ELECTRICAL QUALITY ASSURANCE (ELQA)

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Abstract

The electrical integrity and the safe operation of the superconducting electrical circuits are crucial issues for the successful commissioning with and without beam and for the operation of the LHC machine. Beam based measurements may require in-situ verification of the magnet polarities. The detection, diagnostics, repair and re-qualification of electrical faults and the verification of magnet polarities will inevitably have an impact on the machine availability. Therefore, efficient and fast ELQA methods during beam commissioning shall be established and applied. This talk will initially outline the guidelines of the electrical quality assurance plan and will then depict some scenarios for electrical fault detection, magnet polarity error location and electrical re-qualification after magnet or lead exchange. Some aspects related to the acceptable status of affected electrical circuits will be given.

INTRODUCTION

An electrical quality assurance hereafter called ELQA plan is defined for the LHC machine environment in order to ensure the correct interconnection, and the safe and correct functioning of all superconducting electrical circuits during the assembly phase, the commissioning and operation [1]. The extent of the ELQA plan covers the qualification during manufacturing of the superconducting electrical components on surface, the verification during the assembly of the machine in the tunnel, the qualification of the circuits during the commissioning of the hardware and the operation with beam. The operation phase also includes the shutdown periods and the maintenance. In figure 1 the ELQA plan is represented.

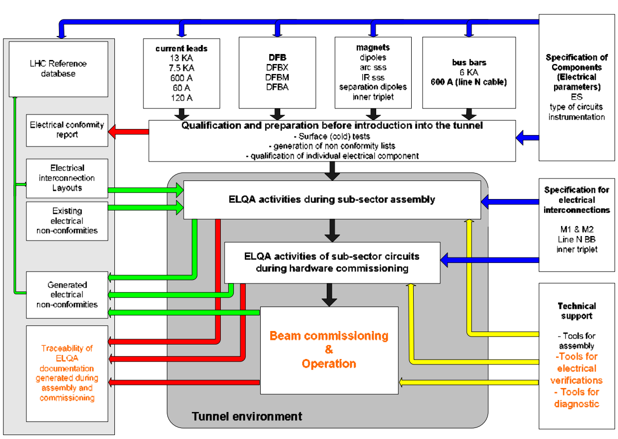


Figure 1: The ELQA plan.

This plan shows the connections between the ELQA activities and the neighbouring environment, such as the machine parameters of the LHC reference data base, the required technical support for the preparation of the tooling and the qualification live of each electrical component.

This document will focus on the ELQA activities during the commissioning and the operation with beam. Their aim can be summarized as follows:

- Define a quality assurance plan to apply to the LHC machine during commissioning and operation with beam.
- Provide the procedures, tools and resources to perform the necessary checks and tests.
- Grant the traceability and availability of the checks and tests performed during the entire live of the machine.

ELQA DURING OPERATION WITH BEAM

Though considered unlikely, it is almost sure that due to the complexity of the LHC machine, we will have to face faults and problems related to the superconducting electrical circuits during operation with beam. A fault affecting a superconducting circuit can be caused by different factors, and in most cases it can neither be predicted nor anticipated. Any electrical fault will have a direct impact on the machine availability and on the beam quality. In addition to the electrical faults that may appear, it could be necessary to verify in-situ the correctness of magnets polarities based on feedback from beam measurements [2].

The accessibility to the LHC machine, the tunnel environment and the radiation levels will inevitably put limits on the time for any diagnostic activity. Moreover the time needed for a repair will be high if we consider the complexity to access the superconducting circuits enclosed inside a cold mass operating at 1.8 K and insulated from ambient space by the vacuum enclosure. In order to limit the duration of machine stop, to grant the long term reliability of the 1740 superconducting circuits and to be capable to clearly localize an electrical fault, an efficient ELQA program shall be established and applied during the commissioning and operation with beam. The program can be summarized in the following three points:

- Define and provide the diagnostic tools, procedures and resources for in-situ measurements and investigation.
- Implement during the shutdown period the necessary measurement campaigns in order to follow-up the electrical status of the circuits.
- Prepare a re-qualification plan to be applied after in-situ repairs or exchange of faulty electrical components.

DETECTION OF FAULTS

The LHC machine is not equipped with systems that allow the on-line monitoring and diagnostic of electrical circuits. Electrical faults of a superconducting circuit can therefore only be detected once they appear by using the following sources of detection:

- **The beam** physicists can verify the action of a give magnet on the beam. In some cases specific tests using the beam can reveal that a magnet is connected with wrong polarity.
- **The power converters** can detect over voltages, detect earth faults and measure the current leakage to ground of a circuit.
- **The quench protection system** can detect the loss of instrumentation, can spot an open circuit and can provide data from consecutive quenches in a given magnet.
- **ELQA activities** can establish whether an electrical circuit is out of its specified parameters by means of measurement of electrical characteristics after a shutdown period or re-commissioning.

The detection of the fault using one of the above mentioned data sources will give preliminary information about the fault type and will indicate the affected circuit. Unfortunately, the way of detecting a fault does not indicate its cause and the location. As an example, an open circuit in a MCD chain composed of 154 correctors connected in series and distributed along 2.7 km will probably be detected by two sources: the quench protection system and the power converter. The location will only be determinable by in-situ ELQA diagnostic.

The experience the personnel will gain in detecting and localizing faults will of course increase proportionally with the time of machine operation. Nevertheless we must admit that experience in the interpretation of the above mentioned data will grow during the assembly and commissioning of the hardware.

CLASSIFICATION OF FAULTS

The electrical faults that will appear during operation of the LHC machine can be classified in two groups. The first one includes the so called notorious faults that remain observable after the stop of the machine. They are therefore more easily detectable and traceable. The second group includes the malicious faults assorted with transitory faults of yet unknown origin which disappear after the stop of the machine.

Notorious faults

As far as the notorious faults are concerned the consequences, the means of detection and the diagnostic methods are established. Faults include wrong polarities of magnets, open circuits, short to ground and loss of instrumentation. All these faults are observable when the machine is not powered which allows a post-mortem diagnostic with proven methods that will de described in the next chapter. Table 1 gives a non exhaustive list of notorious faults and their consequences, their means of detection and their diagnostic methodology.

Table 1: Notorious faults

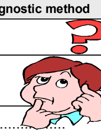
Fault	Consequence	Source of detection	Diagnostic method
Inverted polarity of a magnet within a series (ex: MCS)	Beam quality	- BPM - Beam observations	- Polarity check
Open circuit of a main circuit	Beam abort	- Quench protection system - Power converter	- Continuity check - Transfer function
Short to ground of a main circuit	Beam abort	- Power converter	- High voltage test - Transfer function
Loss of instrumentation used for magnet protection	Beam abort	- Quench protection system	- Continuity check - Time domain reflectometry
....	....	....	....

Malicious faults

The non exhaustive list in Table 2 which contains three malicious faults will have to be extended with new faults appearing during machine operation with beam. It is rather difficult to anticipate what kind of malicious faults we will have to face: if we knew them we could identify the consequences, the detection systems and the applicable diagnostic methods and they would, by definition, become notorious ones.

Table 2: Malicious faults

Fault	Consequence	Detection	Diagnostic method
Quench of bus bar segments or splices	Beam abort	- Quench protection system	?
Transitory shorts to ground or between circuits	Beam abort	- Power converters	?
High ohmic resistance of bus bar interconnect	?	- Quench protection system - Cryo system	....



When a malicious fault appears, the first diagnostic methodology applicable will be the same as for the notorious faults but yet not sufficient. For this kind of faults we will define the diagnostic methods based on the experience we will acquire during the operation. Nevertheless, several solutions and some preliminary tests of new versatile diagnostic methods are under development and are briefly presented in the next chapter.

DIAGNOSTIC METHODS

Table 3 gives the tests to be applied for the diagnostic of notorious faults.

Table 3: Diagnostic tests

Diagnostic test	Applied to	Method
Electrical insulation	segment - ground	DCV supply
	segment - segment	I leakage
Capacity	Circuit - ground	DCV Measurement of C
Continuity	Σ segments	DCA supply
	Circuit	Closed loop
Polarity	Σ segments	DCA supply
	Circuit	Voltage drop via V_taps
Instrumentation	Current lead V_taps	DCA supply Voltage drop via V_taps
Diode polarity	MB,MQ diodes	ACV supply Turn on voltage
Transfer function	Circuit	Z(f)
	Circuit - ground	Z(f)

Insulation resistance between circuits and ground, continuity of electrical segments and magnet polarity tests are common methods for the diagnostic of electrical faults. These established methods, have been adapted to the superconducting electrical elements of the LHC. The tests will extensively be used during the manufacturing of the electrical elements, during the machine assembly and the hardware commissioning. Thus a wide experience will be available at the time of commissioning and operation with beam.

Example 1: Transfer function

Figure 2 shows the transfer function of the impedance measured on two similar quadrupole circuits at cryogenic conditions. RQF is sane, whil RQD has a phase of 0º instead of 90º at a frequency of 10 Hz, indicating a resistive segment somewhere within the RQD superconducting circuit.

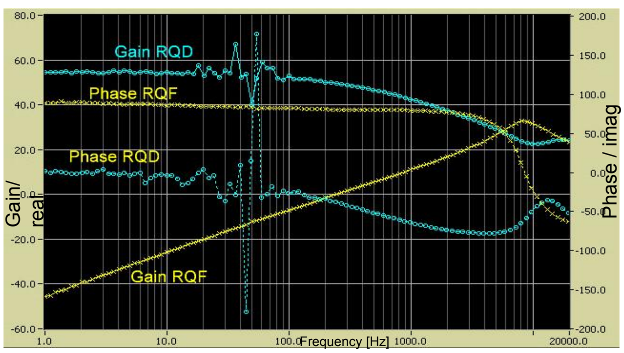


Figure 2: Transfer function of the impedance.

For the diagnostic of malicious faults, systematic approaches are difficult to be applied and the evolution of the methods for diagnostic will mainly be based on the experience acquired during machine operation. We must mention that during operation of String I and II experience with some applicable methods has been gained. Four promising diagnostic tests requiring further developments, however, are listed below.

- **Time Domain Reflectometry + high voltage pulse.** This combination allows localizing transitory insulation faults between circuits or between a circuit and ground. The reflectometry should allow the localization of the distance of the fault to the point of injection of the high voltage pulse.
- **High voltage partial discharge.** The dielectric characteristics of the insulation of a circuit can be verified by the partial discharge method. Partial discharges occurring in a circuit under test may be characterized by measurable quantities such as charge, repetition rate and amplitude. The qualitative and quantitative interpretation of the results can indicate the type of insulation degradation.
- **Power dissipation measurements.** This method allows localizing ohmic resistances such as a bad junction between interconnecting bus bars within a superconducting circuit. This method requires collaboration with cryogenic specialists who will localize the local increase of temperature due to the dissipation by joule effect of the bad junction.
- **Systems to be locally and temporarily installed during operation.** Transitory faults such as shorts to ground or quenches of a bus bar segment can be detected by the sources but none of them are equipped with fast acquisition system. It will be therefore necessary to prepare specific systems to locally acquire transitory events. These systems will have to be installed in positions where the transitory fault will hopefully appear and they will gather the data during operation.

Example 2: Power dissipation measurement

Figure 3 shows the detection of a high ohmic resistance in a superconducting circuit by using the power dissipation measurement method. The current is increased by steps of 100 A up to 1.5 kA. The calculated power dissipation of 900 W gives a total resistance of 0.4 Ω for the 208 meter long superconducting circuit. The recording of the temperatures along the string of magnets could allow localizing the heat source with a precision of couple of meters.

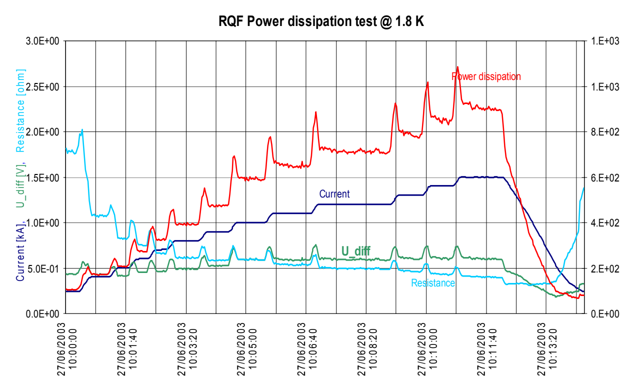


Figure 3: Power dissipation measurements.

ACCESSIBILITY

Two well distinguished accessibility criteria shall be considered when performing ELQA activities during commissioning and operation with beam. The first one concerns the access to the tunnel environment and the second one concerns the access to the electrical circuits for the diagnostic tests.

Access to the tunnel environment

As soon as the machine will operate with beam the access to the tunnel will become stricter and the safety and radiation rules shall be respected. From a practical point of view the application of all the rules will limit the intervention times in the tunnel. For notorious faults this has to be taken into account in the diagnostic procedures. These should be optimized from the duration point of view. For the malicious faults neither the time of intervention nor the method for diagnostic can be determined in advance. It is therefore realistic to say that access rules to tunnel will have a direct impact on the ELQA activities.

Access to the electrical circuits

The particularity of the LHC superconducting accelerator is that the electrical circuits are immersed in a liquid helium bath at 1.8 K and therefore the conductors cannot be directly accessed. The differences of the concept between a warm and (PS) a cold machine (LHC) give an idea of the limits we will face when accessing the superconducting circuits during diagnostic activities.

In a warm machine the bus bars are almost always accessible at the level of each magnet, this allows to electrically separate a segment of the circuit or a single coil from a string of magnets. It is interesting to note that for the diagnostic of warm machines, almost all human senses (hearing, visual, smell, touch) can be used. Figure 4 shows a LEP sextupole magnet where the coils are accessible.

Figure 4: Accessibility to the circuits of a warm machine.

In a cold machine and in particular in the eight arcs of the LHC the electrical circuits will have a developed length of up to 6.4 km and they will be inaccessible all long the 2.7 km of the arc sectors. Circuits will be accessible at the extremities of the arcs at the level of the current leads installed, and via the instrumentation wires that are routed out locally on each magnet via the instrumentation feedthrough system. If for diagnostic reasons it will be required to electrically isolate a segment or a magnet, then an intervention for the opening of the vacuum and helium enclosures will be necessary. This will imply the warming up of a portion of the machine as a first step. Figure 5 shows the string II phase 1 experience corresponding to a portion of 54 meters of an LHC arc, where the circuits are not accessible.

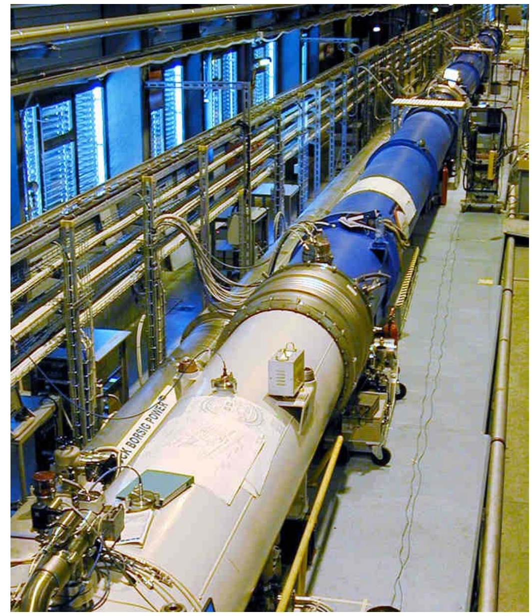


Figure 5: String II phase 1 corresponding to 54 meters of an LHC arc.

SEQUENCE AND DURATION OF DIAGNOSTIC ACTIVITIES

Depending on the type of fault under diagnostic, the sequence and duration for the diagnostic activities can vary.

As it is shown in figure 6, the diagnostic activities of faults not requiring the opening of the machine include two phases separated by an analysis and decision step. After the second diagnostic phase the intervention time for repair of the fault is foreseen. It is then followed by the re-qualification of the repaired circuit. Except for the intervention and repair time the duration of the other steps are quantifiable. This sequence is mainly applicable to notorious faults.

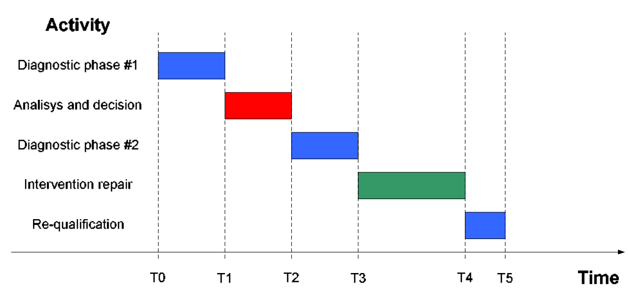


Figure 6: Diagnostic of fault not requiring the opening of the machine.

For most complex faults and especially for the malicious ones, the opening of the interconnections may be unavoidable to carry out the diagnostic tests. For such a case the first diagnostic phase will be split in two parts by an additional task for the warm up and opening of the interconnections. This case is shown in figure 7.

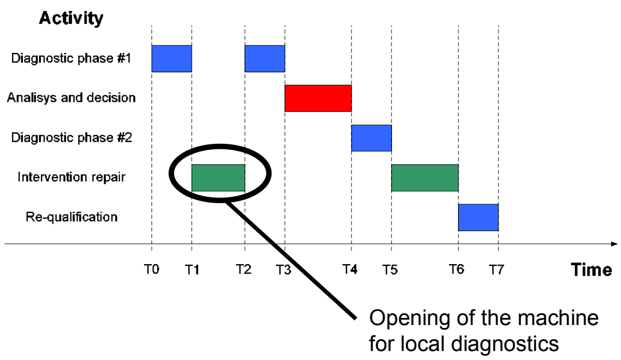


Figure 7: Diagnostic of fault requiring the opening of the interconnections.

Intervals shown in figures 6 and 7 are of course not scaled. A reference value for the two diagnostic phases of a notorious fault is 5-7 hours. For comparison the estimated time for the warm-up, the opening of interconnections and cooldown after a repair is counted in days [3].

EXPERIENCE, RESOURCES AND FAMILIARITY WITH THE LHC MACHINE

The experience need for the ELQA activities during operation will be acquired during the phases of assembly and hardware commissioning. The success of the ELQA is based on the availability of experienced and well trained personnel. The personnel ought to be familiar with ELQA procedures and also with safety rules and the tunnel environment. Figure 8 shows the human resources foreseen for the three phases.

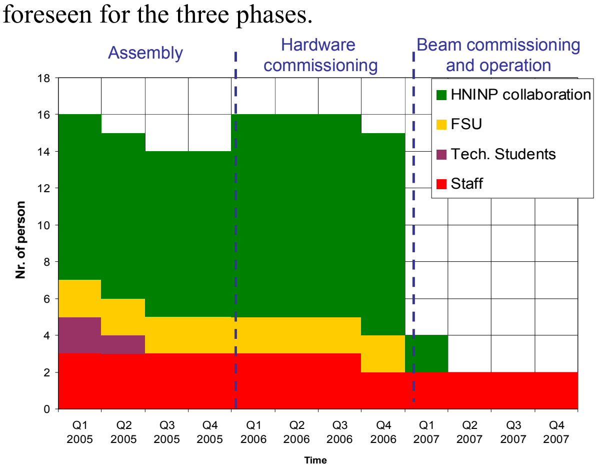


Figure 7: Resources availability

At the start of operation with beam there will be a loss of personnel with installation and commissioning experience, as these work-packages will be performed by project associates. This situation may jeopardize the EQLA activities during operation.

STRING EXPERIENCES

During the String I and String II experiments, the ELQA activities have been developed and applied. The experience from almost 4 years of String experiments should be considered:

The time for diagnostic and analysis was largely underestimated, especially for some malicious faults which have occurred.

- **Some faults could not be resolved** even after an extensive diagnostic phase requiring the warm-up of the string and the opening of the interconnections. More details are available in the String II incident report [4].
- **The environment of String I and II** did not include the boundaries we will face in LHC. The beam, the radiation and space constraints were not an issue.

CONCLUSION

After the successful hardware commissioning, day 1 of commissioning with beam might be smooth operation. Nevertheless we must be prepared for diagnostic interventions during the following days, weeks and years of operation. The experience we have gained during the String experiments shows that we ought to be prepared for unpredictable faults of any nature requiring interventions even including the opening of interconnections. As of spring 2007 the resources allocated to the ELQA activities are not yet assured.

AKNOLEDGMENT

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