EXPERIENCE WITH THE QUALITY ASSURANCE OF THE SUPERCONDUCTING ELECTRICAL CIRCUITS OF THE LHC MACHINE

D. Bozzini, V. Chareyre, A. Kotarba, K.H. Mess, S. Olek, S. Russenschuck,
CERN, Geneva, Switzerland

Abstract

The coherence between the powering reference database for the LHC and the Electrical Quality Assurance (ELQA) is guaranteed on the procedural level. However, a challenge remains the coherence between the database, the magnet test and assembly procedures, and the connection of all superconducting circuits in the LHC machine. In this paper, the methods, tooling, and procedures for the ELQA during the assembly phase of the LHC will be presented in view of the practical experience gained in the LHC tunnel. Some examples of detected polarity errors and electrical non-conformities will be presented. The parameters measured at ambient temperature, such as the dielectric insulation of circuits, will be discussed.

INTRODUCTION

The LHC accelerator is composed of 1750 superconducting circuits powering individual or series of superconducting magnets. From the electrical assembly point of view the most complex parts are the 8 long continuous cryostats that include circuits distributed over a length of 2.7 km. The continuous cryostat is composed of a chain of 204 cryo-magnets mechanically and electrically interconnected. At each interconnection, up to 74 superconducting circuits of three different types have to be joined. During the specification phase of the ELQA activities [1], the baseline method [2] for the Arc Interconnection Verification (AIV) application was developed. The software and the hardware prototypes where tested and calibrated on two chains of 5 cryo-magnets, already interconnected in the tunnel. During these tests, several electrical non-conformities were discovered which had not been detected during the manufacturing and individual test of the cryo-magnets prior to installation. A late discovery of non-conformities after installation in the tunnel has an impact on the overall quality assurance and causes delays in the interconnection activities. Based on the first experience, the ELQA activities have thus been adapted by introducing two additional types of tests which have been optimised to cope with the interconnection rate.

OPTIMIZATION OF THE ELQA ARC QUALIFICATION STRATEGY

During the preparatory and qualification phases of the ELQA, several non-conformities similar to the ones presented below have been discovered on cryo-magnets already installed in the tunnel. A review of test sequences revealed that the assumption of all installed components being free of electrical non-conformities cannot be taken for granted. The baseline assumed that only conform cryo-magnets are released for tunnel installation and that ELQA is concerned with detecting interconnection errors only. In order to grant the coherence of the built machine with the powering reference database, the overall ELQA strategy has been extended by implementing two additional tests during the assembly phase. The baseline AIV application that allows the qualification of two adjacent half-cells including the corresponding two line-N auxiliary bus bars cable segments is maintained. For the early detection of hidden non-conformities a Partial Assembly Qualification test (PAQ) has been introduced. PAQ testing assures the continuity and insulation to ground of the electrical circuits in a half-cell. As this intervention is confined to one half-cell (54 m) the test voltage could be increased to 500 V. Another test aims at discovering damage during the installation of the superconducting multi-conductor cable segments to be inserted in the so-called line-N. This High Voltage Qualification of line-N (HVQN) tests the level of the mutual insulation between the 42 wires and the stainless steel braid to ground and between the 42 wires, with DC voltages up to 1000 V. Fig. 1 shows the optimized strategy of the ELQA.

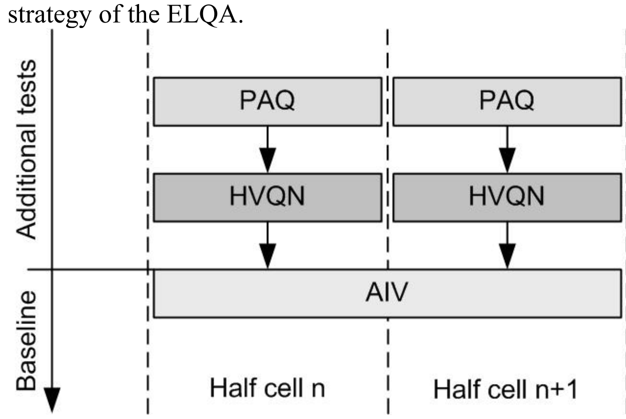

Figure 1: Optimized ELQA strategy to early detect hidden non-conformities at the components level.

Although more demanding in terms of resources, the application of the optimized ELQA strategy has the following advantages:

- Early detection of hidden non-conformities.
- Qualification of shorter assemblies resulting in a more accurate knowledge of the electrical characteristics such as the electrical insulation versus ground of the circuits.
- Preliminary electrical acceptance of a part of the circuitry resulting in an increase of flexibility for the mechanical activities those follow.

FIRST EXPERIENCES DURING LHC ELECTRICAL CIRCUITS ASSEMBLY

Case 1

Two tuning quadrupole (MQT) magnets are mounted in Apertures 1 and 2 of a cryo-magnet. Respectively a voltage-tap pick-up wire is connected to the lead A of each magnet and serves to identify the polarity and the position of the magnet. During the AIV qualification, the magnet in Aperture 1 was powered, but a voltage drop has been measured on the voltage-tap of the MQT magnet in Aperture 2. As shown in Fig. 2 this could be due to three different scenarios:

- Wrong voltage-tap labelling (left).
- Wrong labelling of corrector leads (middle),
- Mounting of the magnet in the wrong Aperture (right).

To conclude, it was necessary to open the beam line of Aperture 1 in order to verify the mounting by field measurements with a Hall-probe [3].

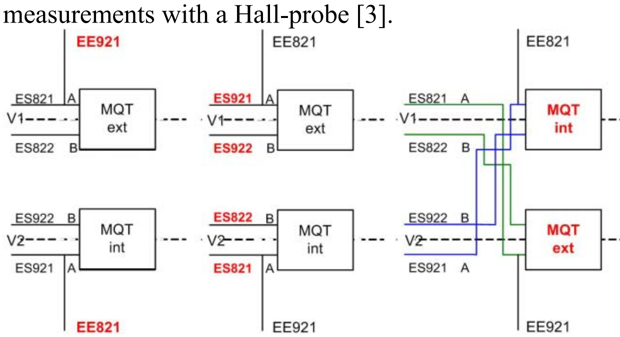

Figure 2: Three types of errors which are impossible to trace unless interventions are performed.

Case 2

During the execution of the first continuity qualification of the 20 spool-piece circuits in a chain of 5 cryo-magnets, a crossing between Conductors 9 and 10 was detected. A local check at the level of the three interconnections confirmed the correct interconnection and showed that the crossing was located inside a cryo-magnet. The non-conformity was resolved and will not affect the powering scheme. The labelling of the conductors has been locally modified at the level of the cryo-magnet and requires the tracing of the changes by the documentation in an as-built database. Fig. 3 shows the corresponding scheme after the corrective action.

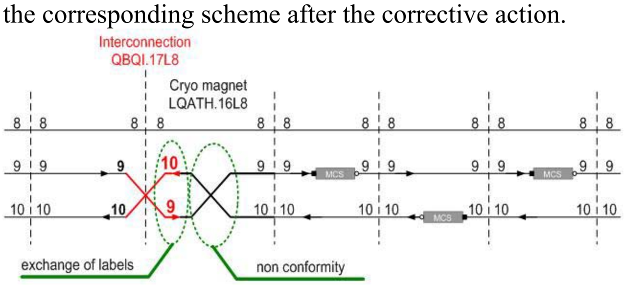

Figure 3: Scheme after resolution of the non-conformity of the spool piece continuity.

QUALIFICATION RESULTS

Status of the qualification activities

Table 1 summarizes the status of the ELQA qualification during assembly of the 8 continuous cryostats and the number of non-conformities discovered.

Table 1: Status of the ELQA qualification tests during the assembly of the 8 continuous cryostats.

Qualification type	Total number of tests	Tests done	Percentage	Non conformities
PAQ	384	52	13.5	3
HVQN	376	11	2.9	0
AIV	768	4	0.5	0

In total 13.5 percent of the total PAQ tests have been performed. During this qualification three non-conformities were discovered. Two were generated by the crossing between two conductors and could be immediately resolved. The third non-conformity consisted of a short to ground of a main dipole circuit segment. The localization of the short to ground required the development of adapted diagnostic methods [4]. The fault to ground was localized to be inside a cryo-magnet and not in the electrical interconnections between two cryo-magnets.

All together 11 Line-N segments have been installed and the corresponding HVQN tests have been carried out, all of them where successful.

Four AIV tests have been performed. The results obtained so far are within the specified parameters.

High voltage test results

The high voltage tests are of primary importance to certify the quality of the interconnection work and to detect any early degradation of the insulation of the-cryo-magnets and of the line-N segments.

Within the 52 PAQ tests completed, 1352 high voltage checks of sub-circuits have been successfully performed. The high voltage checks are done at 500V (DC) for a period varying from 30 to 120 seconds, depending on the circuit type. In Fig. 4 the leakage currents measured during the PAQ on the 26 sub-circuits are shown.

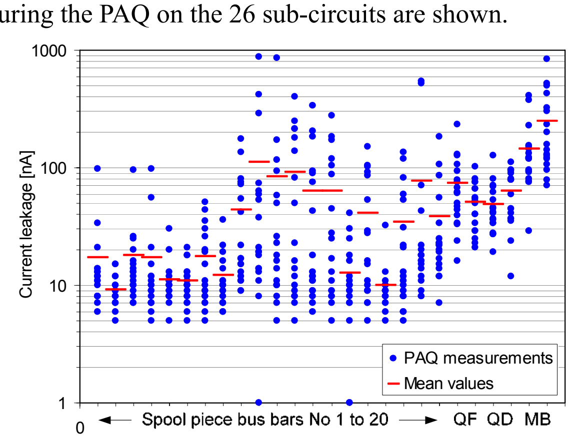

Figure 4: Current leakage measurements at 500 V (DC) during the PAQ qualification.

The mean value of the current leakage is also give in Fig. 4. This value is used to optimize the acceptance tolerances of the current leakages to be applied on the upcoming tests, and it is used to extrapolate the expected current leakage of a complete circuit. The extrapolated current leakages and insulation resistances for the following four types of circuits; main dipole, spool piece octupole, spool piece decapole, and spool piece sextupole are given in Table 2.

Table 2: Estimated current leakages for four types of circuits. Measurements performed at room temperature.

Superconducting circuit	Current leakage [μA]	R insulation [MΩ]
Main dipole	21.3	24
Ext. spool piece octupole	1.4	349
Ext. spool piece decapole	1.90	263
Ext. spool piece sextupole	8.40	59

The HVQN tests are done by sequentially applying 1000 (DC) on each of the 42 wires of the line-N segment while the other 41 wires are connected to ground. The duration of the test is 30 seconds. This configuration allows measuring the current leakage of the wire versus ground, and versus the other 41 wires. The current leakages can directly by compared with the data acquired at the end of the manufacturing of the line-N segment where the same test set-up was used. Fig. 5 compares the HVQN results with the results obtained at the end of the manufacturing of the installed segments.

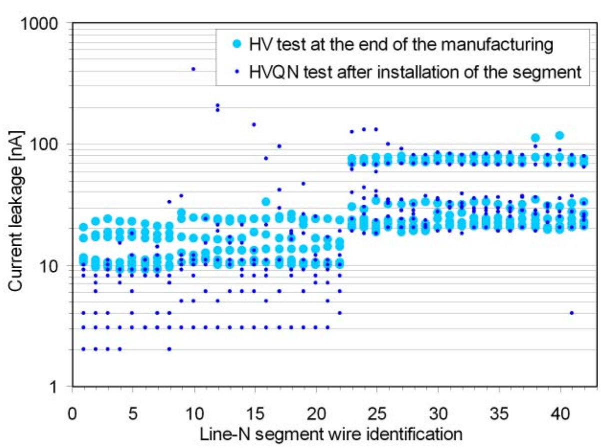

Figure 5: Line-N wires current leakage comparison, a) end of the manufacturing of the cable, b) after installation in the machine.

Three levels of current leakage values are clearly observable in Fig 5, grouping the wires by their position in the line-N cable.

- Wires 1 to 8 (internal layer).
- Wires 9 to 23 (middle layer).
- Wires 24 to 42 (external layer).

The internal and middle layers have seen a decrease of current leakage after installation but with a considerably higher variance. The external layer shows a good correlation of the current leakage measurements prior and after the segment installation.

CONCLUSION

Before starting the ELQA activities on the assembly of the electrical circuits of the machine, the ELQA strategy was revised and optimized. The aim of the new strategy is to detect as soon as possible hidden non-conformities and to anticipate the preliminary electrical qualification of smallest portions of the circuitry. Now, most types of the hidden non-conformities generated during the manufacturing of the cryo-magnets are known and can be detected. The increased number of electrical qualifications has also enhanced the overall assembly rate of the machine. A number of mechanical activities can be performed at an early stage just after the electrical acceptance. The need for improvements has been confirmed by the early discovery of non-conformities. The introduction of the PAQ and HVQN tests also generates a valuable quantity of data necessary to predict the overall quality of each circuit. The values of the dielectric insulation measurements of the tested portion of circuits are within the specified limits.

ACKNOWLEDGEMENTS

The discovery and characterization of the hidden non-conformities on cryo-magnets could not be done without the experience and help of K.M. Schirm. All the members of the Polish HNINP collaboration have to be acknowledged for their daily contribution to the ELQA activities.

REFERENCES

[1] N. Siegel, "Electrical Quality Assurance during Installation of Cryo-assemblies in the LHC Tunnel", LHC Days, Villars, 19-21 March 2001.

[2] D. Bozzini, V. Chareyre, K.H. Mess, S. Russenschuck, R. Solaz-Cerdan, "Design of an Automatic System for the Electrical Quality Assurance during the Assembly of the Electrical Circuits of the LHC", EPAC 04 , July 2004.

[3] S. Russenschuck et al., "Electrical Quality Assurance in the LHC Tunnel (ELQA) and Magnet Polarity Coordination (Mr. Polarity)", LHC Workshop, 23-26 January 2001.

[4] D. Bozzini, F. Caspers, V.Chareyre, Y.Duse, T. Kroyer, R. Lopez, A. Poncet. S. Russenschuck, "Fault Detection and Identification Methods used for the LHC Cryo-magnets and Related Cabling", EPAC 06, 26-30 June 2006.