EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 1157

THE SPECIAL LHC INTERCONNECTIONS: TECHNOLOGIES, ORGANIZATION AND QUALITY CONTROL

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Abstract

In addition to the standard interconnections (IC) of the continuous cryostat of the Large Hadron Collider (LHC), there exists a variety of special ones related to specific components and assemblies, such as cryomagnets of the insertion regions, electrical feedboxes and superconducting links. Though they are less numerous, their specificities created many additional IC types, requiring a larger variety of assembly operations and quality control techniques, keeping very high standards of quality. Considerable flexibility and adaptability from all the teams involved (CERN staff, collaborating institutes, contractors) were the key points to ensure the success of this task. This paper first describes the special IC and presents the employed technologies which are generally adapted from the standard work. Then, the organization adopted for this non-repetitive work is described. Examples of non-conformities that were resolved are also discussed. Figures of merit in terms of quality and productivity are given and compared with standard IC work.

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Presented at the 11th European Particle Accelerator Conference (EPAC'08)
23-27 June 2008, Genoa, Italy

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 20 August 2008

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INTRODUCTION

In order to connect all the superconducting magnets (dipoles and quadrupoles) and the electrical feed boxes between them but also with the cryogenic distribution line, 2123 IC of 175 different types were carried out [1]. The continuous cryostat contains mainly superconducting magnets on an overall length of about 22 km. The special IC are taking place in the zones upstream and downstream from the 8 insertion regions. This paper focuses on the special IC, totalling 134 magnet-to-magnet IC of 86 types and 102 jumper connections to the cryogenic line of 48 types. The latter concerns the cryomagnets of the insertion regions (inner triplets, stand-alone and semi stand-alone magnets) but also the electrical feedboxes and superconducting links powering them, spread over a total length of more than 4 km. Even if representing “only” 11 % of the IC in quantity, it gathers 76 % of the variants and about 30 % of the manpower used. Flexibility and adaptability of the teams involved is obviously required to ensure the success of this task.

TECHNOLOGIES

The connections to perform in the special IC are similar to the ones in the arc so the applied strategy was to tailor the validated technologies and tooling to the particular needs. As the recurrence of the operations was lower, the investment in tooling was reduced because it could not be redeemed on a high number of repetitive operations.

Superconducting Busbars Soldering

In the standard IC, the production has relied on induction soldering for the main busbars (13 kA) [2]. As the cable geometry in the special zone is different, major modifications and re-qualification tests would have been necessary; it was judged more profitable to develop resistive soldering ovens (Fig. 1) that could be optimized more economically for each of the situations met in the special IC. This technique depends more on the ability and expertise of the operators; that is the reason why only some very experienced and skilled technicians were qualified to perform these connections.

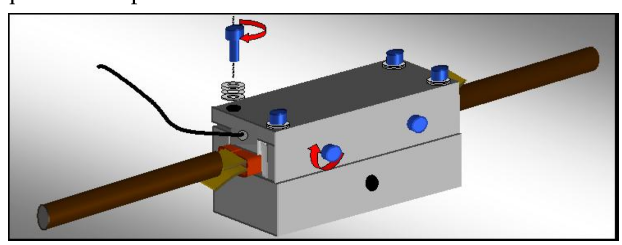

Figure 1: Design of an oven for resistive soldering

Ultrasonic Welding

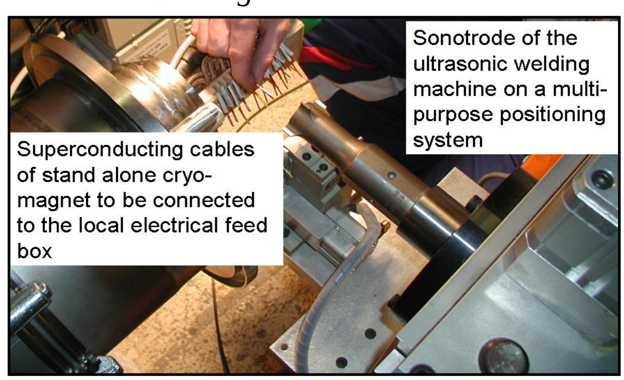

Figure 2: Ultrasonic welding in the special IC

The ultrasonic welding technique used to connect the auxiliary and spool pieces busbars presents many advantages as already reported [3]. As only minor adaptations to the anvil and the mechanical structure were necessary to apply the tooling in the special IC, it was preferred to use it after adaption at a reasonable cost (Fig. 2).

TIG Welding

As the variety of weld configurations was large, it was not economically viable to procure an automatic orbital welding machine for each of them. Some configurations were almost unique. For space constraint reasons, it was not possible to standardize the welding geometries. The applied strategy was to use orbital welding machines from the standard IC whenever possible and, for the other ones, to have them performed by a qualified manual welder. As a compensatory measure, the manual welds were X-rayed or γ-rayed in most of the cases.

Other Assembly Operations

In addition to the previously described operations, the continuity of the thermal shielding and insulation vacuum has to be ensured. Procedures and components similar to the standard IC ones are used. They are nevertheless less industrial, to cope with the singularities of the special IC. There again, the expertise of the technicians was mandatory to achieve conforming connections in a reasonable time.

Access

In the standard regions, even if the access was not easy, investment in tooling and accessories was done to alleviate this. This was not the case for the special IC. As an example, for one of the superconducting links, there was only one IC of a certain type located near the tunnel ceiling (Fig. 3) and so no expensive accessory was procured. Ad-hoc, inexpensive, but more time consuming solutions were implemented.

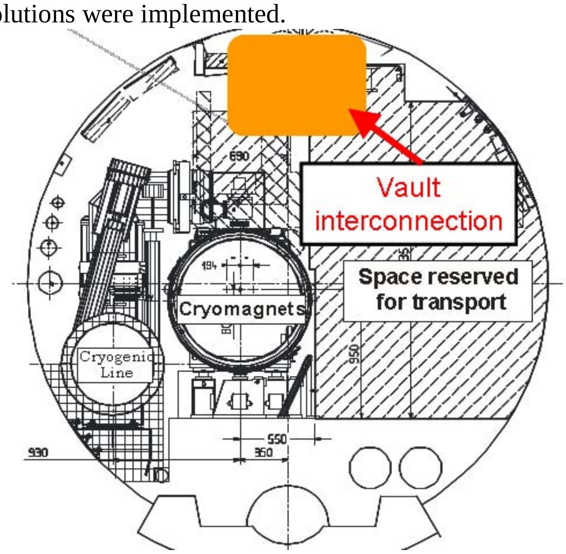

Figure 3: Location of link IC at point 3

ORGANIZATION

In order to benefit from the experience acquired in the IC of the LHC continuous cryostat, it was decided to have the work executed by the same contractor. But, as the work was highly non standard, it was done on a resource-oriented basis and with a strong involvement of the CERN team who had designed and validated all the IC procedures [1].

Even if taking place at geographically separated regions, the progress of the special IC was coordinated with the standard ones because links existed, both from the electrical and cryogenics circuits. Also, some resources were shared and an overall optimisation was necessary. A graphical view (Fig. 4) of the work progress has been defined, dividing the work in four main subtasks

- connection of the beam lines,
- electrical connections,
- connection of the cryogenics lines,
- thermal shielding and closure of insulation vacuum.

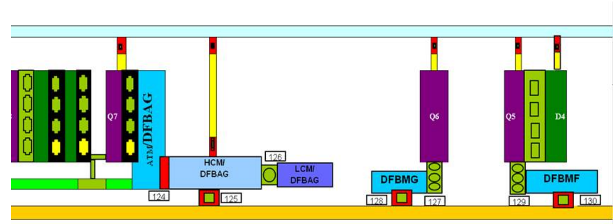

Figure 4: Extract of the graphical follow-up file

Each non-standard type of IC was created in the LHC layout. Workflows with work packages associated with inspection steps and drawing files have been defined. This allowed following the work, ensuring that all activities were carried out and test results were archived. The long-term availability of the relevant data, both for further operation and maintenance, is thus ensured.

NON-CONFORMITIES

Leak Tightness

Two types of junctions had to be leak tested: 2500 welds, equivalent to about 700 m of welded seam and 600 O'rings (up to 1 meter in diameter). The leak tightness specification, depending on the location and needs, was between 10^{-7} mbar l/s and 10^{-10} mbar l/sec. In addition to this tight requirement, the logistics and the access to the equipment were making the leak detection a difficult job. Table 1 summarises the origin of the 73 detected leaks.

Table 1: Origin of the Leaks

#	Component	Origin of the leak
20	O'ring	Dirt
9	O'ring	Incorrect assembly
5	O'ring	Glued O'rings (Imported)
21	Weld	Welding process (Some imported)
4	Weld	Incomplete weld
14	Weld	Imported component

From Table 1, it can be noted that, even with a strategy to leak test as early as possible in the process, at the component and sub assembly levels, 29 % of the leaks found at the final assembly stage in the tunnel were imported. The majority of leaks (45 %) were due to lack of care during assembly. Finally, only 26 % were directly linked to the welding itself. This represents a failure rate of about 0.8 %. This is higher than in the standard IC; this can probably be explained by the higher quantity of manual welds, the reduced possibility of learning and the more complicated access.

Another lesson learnt is that stainless steel bellows and flexible hoses were a significant source of leaks (5%) whose detection took a disproportional amount of time.

As an example, a 3-ply bellow with venting holes in the two outer plies was found leaky. A copper ring and copper sleeves were welded around the convolutions as a squirm protection. Surface stereomicroscopic observations of the central undulation of the inner ply, supposed to be leak tight, revealed oxidation and dimples of ductile rupture indicating that fusion had occurred and melted plies together at the location where the copper sleeve was welded onto the copper ring. An additional leak in the inner ply was found in the weld connecting the undulations to the end piece.(Fig. 5) Repair was delicate since the electrical connection between superconducting cables had to be unsoldered and flange interfaces modified to install the new bellows.

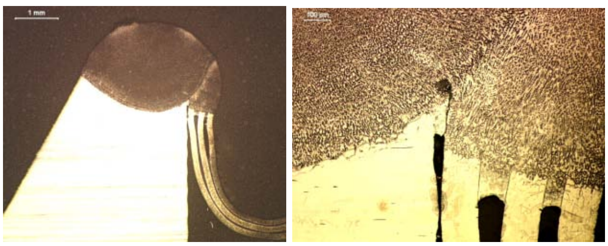

Figure 5: Analysis of leaking bellows

Electrical Tests

Within the LHC electrical quality assurance (ELQA) plan [4], four types of electrical qualification tests were systematically performed: a continuity check of the circuits, a polarity check of the magnetic elements, a verification of the electrical insulation and the measurement of reference parameters such as the transfer function of the impedance. About 1000 electrical splices were certified during the assembly of the special IC, to be compared with more than 60 000 tested in the standard IC. Table 2 summarises the tests and the number of electrical non-conformities detected during ELQA.

Table 2: Electrical Non-conformities in the Special IC

Qualification test	Executed tests	Qualified IC	Non-conformities
Continuity	1440	80	12
Polarity	1300	80	4
Elec. insulation	1950	80	6
Ref parameters	650	80	0

Most of the detected non-conformities where caused by small assembly defects that created local shorts to ground of the electrical conductors. Another type of recurrent faults was the wrong cabling before the ultrasonic soldering of the splices. These faults would have created a functional error in the electrical powering scheme. The two types of faults mentioned above were detected before proceeding to the next assembly phase and repaired without major impact on the IC assembly work. The most severe non conformity discovered was a short circuit to ground appearing on a 84 meter long superconducting link. The fault appeared only when 2 kV d.c. was applied to the tested circuit, while the nominal testing level was 3 kV. In this case the complete cable segment had to be dismantled and replaced with a new one.

The percentage of non conformities with respect to the total quantity of tests is 0.4 %. This good result is explained by the fact that the teams in charge of the execution of the special IC and of the electrical qualification were highly professional with excellent experience. Another factor is the continuous improvement and revision of the electrical testing according to the experience gained in the field.

All non conformities have been resolved and all LHC superconducting electrical circuits were approved to undergo the cool-down and the powering phases.

Cryomagnets Extremities

Being the last intervening team, non-conformities of the extremities were sometimes detected just before assembly and had to be corrected. Very often, the IC were modified to compensate. Making the correction at the last step was not efficient: this has generated a lot of extra-work and impacted the planning. Unfortunately, some inspections could not be anticipated because the extremities were capped, inaccessible for inspection.

CONCLUSION

The realisation of the special IC was carried out by an external contractor but under direct responsibility and supervision of CERN staff on a resource-oriented basis; embedded in a result-oriented contract signed after competitive tendering. This hybrid strategy allowed scale savings and flexibility in the allocation of resources for the special IC work. Due to the specificities of the work, a complete result-oriented contract would have been extremely time consuming to specify. The exhaustive validation and training of a CERN team during assembly of a representative test STRING was also mandatory to ensure the success of the IC work.

ACKNOWLEDGMENTS

Many CERN staff from AT and TS departments, and from external contractors must be praised for their participation in the successful achievement of this delicate and challenging enterprise.

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