# THE COMMISSIONING OF THE LHC TEST STRING 2

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*Abstract*

String 2 [1,2] is a full-size model of an LHC cell of the regular part of the arc. It is composed of six dipole magnets with their correctors, two short straight sections with their orbit and lattice corrector magnets, and a cryogenic distribution line running alongside the magnets. The commissioning of String 2 Phase 1, with one half-cell and the following quadrupole, has started in April 2001. As for String 1 [3], the facility was built to individually validate the LHC systems and to investigate their collective behaviour during normal operation (pump-down, cool-down and powering) as well as during exceptional conditions such as quenches.

String 2 is a stepping stone towards the commissioning of the first sector (one eight of LHC) planned for 2004. It is expected to yield precious information on the infrastructures, the installation, the tooling and the procedures for the assembly, the testing and the commissioning of the individual systems, as well as the global commissioning of the technical systems.

This paper describes the procedures followed for the commissioning and details the preparation for the first cool-down and for the powering.

## 1 LAYOUT

For the first phase, prototype magnets were installed. For the second phase three pre-series dipole magnets will be added completing a full cell of LHC. String 2 Phase 2 will be commissioned in early 2002.

String 2 is terminated on the upstream end by the electrical feed-box (DFBS) [4,5] and on the downstream end by the magnet return box (MRB). The feed-box, with high temperature superconducting current leads for 11 of the 15 electrical circuits, is a first prototype of the arc feed box, the DFBA. The return box contains the short circuits for the current return and the connection to the cryogenic distribution line (QRL) [6] simulating the jumper connection of the following cell. The QRL distributes and recovers helium at different temperatures and pressures.

String 2 has a length of about 120 m and follows the curvature as the machine in the LHC tunnel. It is installed in hall 2173 (SM18) and just fits into the building. Because it comprises the cryogenic line, an artificial difference in level was required to simulate the trench in the tunnel. This was achieved using prefabricated concrete slabs.

## 2 COMMISSIONING

### *2.1 Component and Partial Leak Tests*

Every component that was added to the helium vessel (cooling circuits and cold masses) or to the beam vacuum of String 2 was individually leak tested with a sensitivity of $1\cdot10^{-10}$ Pa m$^3$ /s before it was installed.

After all magnets were installed and interconnected, a partial leak test of the helium vessel was performed. During this test, special diagnostics tooling (clamshells), clamped on the welds at the cold mass interconnects, was used and the procedure, which will be carried out in the tunnel, was validated. With this tooling leaks exceeding $1\cdot10^{-10}$ Pa m$^3$ /s can be detected.

### *2.2 Electrical Tests*

The electrical tests aimed at ensuring the integrity of the insulation as well as the correct implementation of the circuits [7] throughout the different phases of the assembly.

Before installation on String 2, each component underwent an insulation test with a voltage of 1 kV applied for 2 minutes. A leakage current of no more than 10 µA was tolerated. During these tests all conducting parts (like busbars connected to coils inside the cold masses, straight-through busbars and heaters) were connected to ground, except the one under test. In this way a leakage current from any conductor to any other could be detected. This method was applied for all subsequent insulation tests.

Once the cryomagnets were in place, insulation tests were carried out after the following steps of the assembly:

- the soft soldering of the main busbars and the insulation of the joints,
- the ultrasonic welding of the spool-piece busbars and their insulation,
- the welding of the stainless steel sleeve of the lines M1, M2 and M3, which join the helium vessels of adjacent cryomagnets.

A voltage of 200 V was applied for 2 minutes: a leakage current of no more than 1 µA was tolerated.

The busbars in line N, which are used for powering the corrector magnets in the short straight sections, underwent the same test procedure at appropriate installation stages.

The busbars in the feed-box were tested at 1.5 kV before and after their connection to the current leads. Some of the leads showed leakage currents of 50 µA already at about 120 V. This will not be tolerated for the machine, but is sufficient for String 2.

After the installation of the last cryomagnet, the return connections were soldered and the quality of their insulation tested. The DFBS was then connected. The entire circuits were insulation tested at 200 V for 2 minutes. No new irregularities surfaced at this stage.

At various steps of the assembly of the String a current was sent through each of the electrical circuits, and the resistance of the circuit was measured. The voltage drop between voltage taps connected to the circuit and the minus pole was recorded to verify the correct sequence of the taps.

The tests, which were carried-out during the tests of single components and during the different phases of the assembly, revealed some non-conformities. These included the swapping of main busbars inside the DFBS, the alteration of the corrector bus-bar positions when traversing the short straight sections, the swapping of positions of voltage taps as well as a corrector circuit shorted to ground in one dipole. A solution could be found for all these non-conformities.

In addition to the insulation and continuity tests, the transfer function of the main magnets was measured individually and compared to the measurements on the magnet test benches. The transfer function of the complete circuits was measured at room temperature. It will be measured again after the magnets are cooled down to 1.9 K.

## *2.3 Pump-down, Leak and Pressure Tests*

After the closure of the vacuum vessel interconnects, the insulation vacuum was pumped down to 1 Pa. This operation took 4 days. The global leak tightness requirement of the vacuum vessel is $1 \cdot 10^{-6}$ Pa $m^3$/s.

The helium circuits will then be individually tested by a pressurisation to $10^5$ Pa. Leak detectors on the vacuum vessel will allow the localisation and quantification of leaks. The global leak tightness requirement of the helium vessel is $1 \cdot 10^{-8}$ Pa $m^3$/s. The sensitivity of this method should allow the detection of leaks greater than $1 \cdot 10^{-9}$ Pa $m^3$/s.

Eventual leaks will be repaired either before the pressure test if they are large, or at a later stage.

The obligatory safety procedure requires the pressurisation of the helium vessel to 1.25 times the design pressure of the vessels. The heat exchanger, the magnet cold masses and beam screens and the thermal shield will therefore be pressurised to 0.5, 2.5 and 2.75 MPa respectively. These pressures will be kept for one hour.

## *2.4 First Cool-down*

The String is directly coupled to a 6 kW refrigerator. The cool-down [8,9] is achieved in two phases. During the first phase, the refrigerator cools down together with the String supplying gaseous helium at decreasing temperature from 293 K to 4.5 K and maintaining a maximum $\Delta T$ across each magnet of 75 K. Once at 4.5 K, the refrigerator is at nominal operating conditions. It supplies supercritical helium at 4.5 K / 0.3 MPa for the filling and cooling of the magnets as well as gaseous helium at 50 K / 1.8 MPa for the thermal screen circuit.

During the second phase, the cool-down from 4.5 K to 1.9 K is performed using a warm pumping unit which maintains a saturated pressure of 1.6 kPa in the magnet bayonet heat exchanger. The 4.5 K supply is used to feed the corresponding cooling loop after being sub-cooled in a counter flow heat exchanger and expanded in a Joule-Thomson valve. At 1.9 K, the String is at nominal operating conditions. The first cool down of the String is expected to take less than two weeks.

| Phase | Temperature | Time |
|---|---|---|
| 1 | 300 - 50 K | 1 week |
| | 50 - 4.5 K | 2 days |
| | LHe filling | 6 hours |
| 2 | 4.5 - 1.9 K | 12 hours |

During the two days of the cool down from 50 K to 4.5 K some of the cold checks for the magnet protection system will also be carried-out.

## *2.5 Power Permit and Abort System*

The fast power abort system [10] is implemented with hardwired logic which is programmable via switches. The matrix takes all the necessary actions to protect the equipment in case of quench or major faults. A PLC is used to authorise the powering of each circuit (power permit) by verifying the necessary conditions. In case of minor faults, the same PLC is used to shut down the power converters (slow power abort).

The system was assembled in a rack, cabled and tested in stand-alone mode. It was then installed in the powering area of String 2 and connected to the various systems when they became available (magnet protection, power converters, cryogenics, water-cooling for the warm cables). The interfaces were individually tested and the logic was verified within the limits of a partially installed system.

## *2.6 Magnet Protection*

During the electrical tests the integrity of the voltage taps was checked. The quench detection electronics was installed. The heater power supplies were tested and discharged in an external resistors. The energy extraction systems for the main dipole circuit and two lattice corrector sextupole circuits were installed and individually tested in conjunction with the power abort system. Control and monitoring of the system is done with an application in the supervision system.

Following the cool down to nominal temperature and before powering the magnets, numerous verifications are required. These include insulation tests, transfer function measurements, coherence and integrity of the instrumentation and tests of the cold by-pass diodes. The parameters of the quench detectors will be validated. The logic implemented in the power abort and power permit will be individually checked for each circuit.

Each circuit will be commissioned independently. The commissioning will be done gradually in steps from low to nominal currents. At each step, the correct operation of the protection system will be verified. The effectiveness of the quench protection heaters will be measured at injection current and at intermediate levels. The resistance of the electrical joints will be measured by measuring the voltage drop at different current levels.

### *2.7 Power Converters*

All 15 converters were tested at full power on water-cooled dummy loads (heat run test, performance measurement) [11].

The power converters were installed in the String 2 powering area and operated with a short-circuit at the level of the DFBS. All the internal and external interlocks were tested. Power permit, fast power and slow power abort were individually tested for each converter.

The high-precision current loops set for resistive loads and ramp tests were successfully performed with lagging current error and voltage ripple measurements.

Each circuit will be commissioned independently with current limitation as required by the protection system.

### *2.8 Supervision and Controls*

The supervision applications were designed and produced in collaboration with an external institute (BARC, India). The individual applications (cryogenics, interlocks, magnet protection, power converters, vacuum) were separately tested with the process control equipment connected via field buses to the operator consoles. The applications were then merged in a central data server to allow exchange of data between systems (e.g. powering and power permit, powering and magnet protection, vacuum and cryogenics) and permit a further level of testing.

Every control specialist was therefore in a position to test the connection with the instrumentation interacting directly with PLC or process control computer, but also from the supervision application. The instrumentation was verified as the components were installed well in advance of the commissioning. Most of the fault finding and correction process will take place before the String is declared operational.

### *2.9 Data Acquisition and Instrument Database*

All the components of the data acquisition for String 1 are re-used and the system was upgraded to cope with the increased number of channels (more than 1000 for the second phase of String 2) and faster acquisition rate required for a few channels. Its commissioning takes place together with the commissioning of the instrumentation for the process control.

A database, which is designed to manage the data for the sensors, became the interface between the instrument owners, the controls specialists and the team responsible for the cabling. A tool to manage the settings of the acquisition parameters was specially designed and was commissioned together with the data acquisition system.

## 3 CONCLUSIONS

As for its assembly, the commissioning of String 2 allows the full-scale testing of the procedures foreseen for the commissioning of LHC. Care is being taken to record the outcome and the values obtained during these tests. They will be of great help for the setting-up of the final commissioning procedures for LHC.

Because of the late availability of some of the components most of the infrastructure, the cabling, the interlock system, the power converters, the controls, the timing and the data acquisition system could be tested and commissioned well in advance. This scenario is also foreseen for LHC where the magnets will be installed and assembled in a sector after the infrastructure is in place and the QRL commissioned.

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