification and Results

The CERN quality assurance plan imposed to the supplier individual qualification for each machine. A full automatic quality control and welding parameter data logging during production was also required [4].

Three main criteria of weld quality guided the qualification procedure:

- Mechanical resistance
- Electrical contact resistance
- Visual inspection

A. Mechanical resistance:

Mechanical contraction and expansion of busbars during cool down and warm up are simulated in fatigue life tests at room temperature (RT).

Tensile tests are also imposed to verify the mechanical resistance of the joints at room temperature (RT).

The type N and type M busbars are connected in two different ways. Cables are joined "side by side" for line N type and "in line" for line M type (Fig. 8). This explains the differences between the specified values given in Table I.

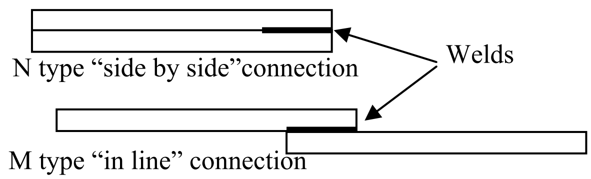

Fig. 8. The two types of ultrasonic welds

TABLE I
MECHANICAL TEST RESULTS

	Type N Busbar	Type M Busbar
Traction Force RT (Specified)	>40N	>480N
Traction Force RT (Measured)	53N	600N
Fatigue Life cycles RT (Specified)	>1000 cycles	>1000 cycles
Fatigue Life cycles RT (Measured)	3000 cycles	5000 cycles

B. Electrical contact resistance

In order to limit thermal losses induced by electrical contact resistance of the busbars joints, a maximum value of 18 nΩ has been specified for each of the about 50,000 joints.

A special measurement method was developed at CERN to measure such small values of electrical contact resistance of superconducting joints at 4.2 K (Fig. 9) [5].


Fig. 9. Superconducting wire loop in the device for contact resistance measurement

This method is based on the measurement of a current decay as a function of time in a superconducting current loop including a resistive junction. The current decay time constant and the loop inductance allow to calculate the joint resistance.

Results obtained during the qualification process of the series machines are as expected and are shown in Table II.

TABLE II
ELECTRICAL TESTS RESULTS

	Type N Busbar	Type M Busbar
Electrical Contact Resistance	**5.21** +/- 1.5 nΩ	**2.56** +/- 1.5 nΩ

For further analysis and reference, all the test results are archived in a dedicated database, as stipulated in the LHC Quality Assurance Plan.

C. Visual Inspection

Two types of visual inspections are carried out to evaluate weld quality.

The first inspection is purely visual and must be performed for each joint immediately after welding. A few parameters can be evaluated (Fig. 10):

- Presence of small "burrs" in the joint
- Absence of surface cracks
- Absence of rupture initiation

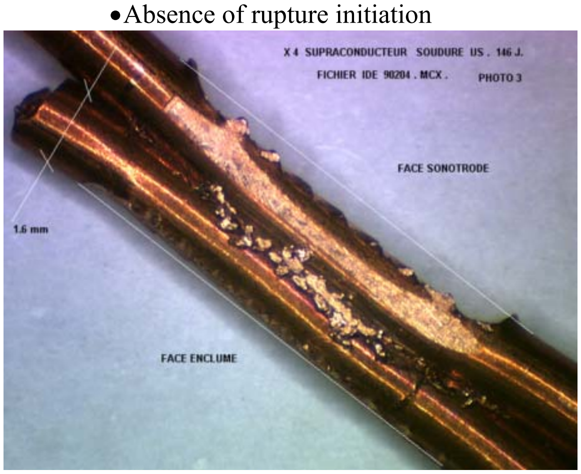

Fig. 10. Ultrasonic weld visual inspection

The second inspection is done on witness samples produced in parallel with the field welds. Samples are submitted to a metallographic analysis (Fig. 11).

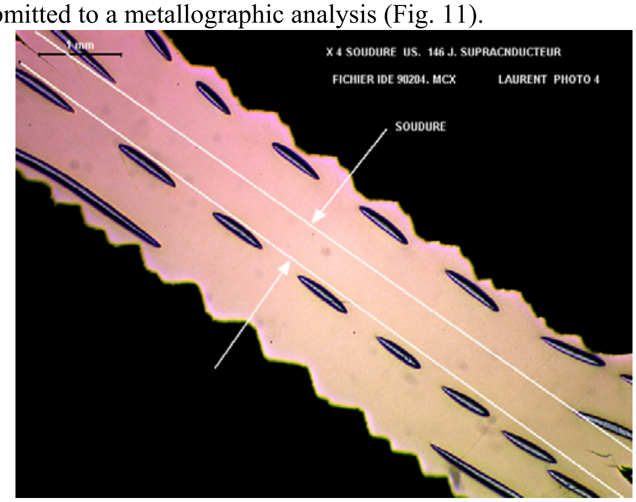

Fig. 11. Longitudinal cut in ultrasonic weld

The inspection must be performed by an expert. The quality control focuses on:

- Integrity of superconducting filaments
- Quality of the copper/copper interface
- Absence of cracks due to mechanical stress during process

VI. Conclusion

The excellent and reproducible results obtained with the ultrasonic welding technique to perform joints between magnet corrector busbars led to the choice of this technique for the LHC interconnections. This joining technology minimizes the thermal losses due to electrical contact resistance. The maximum specified contact resistance (18 nΩ) was easily respected, with a large safety margin (2 to 6 nΩ obtained).

The mechanical resistance of ultrasonic welded joints was also studied and the results obtained for what concerns fatigue life and tensile resistance are excellent.

All the tests carried out and the field validation on the String II prototype LHC cell showed that it was possible to obtain the "laboratory" values on the industrial applications.

Fully integrated industrial ultrasonic welding machines are presently used with success on the assembly of the real LHC machine.

Acknowledgment

The development of the ultrasonic welding process applied to the LHC superconducting busbars has been carried out within the frame of a collaboration agreement between the Laboratoire d'Annecy-le-Vieux en Physique des Particules (LAPP) and CERN. Special thanks are going to CERN, IEG(Ineo-Endel-GTI) and Mecasonic (Annemasse France) technicians and engineers who participated to the success of this specific development.

References

[1] J.Ph. Tock, A. Jacquemod, A. Poncet, B. Skoczen, « The Interconnections of the LHC Cryomagnets », Proceedings of the Particle Accelerator Conference, Chicago, 2001

[2] J.C. Brunet, A. Chatelain, A. Jacquemod, I. Monteiro, An automatic ultrasonic welding process for interconnecting superconducting wires of CERN Large Hadron Collider (LHC), Proceedings of the ICEC 18, Mumbai, India 2000, pp107-110

[3] C.Garion, A. Jacquemod, A. Poncet, F. Schauf, B. Skoczen, JP. Tock, On the reliability oriented optimisation of the LHC interconnections, Proceedings of the EPAC 2002 Paris-La Vilette

[4] D. Bozzini, F. Laurent, S. Russenschuck, B. Skoczen, J.Ph. Tock, Electro-mechanical aspects of the interconnection of the LHC superconducting corrector magnets, Proceedings of the EPAC, Lucerne, 2004

[5] R. Herzog, D. Hagedorn, Inductive method to measure very small joint resistance of superconducting wires, 17th International Cryogenic Engineering Conference, Bournemouth 1998, IOP, Bristol 1998, p495