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EXPERIMENTAL VALIDATION AND OPERATION OF THE LHC TEST STRING 2 CRYOGENIC SYSTEM

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Abstract

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ABSTRACT

The LHC Test String 2 is a 107-m long superconducting magnet string representing a full-cell of the LHC machine. It was designed and commissioned at CERN in order to validate the final design choices and to investigate the collective behavior and operation modes of the LHC machine systems. It has been commissioned and operated since April 2001 and has accumulated more than 8000 hours at its nominal operating temperature of 1.9 K under machine-like conditions. We report on the experimental validation of the supercritical and superfluid helium cooling loops, quench propagation and recovery, heat loads, as well as on investigation of operational performances, advanced control techniques, process control, instrumentation and long term behavior under electrical and thermal cycling.

INTRODUCTION

A major milestone in preparation of the commissioning and operation of the Large Hadron Collider (LHC) is the commissioning and operation of a full-scale model representing a full-cell of the machine lattice, corresponding to the length of the elementary cooling loops.

Following the successful testing and excellent results between 1994 and 1999 of the first half-cell operational model [1], a new full-cell model, the LHC Test String 2, has been designed, assembled and commissioned in 2001 [2]. It evolved from about half-cell length to its final configuration with 2 quadrupoles and 6 dipoles stretching over the 107-m full length in 2002.

OPERATIONAL PERFORMANCES

The LHC Test String 2 - the world's longest stretch of superfluid helium before the first LHC sector cool-down in 2005 - has accumulated more than 8000 hours of operation at cryogenic conditions required for magnet powering (i.e. superfluid helium at 1.9 K and

FIGURE 1. Simplified flow-scheme of the LHC Test String 2.

1 bar in the magnet cold masses, liquid helium level in the Electrical Feed Box and the HTS current leads between 4.5 K and 300 K with intermediate heat interception at 50 K by 20 K helium gas flow). A cryogenic distribution line distributes cooling power along the LHC Test String 2 (FIGURE 1). Two service modules feed the superfluid helium loop via a very low pressure heat exchanger and two J-T valves, the beam screen cooling loops and the magnet cold mass. Two prototype quench relief valves, one at each end of the magnet string in their respective service modules, protect the cold mass from overpressure by opening as pressure actuated safety relief devices. The bayonet heat exchanger running inside the cold mass is fed via an inner tube that deposits saturated superfluid helium at the far extremity of the magnets string.

The LHC Test String 2 has operated under machine-like conditions for more than 8'000 hours. Combined, the two operational models ran, between 1995 and 2003, under machine-like conditions for more than 20'000 hours, representing more than 3 years of continuous operation of the future LHC collider.

The accumulated running time for the two models consisted of steady-state operation as well as transients such as cool-down, warm-up, current ramp-up and ramp-down, magnet resistive transitions (quench), thermal and powering cycles.

Over the years, continuous improvements of the process and the control system has made it possible for the over 160 t cold mass to be cooled down from 300 K to 80 K in less than two weeks, from 80 K to 4.2 K in about 24 hours and from 4.2 K down to 1.9 K in less than 12 hours. These times are representative of an LHC machine sector cooldown and were limited by the available cryogenic cooling capacity of the existing 6 kW refrigerator and the very low pressure pumping system coupled to the LHC Test String 2 [3]. FIGURE 2 represents a typical cooldown from 4.5 K to 1.9 K with 10 g/s liquid helium cooling flow in the bayonet heat exchanger. The cooling flow rate, and therefore the speed of the cooldown, is limited to 7.8 g/s by hydrodynamics [4]: liquid entrainment at vapor

FIGURE 2. Cooldown from 4.5 K to 1.9 K with 10 g/s flow in the HX and consequent onset of instabilities.

flow rates above about 7.5 m/s (or 7.8 g/s at 1.8 K saturation pressure) in the bayonet heat exchanger prevents its proper functioning. Too much liquid traverses the full heat exchanger length without having had the possibility to exchange heat at the heat exchanger walls. The cooling speed can only be optimized by regulating the saturation temperature (pressure) in the bayonet heat exchanger to the coldest magnet temperature and decreasing it progressively during the cooldown.

In order to complete the overall picture and make it representative of the future machine operation, 3 thermal cycles and the recovery from more than 37 provoked and 5 natural quenches were performed.

The LHC Test String 2 cryogenic system was operated continuously and in fully automated mode during non-experimental periods, requiring only a cryogenic on-call operator who could be alerted by SMS messages sent by the process control system to describe the faults and status of main parameters. These alarms were doubled by a hardwired general-fault alarm to a centrally manned control room. During working hours, a cryogenic operator and an experiment technical responsible took care of operating the system for powering conditions or off nominal operating ranges. The skills of the operations team and the robustness of components and process, permitted to limit operators' on-call interventions outside normal working hours to less than 3 % of the total machine operating hours, while keeping an average overall cryogenics availability of more than 97 % of total operation time. All components have been operated in machine-like conditions mimicking all aspects of an underground installation, including the length of cabling between devices and the control system outputs. The only aspects that could not be tested or experienced concern beam guidance and focusing. Nevertheless, the effect of the beam itself on magnet temperature control and stability has been simulated via electrical heaters. The effect of beam-induced radiation on system components has been extensively studied in dedicated irradiation facilities [5].

INSTRUMENTATION AND PROCESS CONTROL

The LHC Test String 2 requires about 700 cryogenic sensors and actuators distributed along four Profibus-DP and three Profibus-PA field buses to fulfil its extensive and

thorough experimental program. The process automation is handled by two controllers, running 126 Closed Control Loops. The control system is representative of an octant of the LHC machine. In the final stages of the test program, a large part of the control system has migrated into the CERN's newly adopted unified controls framework, comprising new programming methodology, Programmable Logic Controllers (PLC) and man-machine interface. Radiation tolerant WorldFIP field bus and signal conditioners for temperature and pressure have been tested, together with a gateway between WorldFIP and the PLC. For radiation shielding requirements, several electromagnetic control valves for current leads temperature control have been operating at distances of up to a few hundred meters from the electronics. For the same reason, a set of "intelligent" valve positioners have functioned with electronics and pneumatic actuators separated by 1 km of cable, representing the real machine conditions inside the LHC tunnel. Electromagnetic compatibility tests have been performed identifying possible sources of electrical noise from power converters and kickers magnets power supplies. High-frequency noise generated by the power converters was found to be coupled via the superconducting coils to the thermometers inside the cryostat. The warming up by Joule effect resulted in a few tens of mK offset. Capacitive filters will be required in the machine to reduce this noise to levels compatible with the required accuracy for temperature control.

EXPERIMENTS

The main goals of the experimental runs were the validation of the basic technical choices of the LHC design, testing of cryogenic components prior to tunnel installation and investigation of operation modes to verify possible limitations and to optimize performance.

Superfluid Helium Loop and Bayonet Heat Exchanger

Intensive testing has permitted validation of the performance and sizing rules of the bayonet heat exchanger for transporting linear heat loads in the W/m range (LHC static and dynamic load) over the 100-m long magnet string.

The superfluid helium loop exhibits the following control characteristics: asymmetric inverse response, variable dead time depending on heat load and non-uniform cold mass temperatures. These characteristics largely condition the dynamics of the process.

The inverse response appears as a consequence of: pressure drop variation in the heat exchanger tube and inner supply pipe during transients, and magnets interconnections thermal impedance.

The variable dead time response corresponds to the fact that with different static heat loads, the wetted length in the heat exchanger will vary accordingly in length. This is a pure effect of transportation lag due to liquid helium advance in the tube. The existence of the non-uniform cold mass temperature along the same cell corresponds to the existence of non negligible impedance in the magnets or interconnections.

The major challenge is the temperature regulation. PID controllers were extensively tested. Special care had to be taken with the selection of the tuning parameters to take into account constraints imposed by the maximum temperature at which the magnets can operate as well as the inverse response of the loop. The PID controller showed a poor performance due to the nonlinear nature of the process and had to be re-tuned after any change in configuration or heat load to obtain barely minimal performances that did not avoid overflow of the heat exchanger in the pumping line.

FIGURE 3. MBPC vs. PID: Temperature excursion following a heat load change.

Advanced Control Techniques

A novel advanced controller based on a linear predictive regulator complemented with a nonlinear estimator was designed. The regulation methodology is based on two different layers: a low-level layer where a PID is implemented using the Siemens-S7TM PLC facilities (modular PID control) and a high-level layer where an advanced controller is running in a dedicated PC and communicating to the PLC through Ethernet.

MBPC (Model-Based Predictive Control) methodologies use a dynamic model of the process to predict the behaviour of the process [6]. The controller implements an on-line optimization procedure where the controlled variable and the desired response are involved. Considering the static heat load as the critical factor, its estimation at any moment is a decisive issue. An estimator unit provides the controller with the specific operation information, thus improving largely the performance of the MBPC controller.

The response of the controller was compared to the one produced by the PID regulator under the same disturbance (FIGURE 3). When the heat load is applied there is an unavoidable temperature excursion which takes place in both cases, but afterwards the MBPC controller is able to cancel the excursion before the PID and also to bring it back to stability around the setpoint faster and more accurate than what PID does. Improvement can be rated in the order of 50% both in temperature excursion and stabilization time.

Supercritical Helium Loop

The experiments performed with the beam screen circuits showed a relatively simple process dynamics which can be controlled by a classical PID regulator. The open-loop tests together with system identification gave a sufficiently good dynamic model to be used for the tuning procedure. The resulting tuning parameters were implemented and proved successful under realistic LHC machine conditions.

The two main operating modes of the LHC machine were tested. Heaters glued on the beam screen itself, representing the beam-induced heat loads, were powered to 0.79 W/m for both apertures, giving an overall load of 43 W per aperture corresponding to ‘nominal operation’ at 7 TeV beam energy, 2 x 0.56 A beam current and $10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$ luminosity. The second mode, called ‘ultimate operation’, corresponds to a 7 TeV beam energy,

FIGURE 4. Beam screen temperature regulation stability: Nominal and Ultimate loads.

2 x 0.845 A beam current and $2.5 \cdot 10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$ luminosity, assuming a two-fold reduction of residual pressure in the beam channel over long term operation scenario. It consisted in applying 2.19 W/m or a total of 116 W per aperture.

FIGURE 4 shows the regulation performances of the beam screen temperature regulation with nominal and ultimate loads. Despite the abrupt change of applied load - in the machine it will be smoothed over a 20 minutes period - the controller was able to take back the beam screen output temperature to the nominal value of 20 K. No density wave oscillations in supercritical helium [7] were detected in the introduced working modes. The inlet temperature was always slightly above 5 K without the use of the inlet heater.

Quench Propagation and Recovery

The aims of the experiments were the validation of system components (cold safety relief valves [QRV], magnets cryostat, recovery line D, Quench and Warm Buffer recovery Vessel) and recovery procedures, as well as studies on the quench propagation from magnet to magnet to forecast the consequences and recovery of a magnet quench in the LHC machine.

Components and procedures were validated during more than 37 provoked and 5 natural quenches, culminating with a provoked quench on all quadrupole and dipole magnets and the helium discharge via only one of the two pressure actuated QRV's opening at 1.7 MPa (FIGURE 5). The cold mass was safely maintained below the design pressure of 2 MPa and the recovery system and procedures performed as expected.

Several experiments on quench propagation from magnet-to-magnet confirmed the thermohydraulics models developed with the previous LHC Test String [8] and the limitation of a magnet resistive transition propagation to few adjacent magnets via thermal convection of bulk helium, warm helium “bubble” expansion and discharge flow via the safety relief devices. A typical test consists in provoking, via electrical heaters, a magnet resistive transition on the magnet furthest (MB6) from the discharge point of the magnet string at nominal operating field (the second relief device opening is at a higher pressure). The quench slowly propagates, because of the “warm bubble” heating of magnets, along part of the magnet string while the current is driven down to the injection current of 800 A with a machine-like exponential decay (FIGURE 6). Typically the quench of a dipole provokes the quench of 5 other dipoles and 1 quadrupole.

FIGURE 6. Provoked quench of all magnets at 11850 A.

Heat Load Measurements

Global heat loads on the LHC Test String 2 cold mass at the 1.9 K level were constantly monitored in steady-state as well as in transient phases to verify compliance with the estimated budget for the LHC machine. Preliminary measurements showed worryingly higher than budgeted static loads. The presence of non-standard components and additional instrumentation to improve diagnostic capability were identified as a major source. To accurately determine the expected thermal performance of the machine components it was therefore decided, for the last operational run, to strip down the LHC Test String 2 cold masses to the configuration expected for the LHC machine. Heat load evaluations were performed by measuring flow rate with cryogenic Coriolis flowmeters, Hastings™ mass thermal flowmeters at the 1.9 K pumping circuit recovery and with temperature and pressure sensors to infer the enthalpy difference between inlet and outlet

FIGURE 5. Provoked quench of single magnet at 11850 A.

of the superfluid helium cooling loop. The results were independently confirmed by measurement of the internal energy evolution during cooling stops and natural warm-ups.

The total heat load for the magnet cold masses at 1.9 K was measured to be 32.4 W $\pm$ 1 W. Taking into account end effects specific of a single magnet string, the representative heat loads for the standard cell is reduced to 24.4 W $\pm$ 1.6 W, to be compared with an estimated theoretical value of 20.7 W. This larger than expected value can be explained by the use of non-standard superinsulation in the dipoles of the first half-cell and by the remaining presence of parasitic instrumentation wires for additional diagnostics [9].

It can be therefore concluded that there are no major cryogenic problems in cryostat design and construction. Additional calorimetric measurements performed during powering cycles of the LHC Test String 2, did not show any anomalies of the contact resistances of superconducting cables (less than 0.6 nOhms per joint were measured on average).

CONCLUSIONS

The LHC Test String 2 together with its predecessor String 1, have been extremely valuable tools to validate cryogenic components and design choices, investigate operational scenarios, improve the process and operating conditions, and finally, train future operating crew. It has also provided confidence in and expertise for the assembling and commissioning of the cryogenic system of the LHC machine in the coming years, and will contribute to a significant reduction in the commissioning time in preparation of the first beam interaction in 2007.

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