LHC HARDWARE COMMISSIONING SUMMARY

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Abstract

The operation of the Large Hadron Collider relies on many systems with technologies often beyond the state of the art and in particular on hundreds of superconducting magnets operating in superfluid helium at 1.9K powered by more than 1700 power converters. The many systems making the superconducting magnet chain (cryogenics, vacuum, quench detection, energy extraction, power converters and interlocks) depend on each other and on the infrastructure systems (controls, electricity distribution, water cooling, ventilation, communication systems, etc.). The commissioning of the technical systems together with the associated infrastructures is therefore mandatory in order to ensure safe operation. The paper summarizes the commissioning campaign, describes the main issues encountered, presents the results obtained and the lessons learnt.

THE LAYOUT

The LHC [1,2] is a two-ring superconducting proton proton collider made of eight 3 km long arcs separated by 528 m long straight sections. While the eight arcs are nearly identical, the straight sections are very different. Four straight sections house physics experiments, ATLAS CMS, ALICE and LHCb; the latter two also include the beam injection systems. Two insertions are for the beam cleaning systems capturing off-momentum and halo particles, one insertion is for the superconducting RF cavities and beam instrumentation and finally, one insertion is for the beam dumping systems to deposit the two beams onto external dump blocks.

THE SECTORIZATION

The LHC is electrically and cryogenically sectorized in eight. This sectorization permitted the independent commissioning of each of them. Each one of the eight sectors contains around 200 superconducting circuits which range from simple, single magnet circuits to circuits containing up to 154 32-ton 15-m dipoles in series. Two of the sectors contain the RF cavities around Point 4 operating at 4.5 K. In addition to the cryogenic components, the LHC relies on a number of warm systems for its operation. These include the normal conducting magnets, the septa, the kickers, the collimators, the beam instrumentation, etc. The presence of these systems in a sector depends on the function of the sector extremities; those ending in Points 2 and 8, for example, contain the injection systems.

THE TEST PHASES

The commissioning activity [3], which started in October 2005, consisted in the short circuit tests, the commissioning of the non cryogenic systems and the finally the powering tests of the superconducting components of the LHC. While most of the infrastructure systems were tested during the short circuit test campaign, the final validation for operation of each sector was obtained only after the commissioning of both its warm and its superconducting components.

The short circuit tests

The objective of these tests [4,5,6] was the validation of the warm part of the superconducting circuits from the 18 kV and 400 V AC feeds down to the water and air-cooled cables before their connection to the superconducting elements in the circuits as shown in Figure 1 below.

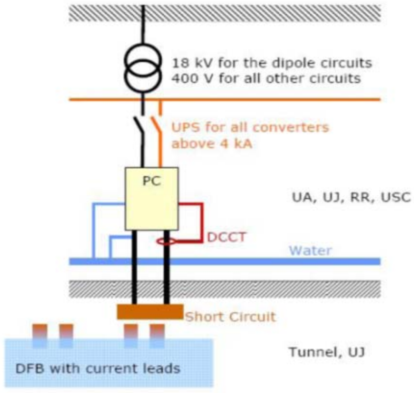

Figure 1: The short circuits in the tunnel outside the powering areas (UA, UJ, RR) of the LHC

The tests yielded the verification of the individual and global thermal aspects, the verification of the interlocks and the calibration of the power converters. They were carried out in the 15 underground powering areas of the LHC.

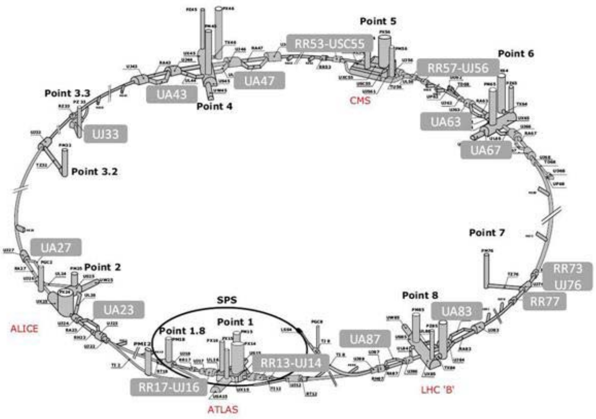

Figure 2: The underground powering areas of the LHC

The individual commissioning of each power converter in short circuit is followed by a 24-hour heat run of all the power converters at their *ultimate current*; this corresponds to the maximum design current of the magnets. The stability of the current in the magnets, the AC distribution and the temperatures of the demineralised water, of the air, of the electronics and of the cables are recorded in order to validate the correct functioning of the area as a whole. The test ends with an interruption of the general AC supply in the cavern in order to check the correct connection of the Uninterruptable Power Supplies and the recovery following the interruption.

While non-conformities related to the circuits are detected during the individual test, those related to ventilation, distribution of cooling water, layout of cables are detected during the 24-hour heat run. An example of this is given in Figure 3; the layout of cables had to reviewed twice, in one of the powering areas (UJ33) before the temperatures were brought to a level acceptable for operation.

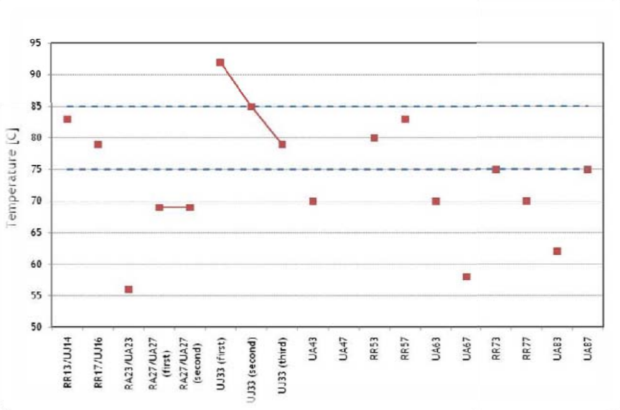

Figure 3: Comparative cable temperature measurements

The type of non-conformities which were detected and corrected during this phase include cabling errors in the signals between the interlock system and the converters, loosely bolted power cables leading to poor quality contacts, cabling layout, layout of air cooling ducts, etc.

THE SUPERCONDUCTING CIRCUITS

The superconducting circuits are powered from the underground areas situated at the extremities of each 3 km sector via the electrical feed boxes (DFB) or, for the low current (60 to 120 A) dipole corrector magnets, directly via conduction cooled current leads situated on the magnet cryostats themselves. Most of the circuits fed via the DFBs traverse the whole sector.

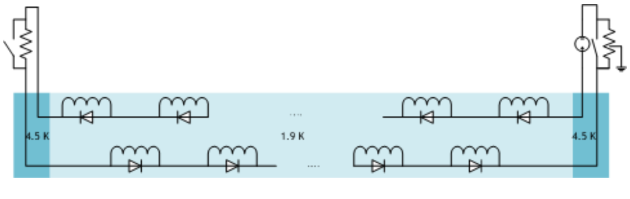

Figure 4 : The dipole circuit of each sector of the eight containing 154 dipoles.

After the sector is cooled down and before tests with current in the superconducting circuits take place, the cryogenic instrumentation (7000 channels) as well as the process parameters (600 PID loops) must be validated. This is followed by a phase of preparation for powering which ensures that the circuits are fit to be powered. This phase includes:

- the electrical quality assurance at cold [7] (continuity of instrumentation wires, transfer function measurement, insulation tests)
- the individual system tests of the quench detection system at cold (individual discharge of all the quench heater power supplies)
- the interlock tests without current in the magnets
- the connection of the power converters to the current leads and
- the commissioning of the DFBs without current (helium levels, condensation, temperature of the current lead ends, lead head heater system, etc.)

The powering tests proper start with a repetition of the interlock tests with the magnets connected to the power converter at their minimum operational current and continue with a number of steps aiming at

- the validation of the protection strategies under the different failure scenarios (forced energy extraction, a provoked quench, a Fast Power Abort triggered by the interlock system, a powering failure of the converter, a Slow Power Abort triggered by the interlock system) and
- the evaluation of the proper behaviour of the magnet chain, the current leads and the power converters during a normal LHC ramp and steady state.

For those circuits equipped with an energy extraction system, some of the test steps are repeated at intermediate current levels in order to validate the energy extraction system and to make sure the quench heaters perform as expected.

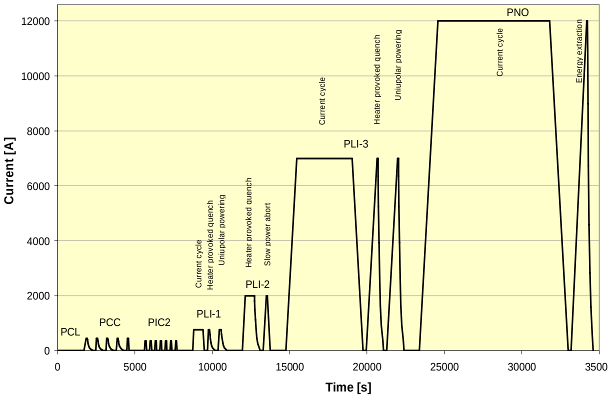

Figure 5: The current cycle foreseen for the powering test sequence of the dipole circuit

THE PROCEDURES

A set of engineering specification describing the sequence of operations for the powering tests of each circuit type has been prepared, circulated and approved by all the equipment specialists as well as the departmental and interdepartmental bodies controlling Hardware Commissioning. For each type of circuits, additional documents have complemented these engineering specifications by detailing the specificities of each sector in terms of reference magnets, set of magnets where a provoked quench is to be triggered during the test sequence, etc.

After the commissioning campaign of every sector, the test procedures were reviewed with the objective of improving the test method, the safety conditions around the test, the organization in the control room and in the field as well as with the objective of finding ways to shorten the time needed for the tests without jeopardizing personnel safety and equipment integrity. This exercise has always yielded improvements of the test procedures and of the test conditions as well as a substantial reduction of the time needed for the tests.

THE TOOLS

After a formal approval process, the documentation describing the tests is used as the reference to programme the **sequencer,** which assist the operators during the tests. A predetermined set of test steps is derived from the documents and proposed to the operator for execution; for each step a predetermined set of parameters are recorded; after each step the operator or a body responsible for the analysis of the results is consulted before the next step is carried-out. All this ensures the same tests are applied to the same type of circuit, sector after sector, campaign after campaign.

Process data belonging to the different systems is continuously recorded by the **logging system**. The trend curves can be visualised or extracted for offline processing; process parameters belonging to the different systems can be displayed on the same graph and correlated.

Transient data is captured by a **post mortem system** [8] which collects data acquired by the different systems (quench detection, energy extraction, power converters, powering interlocks, etc). Like for the logging system, process parameters belonging to the different systems can be displayed on the same graph and correlated.

All this is made possible by a **real-time database system** which serves the process specific parameters to the sequencer and stores the data acquired by the logging and the post mortem systems.

The result of the tests and the associated data is recorded in the **manufacturing and test folder** either automatically of manually after human processing and analysis. This tool ensures that the data is recorded in a standard way, according to a predefined profile. Also, the system ensures the perennity of the data.

A number of other on-line tools assist the operators and the staff carrying out analysis work: they provide the means to define the set of the circuits which will be tested, to keep track of what is being carried-out at any given time, to report what has been done during the shift or the day, etc.

THE ORGANIZATION OF THE TESTS

The tests [9] are carried-out from the CERN Control Centre by a team composed of operators, equipment specialists and experts who analyse the outcome of the tests. The team, which operates during two shifts five days a week, is manned to carry out tests on four different fronts in the tunnel.

Operators of the cryogenic system assist with the cool down and the recovery. Other specialized teams in the field and in the control room provide assistance to the operation team: these include the equipment specialists who are needed when faults are detected and need to be fixed, those who are in charge of the locking and unlocking of the voltage sources for safety reasons, those who handle access [10] to the tunnel, etc.

Safety is intrinsic to the organization of the Hardware Commissioning. Work in the vicinity of live circuit terminals requires that the voltage sources are locked and the terminals grounded following well defined and widely known procedures and rigorously followed.

THE STRATEGY

The mandate of the Hardware Commissioning Team stated that all the circuits of each LHC sector had to be taken to nominal current for operation at 7 TeV. The first training quench which was observed in Sector 45 was below 6 TeV (5.8 TeV). At that moment it became clear that if the summer 2008 milestone of beam commissioning with the LHC had to be met, the LHC would have to be commissioned to a current level corresponding lower beam energy. The figure of 5 TeV was proposed to the experiments on the grounds that 5 TeV required a current level in the dipoles which was readily reached without any training quench. After confirmation of this observation also in Sector 56, this was adopted as the baseline for the other sectors. It was however decided to continue with the training quenches in Sector 56 to confirm the number of quenches needed to train a full sector to 7 TeV.

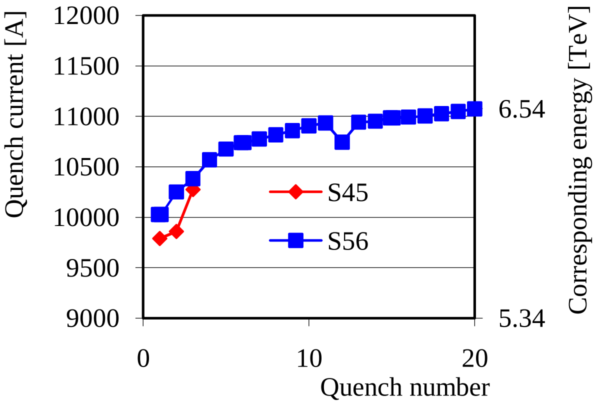

Figure 6: The training quenches in Sectors 45 and 56

While most of the other circuits reach 7 TeV equivalent current levels with no or little training, a further reduction of the testing time can be achieved by taking each circuit to the current level required by the initial LHC optics which in many cases is much below the nominal current level of each circuit.

TEST RESULTS

All the systems connected to the superconducting circuits including the individual magnets, the strings of magnets, the power converters, the quench detection system, the energy extraction system, the powering interlocks, the current leads and the DFBs were extensively tested during the commissioning campaigns. Their performance is reported in detail in [11-17].

The results of the three sectors so far commissioned have validated the performance of all the different types of **power converters**. The main achievements were the optimization of the start-up algorithm which was smooth enough not to trigger the quench protection system, the setting of the current loop parameters on large time constant loads, the validation of the current loop algorithm (no lagging error and no overshoot) and the validation of the high precision performance. The quadrupole circuits of the Inner Triplet system is composed by four magnets connected in series and powered by a main power converter ([7kA/8V]) and two trim power converters ([±600A/±10V] and [5kA/8V]). The challenge of this circuit is to control the magnet currents with 3ppm accuracy in spite of the inductive coupling effect between the three power converters (the variations of output voltage of one power converter have effects on all power converter currents). A special control strategy (decoupling control by state feedback) has been developed and implemented. Successful powering of the low-beta triplet to nominal current was performed in Sector 56 in April 2008 and in Sector 78 in June 2008.

At the time of writing, nine out of the twenty-four 13 kA **energy extraction systems** were tested up to 11 kA. Sixty out of the 202 systems rated at 600 A were tested up to current levels of at least 200 A and many up to the nominal current of 550 A. Almost 500 switch openings under load were needed to reach this stage in hardware commissioning. All systems worked according to expectation and no opening failures or systems faults were reported.

The commissioning of the more than 3000 **current leads** for the LHC machine has confirmed the expected performance of the components. Up to now, with electrical insulation tests performed almost on all circuits and powering tests performed on more than 1200 leads, no specific failures were encountered. Both the HTS leads and the normal-conducting leads met the specified design parameters in the tunnel environment.

The electronic systems for the **protection of the superconducting devices** of the LHC have successfully proven the reliability and readiness required for operation with beam. The tests highlighted an unexpectedly symmetrical quench of the two apertures which took long to detect: solutions for this are being engineered. Future developments will focus first of all on consolidation of the LHC as well as on the necessary replacements of obsolete electronic components. While quench propagation to neighbouring magnets was observed to be in line with experiment carried-out at the LHC Test String, in a few cases (4 so far) unexplained propagation to distant magnets (1 km) in a very short time (10 ms) were seen: transmission line effects are suspected and are being investigated with ad-hoc instrumentation.

Most of the coordination effort went into the commissioning of the superconducting circuits because of their number (more than 1700) and the number of systems which make them. Commissioning activities of the other systems [18-20] took place in parallel and were also coordinated to minimize the impact of co-activities.

THE NON-CONFORMITIES

The problems encountered can be roughly divided in two categories: the standard installation and in-situ assembly defects or system failures and the more complex issues which stem from the high-tech nature of the equipment.

The most common defects were the systematic **signal cable inversions** at the interface between systems. Although preventive campaigns are organized to make sure this is fixed before the tests take place, these have regularly popped up and consumed precious time. In the same category - but experience shows this always happens - the **filters** of the demineralised water circuits regularly get obstructed; again, preventive cleaning campaigns do not solve the problem. Their exchange for a larger mesh size compatible with the power converter heat exchangers is planned.

The less trivial non-conformity which was detected during one of the test steps of the quadrupole test procedure was an **energy extraction dump resistor** with a lower resistance value; this occurred on two separate circuits and was traced to a manufacturing defect. The resistors were replaced.

The **short to ground of the heaters** on one aperture in one dipole magnet was resolved by using the spare low field heaters in the dipole: the magnet was cold and its replacement would have considerably delayed the delivery of the sector to operation. Similarly, a high resistance in one of the dipole correctors in the matching section quadrupole (Q5) left of Point 8, made the magnet unusable. In this case, a spare magnet with the configuration needed for that location was not available: the repair of the magnets or an assembly of a new magnet would have taken several months. This non-conformity was resolved with the installation of a normal conducting dipole corrector.

The occasions were most time was lost were generated by the **failures of infrastructure systems**, namely AC distribution, cooling water and the communication networks, which by a domino effect, impact the cryogenic system: the recovery of nominal conditions of the latter system, for the time being, takes from 24 hours to a few days depending on the duration of the infrastructure failure as well as the time of occurrence in the week. Studies and actions are underway to reduce the number of failures and time to recover in order to minimise the impact on LHC availability.

On the cryogenic system front, the cutting edge technologies brought into action required some study and tuning time; this gave close to final availability figures of 98% for the 4.5 K magnets and 90% for the 1.9K magnets in some individual sectors presently under test during quiet periods. Three non-conformities presently affect the commissioning: the level measurements in some 4.5 K magnets are not yet reliable, the missing instrumentation (heaters, temperature sensors) on the current leads of the inner triplet feed boxes; finally, the interruption of a cryogenic line inside the 16 mbar heat exchanger tube which slows down the cooling of the main magnets in the concerned half cell. While the former two are being resolved, the latter cannot be dealt with until the sector is warmed up for consolidation work.

CONCLUSIONS

All the non-conformities discovered so far could either be fixed, or accepted-as-is, or cured with compensatory measures.

The quality of the test procedures and the depth of the analysis which follow every test step have so far allowed a safe and thorough progress of the commissioning process. Several quality control layers in the analysis procedures and very cautious progress when unexpected events are discovered have so far paid: a better understanding of the systems is gradually achieved and no equipment was damaged. This attitude must be continued throughout the final phases of the commissioning when pressure will build up to deliver the collider for physics.

ACKNOWLEDGEMENTS

The commissioning activity started slowly as the underground powering areas were installed and cabled. It then took place in a little over one year but was really concentrated in the last six months. The Hardware Commissioning Team included members of equipment Groups all around CERN, operation teams and colleagues temporarily deployed by national institutes from member (Greece, France, Italy, Poland, Spain) and non-member states (India, Pakistan, Russia and the USA). They all made the success of this unique challenge by integrating in one team regardless of their origin. On behalf of all my CERN colleagues, I would like to express my gratitude to our colleagues detached from the national institutes for their dedication and for making available their competence to CERN in this delicate moment when it was most needed.

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