COMMISSIONING OF THE LHC CURRENT LEADS

A. Ballarino, K. H. Meβ, S. A. March, CERN, Geneva, Switzerland

Abstract

The powering of the LHC superconducting magnets relies on more than 3000 current leads transporting the current to/from the cryogenic environment and rated at currents ranging from 60 A to 13000 A. The design of these leads, about 1000 of which are based on high temperature superconducting material, was entirely done at CERN, where prototype assemblies were also assembled and tested, while the series production and testing was done in external laboratories and companies on the basis of build-to-print specifications. This report summarizes the results of the tests performed during the commissioning of the LHC machine, when the leads underwent the thermal and electrical cycles necessary for the powering of the LHC superconducting circuits

INTRODUCTION

The magnets of the LHC machine are powered via more than 3000 current leads. Among these leads, those rated at currents ranging from 600 A to 13 kA [1], [2] are gas-cooled and incorporate HTS (High Temperature Superconducting) material in the form of stacks of Bi-2223 tape [3], while the others, transferring 60 A or 120 A, are resistive and conduction-cooled [4]. All the LHC leads were designed at CERN, where also prototypes of each type were assembled and tested. The final production was done in external laboratories and companies on the basis of built-to-print specifications. All HTS leads and some assemblies of resistive leads were cryogenically tested under nominal operating conditions using purpose-built test stations, prior to integration in the LHC cryostats [5], [6].

In their final environment the current leads were tested for the first time in the LHC tunnel during the ongoing hardware commissioning. This report summarizes the results of the commissioning of the current leads.

COMMISSIONING OF THE LHC LEADS

Most of the current leads powering the accelerator magnets are grouped in cryostats located on either side of the eight LHC interaction points [7]. From these locations all the magnets in the arc and in the insertion regions are fed via the circuits of the main dipole and quadrupoles, of the low beta triplets, of the individually powered quadrupoles, and of the auxiliary corrector magnets. Only the 60 A and 120 A dipole orbit correctors are individually powered via more than 2000 specially designed current leads that are locally integrated in the Short Straight Sections (SSS) of the arc and of the Matching Sections (MS).

During the first phase of the hardware commissioning, each of the eight LHC sectors is individually cooled-down and powered. This approach, which is made possible by the sectorization of the utility and machine systems, involves first the powering of each individual circuit at different current levels up to nominal, and then the simultaneous powering of all circuits in the same sector with steady state conditions maintained during a run of several hours. Each sector contains up to 380 current leads, among which about 130 are HTS and the remaining are resistive.

The instrumentation required for the operation and protection of the leads (temperature sensors and voltage signals) was incorporated in the lead body. For the HTS leads, the voltage signals are routed to the quench protection electronics, which protect respectively at 100 mV and 3 mV the resistive and the HTS part of the lead, while the temperature signals are routed to the cryogenic system for monitoring and for control of the helium flow rate. Software interlocks prevent the powering if the temperature at the top of the HTS (T_{HTS}) deviates from nominal (50 ± 2 K). Slow power abort is activated if T_{HTS} reaches 60 K.

The resistive 60 A and 120 A conduction-cooled leads are cryogenically passive devices that do not require control of the flow. However, the temperatures of the intermediate heat sinks have to be kept at nominal values as given by the cryogenic lines cooling the LHC thermal (50 – 75 K) and beam (4.5 – 20 K) screens, respectively. These temperatures are used as interlocks for the powering of the corresponding electrical circuits. The protection of the resistive leads is assured by the power converters, which ramp down the current in the circuit if the voltage across a lead reaches 150 mV.

Temperature controlled cartridge heaters maintain the room temperature at the top of the HTS leads in stand-by mode and at operation below nominal current. For the resistive leads, a ventilation system is enough to guarantee room temperature in all transient conditions.

Tests

In the framework of the hardware commissioning [8], the LHC current leads undergo the room temperature and cold tests foreseen for the system verification. These tests include:

- Pressure and leak tests at room temperature. The pressure tests are 0.35 MPa for the HTS leads and 2 MPa for the resistive leads in the SSSs and in the MSs.
- Electrical insulation tests at room temperature.
- Electrical insulation tests at nominal cryogenic conditions.
- Powering tests of individual circuits.
- Simultaneous powering tests of all circuits in the same sector.

The design withstand voltage is 3.5 kV in warm helium gas at atmospheric pressure for the 13 kA leads feeding the main dipole and quadrupole circuits, and 1.5 or 1 kV for all the other leads. In the LHC machine, the leads are tested at 1.9 kV for the dipole circuits and between 240 V and 600 V for the other circuits, all in nominal cryogenic conditions.

During the high voltage tests, the power converters are kept isolated from the rest of the circuit by disconnecting the electrical cables at the room temperature end of the leads. The connection of the cables is performed, while the system is cold, before the powering tests.

The powering test of a circuit is preceded by a check of the interlocks at low current levels. Ramps to different current levels are then performed to validate the protection system under different failure scenarios and to verify the performance of the electrical components. The individual tests of the circuits terminate with a 2 hour run at nominal current to validate the performance of the current leads in steady state conditions.

The simultaneous powering test of all circuits in the same sector lasts several hours and verifies the system's performance during a long run.

The cryogenic and electrical signals of the leads are recorded in the LHC logging database [9]. A Post Mortem LabVIEW™ application has been specially developed for the analysis of the current leads performance with predefined signal analysis and check [10].

Test results

No failures of the current leads were encountered during the insulation tests of all circuits of the LHC machine. Electrical insulation tests passed both at room and cryogenic temperatures, and the instrumentation in the leads performed as expected, with no signals missing.

As of 1st June 2008, three sectors of the LHC machine had been powered under nominal operating conditions, i.e. sectors 7-8, 4-5, and 5-6. During these tests, the LHC leads were powered for the first time in the LHC tunnel as part of the accelerator circuits. No failures were encountered and all the leads worked as expected.

The leads showed performances similar to those measured during the test of the components in dedicated cryostats [5] [6]. The conduction-cooled leads have a typical voltage drop at maximum current of 50 to 70 mV, depending on the temperature of the heat intercepts which varies with the location of the leads in the tunnel.

Neither spurious nor real quenches were measured in the superconducting part of the HTS leads.

EIGHT HOUR STEADY STATE RUN

In order to verify the performance of the electrical circuits over extended runs, each sector was powered as a whole over several hours. On the 21st of May 2008 sector 5-6 of the LHC underwent this process with the magnets powered to a level corresponding to 5 TeV beam energy. Overall the run lasted just under 10 hours including powering up/down transients, with the steady state condition being maintained for 8 hours. The data for the HTS currents leads, comprising several hundred variables, was recorded via the LHC logging database, the first stage of the post mortem analysis software used for the hardware commissioning of the LHC. The data represented herein was interpreted at 10 s intervals. There were 53 circuits powered by 122 HTS leads. Among these leads, 8 are rated for 13 kA, 40 for 6 kA and 74 for 600 A. The main dipole circuits have a centre tap and utilized 4 leads, some quadrupole circuits 3 leads, and the remaining circuits 2 leads. There were 122 recorded HTS voltages and 122 resistive voltages. There were 244 temperatures for the HTS leads, half at the top room temperature end of the lead (T_{WARM}), and half at T_{HTS}. The remaining variables were associated with other electrical and cryogenic parameters.

Thermal parameters

The temperatures at the top of the 122 leads were about room temperature during the whole run. The warmest lead had a mean temperature of 310 K, the coldest 291 K, and the maximum standard deviation of the temperature was 0.7 K. (Fig. 1). During the run, the temperature at the top of the HTS element is set at 50 K. For all of the leads, regardless of both nominal current rating and transport current, the warmest lead had a mean temperature of 50.7 K, the coldest 49.7 K, and the maximum standard deviation of the temperature was 0.6 K. The overall mean was 50 K with a standard deviation of 0.2 K (Fig. 2).

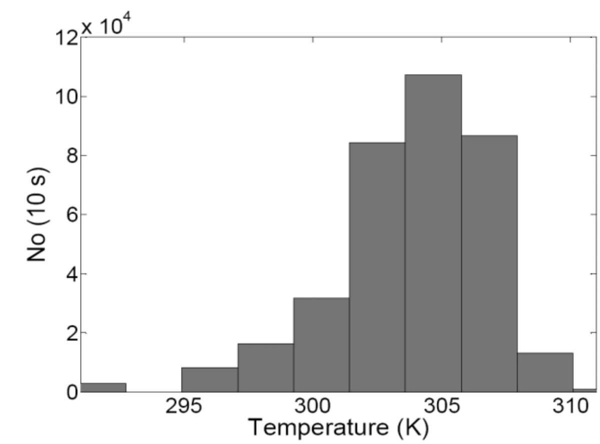

Figure 1: Histogram of the temperatures at T_{WARM} for all 122 HTS leads during the 8 hour run in sector 5-6.

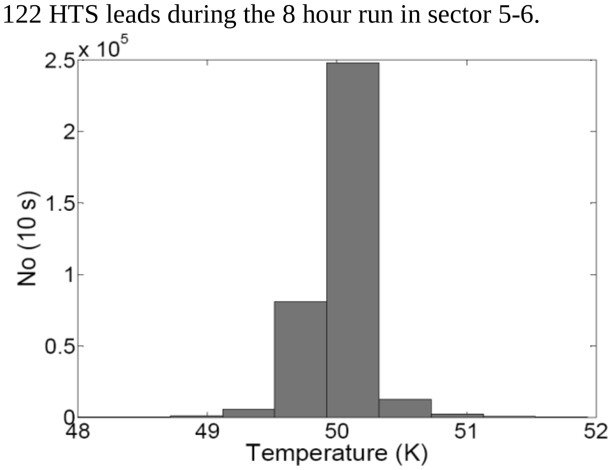

Figure 2: Histogram of the temperatures at T_{HTS} for all 122 HTS leads during the 8 hour run in sector 5-6.

Electrical parameters

The 122 HTS leads in sector 5-6 were powered at currents ranging from 8.42 kA to 135 A (Fig. 3). In addition, there were about 250 resistive leads that operated at currents of 120 A or less.

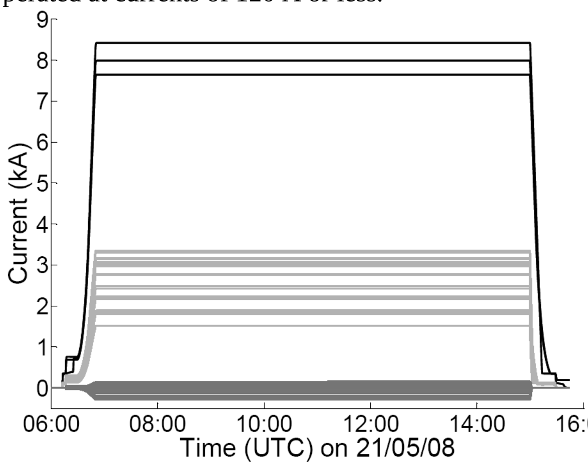

Figure 3: The currents during the eight hour run, including the powering up/down transients. The 13 kA circuits are shown in black, 6 kA in light grey, and 600 A in dark grey.

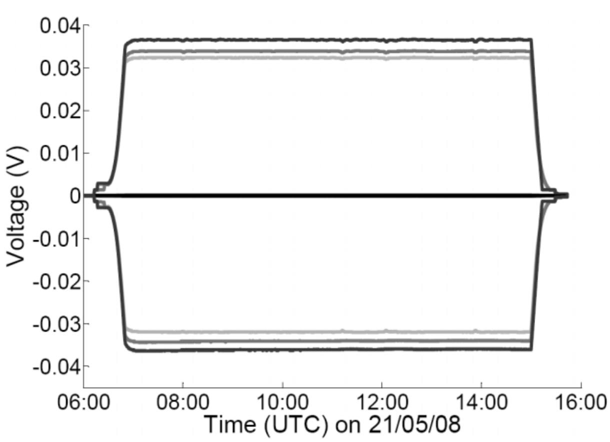

Figure 4: The voltages for the 13 kA circuits during the 8 hour run, including the powering up/down transients. HTS voltages are shown in black, resistive section voltages for the leads transporting 8.42 kA in dark grey, 7.99 kA in lighter grey, and 7.64 kA in lightest grey.

The measured voltages across the leads both during transient and constant powering were within expected values. Voltages measured across the HTS section of the leads were generally 0.01 mV to 0.1 mV. For the 13 kA circuits at 8.42 kA the voltage drop across the HTS section was less than 0.15 mV. This voltage includes the drop due to the resistance of the HTS-Cu joint at 50 K (~15-20 nΩ), which is cooled by the gas in the resistive part of the lead, and of the HTS-LTS joint at 4.5 K, which has a resistance of about 1 nΩ. The voltage drop across the resistive part of the main dipole and quadrupole HTS leads are shown in Fig. 4. These leads were designed for operation at 13 kA with a voltage drop at this current of about 60 mV. The voltage measured during the run in steady state conditions at 8.42 kA was about 37 mV.

CONCLUSIONS

The commissioning of the more than 3000 current leads for the LHC machine is in progress, and results confirms 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 resistive leads met the specified design parameters whilst in the tunnel environment.

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