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ELECTRICAL QUALITY ASSURANCE OF THE SUPERCONDUCTING CIRCUITS DURING LHC MACHINE ASSEMBLY

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Abstract

Based on the LHC powering reference database, all-together 1750 superconducting circuits were connected in the various cryogenic transfer lines of the LHC machine. Testing the continuity, magnet polarity, and the quality of the electrical insulation were the main tasks of the Electrical Quality Assurance (ELQA) activities during the LHC machine assembly. With the assembly of the LHC now complete, the paper reviews the work flow, resources, and the qualification results including the different types of electrical non-conformities.

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Based on the LHC powering reference database, all-together 1750 superconducting circuits were connected in the various cryogenic transfer lines of the LHC machine. Testing the continuity, magnet polarity, and the quality of the electrical insulation were the main tasks of the Electrical Quality Assurance (ELQA) activities during the LHC machine assembly. With the assembly of the LHC now complete, the paper reviews the work flow, resources, and the qualification results including the different types of electrical non-conformities.

INTRODUCTION

The LHC accelerator is composed of the eight continuous cryostats in the arcs that include electrical circuits distributed over a length of 2.7 km. Every arc is composed of a chain of 204 cryo-magnets which are mechanically and electrically interconnected. At each interconnection up to 74 superconducting circuits of three different types had to be joined.

ELQA activities [1] were performed on the component level in the workshop and on the system level in the LHC tunnel. The workshop activities covered the preparation and validation of equipment and tooling as well as the validation of testing procedures on a powering circuit mock-up. The main ELQA tests were performed in the LHC tunnel and covered the testing of all superconducting electrical circuits. These tests included the verification during the assembly of the 24 main dipole and quadrupole circuits, the corrector magnet circuits, voltage taps on the magnet coils, and the 380 cable segments with 42 superconducting wires for the powering of corrector magnets mounted in the so-called short-straight-sections. The 42-wire cable segments are housed in a separate cryogenic line (Line-N).

The different types of electrical tests required computer controlled measurement equipment controlled by dedicated LabView software applications. The equipment was designed and constructed by the ELQA team. It allows performing all necessary types of tests, such as the circuit continuity, the polarity check of magnets and the integrity of the electrical insulation.

ELQA TESTS

Types of tests

Originally, the ELQA activities were only concerned with electrical continuity and polarity errors occurring during the installation of the arc cryo-magnets in the LHC tunnel. This type of test [2] was performed on two neighbouring half-cells, and is referred to as AIV (Arc Interconnection Verification). One test (AIV1) was performed before and one (AIV2) after ultrasonic welding of the electrical connections. The double check was necessary to verify that no changes on the cabling had occurred. After the first learning phase covering end of 2005 and beginning of 2006, experience and detected non-conformities revealed the necessity to add two preliminary tests to the ELQA program. A partial assembly qualification of a half-cell (PAQ) and a high voltage qualification of the Line-N cable segments HVQN before the preparation of the electrical interconnections [3]. At the end of the first LHC arc installation, two additional ELQA tests were considered mandatory to meet the LHC quality assurance standard. The “Mega” Partial Assembly Qualification (MPAQ) allowed qualifying a chain of up to 16 half-cells interconnected. The “Mega” High Voltage Qualification of the Line-N cable segments (MHVQN) concerned the testing of the electrical insulation of up to 16 interconnected segments. Table 1 summarizes the ELQA test procedures with the electrical verification performed for each one. The length of the circuit covered by the tests is also presented.

Table 1: ELQA tests during LHC machine installation.

Type of test	Electrical insulation	Continuity	Polarity	Tested length m
PAQ	X	X		54
HVQN	X			54
AIV 1		X	X	108
AIV 2		X	X	108
MPAQ	X	X		800-2700
MHVQN	X	X		800-2700
TP3	X	X	X	2700

At the end of the interconnection works all circuits were tested with a final ELQA test (TP3) covering the entire circuit. The TP3 tests were done from the “warm” circuit connections accessible at the extremities of each powering subsectors. The powering circuits are connected to 55 different types of distribution feed boxes (DFB), and therefore the qualifications had to be done in a semiautomatic way, and for complex and unique cases even manually. Figure 3 shows the sequence of tests from a single half-cell qualification to the complete powering circuit.

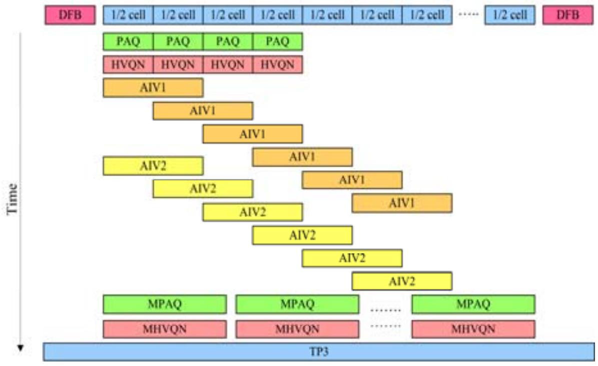

Figure 1: Sequence during a sector qualification.

COORDINATION AND RESOURCE PLANNING

Considering the location of the access points to the LHC machine and the length of arc powering sectors, a considerable amount of time for transport and access had to be considered. Finally it amounted to about 12% of the total resources.

The baseline manpower plan considered two-people per team (one engineer and one technician) for the tests in the arc powering sector. Experience has shown, however, that three-person teams with two technicians were able to operate more efficiently, because the time for connection, disconnection and displacement of equipment from one measurement point to the other could be minimized. The number of people involved in the ELQA activities is shown on Figure 2 for the years 2006 and 2007, with a peak of 12 people and with the total number of person-month of 218. On average 8.5 hours/circuit have been spent for the electrical qualification during the assembly.

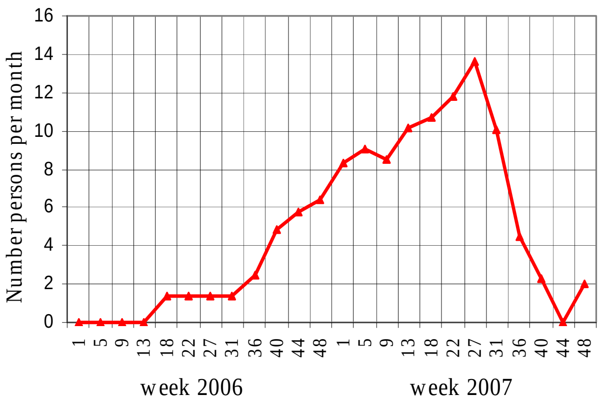

Figure 2: Planned number of persons.

The total number of tests done per week is shown on Figure 3. After a first phase with the number of tests smaller than 15, the test quantity increased steadily to reach an average of 32 tests/week which could be performed by ten team members.

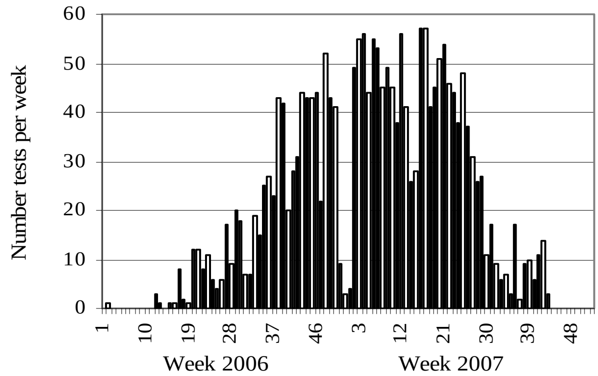

Figure 3: Number of tests per week.

The breakdown of all ELQA tests performed in the eight arc powering sectors and the number of discovered non conformities (NC) are presented in Table 2.

Table 2: ELQA tests in the eight arc powering sectors and number of detected non-conformities.

type of test	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-1	NC
PAQ	54	54	54	54	54	54	54	54	52
HVQN	48	48	48	48	48	48	48	48	1
AIV 1	54	54	54	54	54	54	54	54	55
AIV 2	48	48	48	48	48	48	48	48	0
MPAQ	5	5	5	5	5	5	5	5	7
MHVQN	5	5	5	5	5	5	5	5	4
TP3	54	32	29	29	61	8	32	55	19

TEST RESULTS AND DISCOVERED NON CONFORMITIES

Tests results

All the test data was automatically stored into a database. The software developed to control the test applications was designed to provide the result status by comparing the acquired data with reference values. The final acceptance of the test was done at the end of the test by the engineer-in-charge. Once a test was approved, a report was automatically generated and stored in a centralized database. In case of doubt or in case of a negative result, the engineer was requested to launch a detailed analysis by means of advanced tests also supported by the software application. If the test was still not passed, a non-conformity report was generated and managed with a shared data management tool. Off-line analysis allowed determining global factors of quality such as the example given in Figure 4: the leakage current of all circuits grouped per sector and per circuit type.

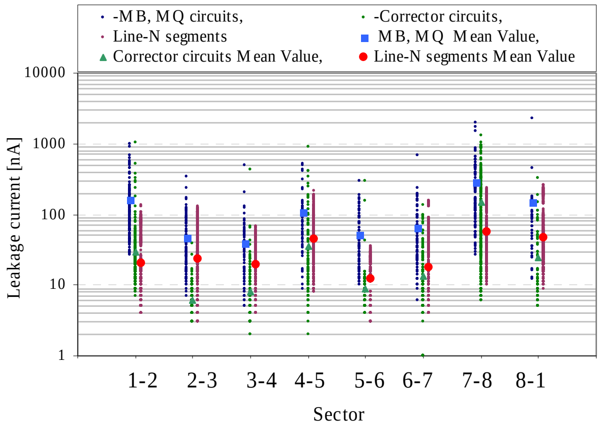

Figure 4: Leakage current vs circuits for all sectors.

Non conformities

The 140 non-conformities may be grouped in four categories. Category A comprises abnormal voltage drop measurement caused by the temperature dependent copper conductance, as well as high leakage currents caused by high relative humidity in the LHC tunnel. Category B includes known non-conformities discovered at the manufacturing acceptance tests and confirmed during the interconnection by the ELQA tests, e.g., a wrong position of a voltage pick-up signal. Category C is composed of non-conformities detected for the first time during the interconnection in the tunnel. Examples are the wrong labelling of a conductor yielding a continuity error, and an electrical insulation fault between a conductor and the helium enclosure. Category D includes non-conformities created in the tunnel such as the cabling errors during the ultrasonic welding preparatory work. Category A faults depend on the testing environment, category B errors are "inherited" from the component manufacturing phase. Most of type B non-conformities required a change in the LHC powering layout, in order to re-establish the requested functionality. Cat. C and D faults where typically generated during the interconnection work and could be resolved before passing to the next interconnection step. Figure 6 shows the number of the non-conformities per sector and per category. The sectors are arranged from left to right in a chronological order according to the machine interconnection sequence.

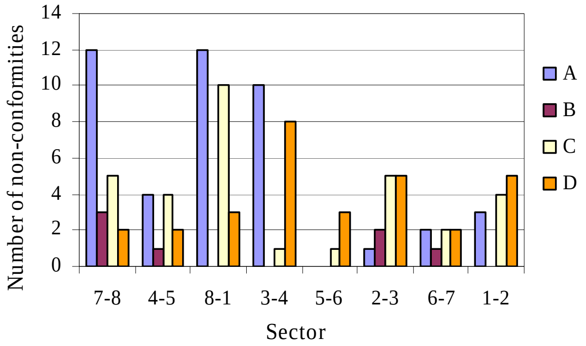

Figure 6: Non conformities per sector and per category.

The number of non-conformities resulting from assembly faults (category D) is all-together relatively low, but was influenced by the speed-up of the assembly work in the tunnel. During the insulation tests a strong correlation between the relative humidity and the measured leakage current values has been observed. The moisture problem affected both the magnet elements installed in the tunnel and the test equipment. In some suspicious cases, the measurements were repeated with a back-up system stored in the workshop.

The examples of accepted and not accepted current leakage of the main dipole corrector magnet in half-cell 20R4 during high voltage test are shown on Figure 5.

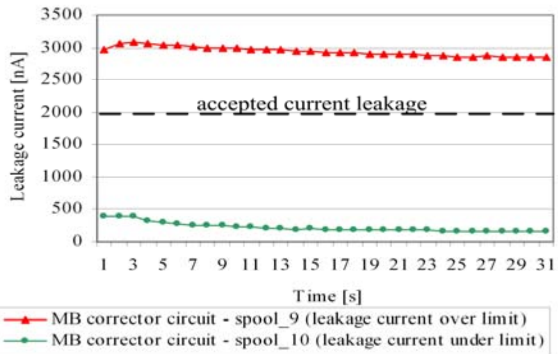

Figure 5: Leakage current in corrector magnet circuits

CONCLUSION

Due to the stringent ELQA procedures we have good reasons to believe that all electrical circuit where correctly interconnected according to the LHC powering and optic layout. Thanks to the experience acquired in the learning phase and the implementation of additional qualification tests to the ELQA baseline, it was possible to intercept 140 non-conformities which, if not detected, would have seriously compromised to the operation of the accelerator.

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