FIRST RESULTS AND STATUS OF THE LHC TEST STRING 2

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Abstract

After the commissioning of String 2 Phase1 and the powering of the main circuits in autumn 2001, a short yet vigorous experimental program was carried-out to validate the final design choices for the technical systems of LHC. This program included the investigation of thermo-hydraulics of quenches, quench propagation, power converter controls and tracking between power converters, as well as the measurement of currents induced in the beam screen after a quench and crossing the interconnects. Parameters significant for the LHC, such as heat loads, were also measured. During the winter shutdown the String was completed to a full cell with the addition of three pre-series dipoles (Phase 2).

After a short description of the layout of Phase 1 and Phase 2, the results of the experiments are presented and the future experimental program is outlined.

1 INTRODUCTION

String 2 [1,2,3] 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. It is a full-size model of an LHC cell of the regular part of the arc. It is composed of two sets of three dipole magnets with their correctors and one short straight section (SSS) for each set of dipoles. Each SSS contains a lattice quadrupole with closed orbit and lattice corrector magnets. The first SSS is connected to a prototype cryogenic distribution line (QRL) [4] running alongside the magnets. The QRL distributes and recovers helium at different temperatures and pressures.

For Phase 1, five prototype cryomagnets, two short straight sections and three dipoles were installed. The main circuits (dipole, focussing and defocusing quadrupoles circuits) were first powered in September 2001 [5]. The experimental program lasted until mid-December of the same year.

For Phase 2, three pre-series dipole magnets were added thus completing a full cell of LHC. The commissioning of String 2, Phase 2, started in May 2002.

2 THE LAYOUT

In its present state, String 2 is terminated on the upstream end by the electrical feed-box (DFBS) [6] and on the downstream end by the magnet return box (MRB). The DFBS is a 6 meter-long (4.5 K / 0.135 MPa) cryostat, which supports and cools 32 high-temperature superconductor (HTS) current leads [7]. The DFBS also supports the λ-plate that thermally and hydraulically separates its saturated liquid helium bath from the magnet pressurised superfluid helium bath at 1.9 K / 0.13 MPa.

Situated at the other extremity of the string of magnets, the MRB contains the short circuits for the current return and a second connection to the cryogenic distribution line simulating the jumper connection of the following cell.

String 2 is 120 m long and is curved, as the machine in the LHC tunnel.

3 EXPERIENCE DURING THE COMMISSIONING

3.1 Cryogenics

After assembly, all process instrumentation and components were checked and the control loops verified to be ready for cool down. An important number of sensors were found to be malfunctioning due to inverted or broken wires, shorts to ground or swapped sensors. After the commissioning most (97%) sensors had been recovered or made to work with degraded performance.

At nominal operating conditions, (1.9 K on the magnet string and 4.5 K with liquid helium touching the bottom end of the HTS current leads in the DFB) additional systems and instrumentation checks took place, followed by the fine tuning of all control loops prior to magnet powering.

3.2 Current Leads

Six 13000 A and twenty-six 600 A HTS prototype current leads, previously characterized in a dedicated setup, were integrated in the DFBS. During Phase 1, the 13000 A leads, for the first time operating in a real setup, have successfully undergone a number of electrical and thermal cycles.

The commissioning of the 600 A corrector circuits will be made during Phase 2.

3.3 Quench Protection System (QPS)

At various stages of the cool down process the continuity of the electrical circuits, their resistance, the integrity of the instrumentation sensors and wires, the electric insulation (coil to ground, quench heaters to coil, coil to coil, quench heater to quench heater), characteristics of the cold diodes and AC impedances were measured. Incomplete or missing documentation of the instrumentation on the cryomagnets and DFBS contributed to lengthen the analysis process. The electrical performance of the String 2 elements was always found to be within specifications.

The first powering of the main circuits was made gradually: quench heater power supplies and the energy extraction system were triggered at intermediate current levels to ascertain their effectiveness and proper quench detection.

The interfaces to the interlock system and to the power converters were carefully commissioned. In some cases, cross talk between power converters and QPS was observed: modifications to the parameters had to be applied to prevent undesired triggering.

The performance of the QPS for the main magnets was as expected from single magnet tests and from calculations. The commissioning of the energy extraction was performed for the first time on an inductive load storing an energy of 21 MJ at nominal field. The current breaking capability of the energy extraction switches at low current levels was also verified.

3.4 Interlocks

The use of a programmable logic controller (besides a hardwired matrix), was instructive for the design of the future LHC Powering Interlock system: the hardware characteristics (robustness, processing power, response time, etc.) as well as programming tools and communication system make PLCs well adapted to fulfill the needed safety levels.

The remote analysis, monitoring and recording capabilities have significantly contributed to reduce the time required to qualify a circuit for powering.

4 THE EXPERIMENTAL PROGRAM

4.1 Cryogenics

Studies of the thermohydraulics of saturated HeII in the 1.9 K heat exchanger have shown that the velocity (0.15 m/s) of the liquid was higher than in the corrugated tube of String 1 despite the lack of slope, hence improving the control dynamics.

The choice of controlling the magnet temperature 30 mK above the saturation temperature [8] can be retained and it should give enough room to regulate the magnet temperatures without any undesired liquid overflowing in the phase separator.

Heat exchanger conductivity predicted by theoretical calculations was found to be in agreement with experimental data

Concerning the dynamics of the LHC 1.9 K cooling loop, the following characteristics have been observed: (1) asymmetric inverse response, where temperature excursion varies in function of its direction, (2) variable dead-time depending mostly on the heat load situation, and (3) non-uniform coldmass temperature across magnets due to a constrained heat transfer through the coldmass interconnections.

All these complex characteristics point towards a more advanced control technique than a simple PID controller can provide [9]. It also suggests that fault detection techniques should be implemented to adapt in real time and take the right process variables (temperature sensors).

The quench propagation experiment results from Phase 1, when extrapolated to the longer LHC hydraulic unit of 214 m by applying the scaling rules derived in [10], permitted to confirm that the propagation of a magnet quench in the LHC will be well contained within one full-cell. The industrial prototype quench relief valves allowed to safely discharge a full-cell while keeping the cold masses within the design pressure.

Continuous measurements of the heat loads of the main components, in steady state as well as in transient conditions (e.g. ramping the current in the magnets), confirmed the order of magnitude of global heat inleaks in the cryogenic system. These measurements gave an overall heat load of about 30 W on the 1.9 K bath of the magnets, which is twice the budget for a standard full-cell in the arc. Detailed analysis showed that this is due to non-standard components and instrumentation as well as end-effects [11]. The measurements made on the helium boil-off rate of the DFBS pressurised helium bath indicate a heat load of 10.3 ± 0.6 W. The heat load passing through the lambda plate from the helium bath at 4.5 K to the 1.9 K bath of the magnets is 7.2 ± 1.1 W [12].

During Phase 2, the superfluid helium loop as well as the quench propagation experiments will be repeated and more extensively performed to obtain final validation this time, on a complete cell. The non-conformities, due to instrumentation of the cryostat components, will be removed and global heat load measurements performed again during a future run in early 2003.

4.2 Power Converter Tests

String 2 Phase 1 provided the opportunity to test all the main power converter families and the digital control of current in conditions similar to those expected in LHC.

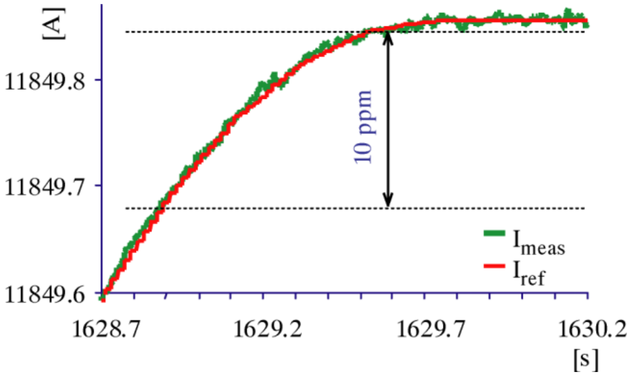

Figure 1: End of a ramp to nominal current (11850 A) of the defocusing quadrupole circuit

The voltage ripple of the converters on the magnets and the effect of electromagnetic perturbations generated by the power converters on other systems such as the protection system were observed. The behaviour at low current of one- and two-quadrant converters as well as the stability of the four-quadrant converters at zero current and across their full range of operation were measured. The discharge of the energy stored in the magnets through the free-wheel diodes and thyristors for the one- and two-quadrant converters as well as through the crowbars for the four-quadrant converters was studied. The effect on the current of the loss of one redundant converter module of the one-quadrant converters was observed.

The performance observed generally matches the requirements for LHC. The experiments planned for Phase 2 aim at improving the precision of the current in the magnets and at validating the complex circuit topologies which include several electrically coupled converters.

4.3 Tracking Tests

The aim of the tracking tests was to verify that the quadrupole field could be ramped synchronously with the dipole field. In order to achieve the requested maximum tune variation of 0.003, the ratio of quadrupole and dipole field can deviate from a constant by at most 40 ppm at full current. Independent measurements, performed on the test benches dedicated to series tests of single magnets, have shown that the transfer functions (ratio of produced field and operating current) of the dipole and quadrupole magnets are significantly different, especially at high field where saturation effects introduce a mismatch of the order of 3500 ppm of full scale.

Using a feed-forward algorithm, which corrects the expected mismatch, the tracking of the fields was measured at the power converter and in the magnet cold bore using a set of 2-m long fixed coils. The latter had been calibrated in situ and connected to integrators thus providing a measurement of the field change during the ramp. The current setting was found to be better than 20 ppm with a tracking error below ± 2 ppm of full scale. The error in the field matching was of the order of 300 ppm of full scale. During Phase 2 the tracking tests will be repeated to show that the objective of 40 ppm at full current can be safely obtained by applying successive corrections.

4.4 Currents in the Beam Screen

Due to a slightly unbalanced magnetic field in the magnet yoke of the LHC dipoles, it is expected that an eddy current in the order of 350 A is induced in the beam screen [13]. To determine which portion of this eddy current propagates to neighbouring components and magnets, some interconnects were equipped with Rogowski-coil current transducers and voltage taps. Preliminary results indicate that the currents, in particular across the RF-contacts, are less than 10 A. For Phase 2 the instrumentation has been improved to confirm this result with a better precision.

5 CONCLUSIONS

The relatively fast commissioning of the main circuits, the smooth running of the experimental program is certainly due to the quality of the engineering but also relies on the experience gained on String 1 by the people responsible for the individual systems and the operation crews.

String 1 and String 2 have both been valuable tools for understanding the dynamic of the processes, for the validation of commissioning procedures and for the training of the operation crews. With respect to installed instrumentation as well as process complexity, String 2 is close to an LHC Sector: the commissioning and the experimental programs presently taking place will undoubtedly have a direct impact on the commissioning of the LHC sectors

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