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Operation, Testing and Long Term Behaviour of the LHC Test String Cryogenic System

J. Casas-Cubillos, Ph. Provenaz, L. Serio, A. Suraci and R. van Weelderen

Abstract

Since the end of 1994 we have been operating a prototype half-cell of the machine lattice, accumulating more than 10,000 hours at superfluid helium temperatures and recovering from 150, mainly provoked, magnet resistive transitions. The system has confirmed the validity of the basic design choices of the LHC cryogenic system. Furthermore, extensive testing on the response of the system to current ramp and discharge, and to magnet resistive transition, has provided sufficient information to enable a simplification of the cryogenic scheme that fulfils the LHC requirements. We report on the cryogenic operation, testing and long-term behaviour of the LHC Test String during the last 4 years of operation.

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Administrative Secretariat
LHC Division
CERN
CH - 1211 Geneva 23
Switzerland

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J. Casas-Cubillos, Ph. Provenaz, L. Serio, A. Suraci and R. van Weelderen

LHC Division, CERN, Geneva (Switzerland)

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1 INTRODUCTION

As far as main accelerator systems - magnets, cryogenics and vacuum - are concerned, a major milestone in the validation of basic technical choices of the Large Hadron Collider (LHC) project [1] is the testing and operation of a full-scale superconducting magnet string, representing a half-cell of the machine lattice.

The first version of the LHC test string was assembled, commissioned and successfully operated for the first time at the end of 1994 [2], confirming the validity of the basic design choices of the LHC cryogenic system [3].

After three major shutdown periods [4] to exchange and install new magnets, components (e.g. an actively cooled beam screen) and instrumentation, and after four experimental runs (each lasting several months), the experimental program of the string will terminate this year. A new test string based on systems in their final version (e.g. 15-m long magnets and a cryogenic separate distribution line) and based on a 107-m long full-cell hydraulic scheme will replace it.

2 OPERATIONAL PERFORMANCE

The LHC test string has now accumulated more than 20,000 hours of operation. This consisted in steady-state operation and transients such as cool-down, warm-up, current ramping/de-ramping, magnet resistive transitions, thermal and powering cycles. More than 10,000 hours were spent at superfluid helium temperatures, of which more than 2200 hours with the magnets powered.

Continuous improvement of the process and the control system has made it possible for the 10^5 kg cold mass to be cooled down from 300 K to 1.9 K in about two days. The warming-up is limited by the available heating power (25 kW) and takes about four days. The string cryogenic system is now operated continuously in fully automated mode during a non-experimental period, requiring only a cryogenic on-call operator who can be remotely alerted by the process control software in case the main system parameters fall outside of their authorised range.

Fourteen thermal cycles were performed in order to get information about effect of thermal stresses (see figure 1).

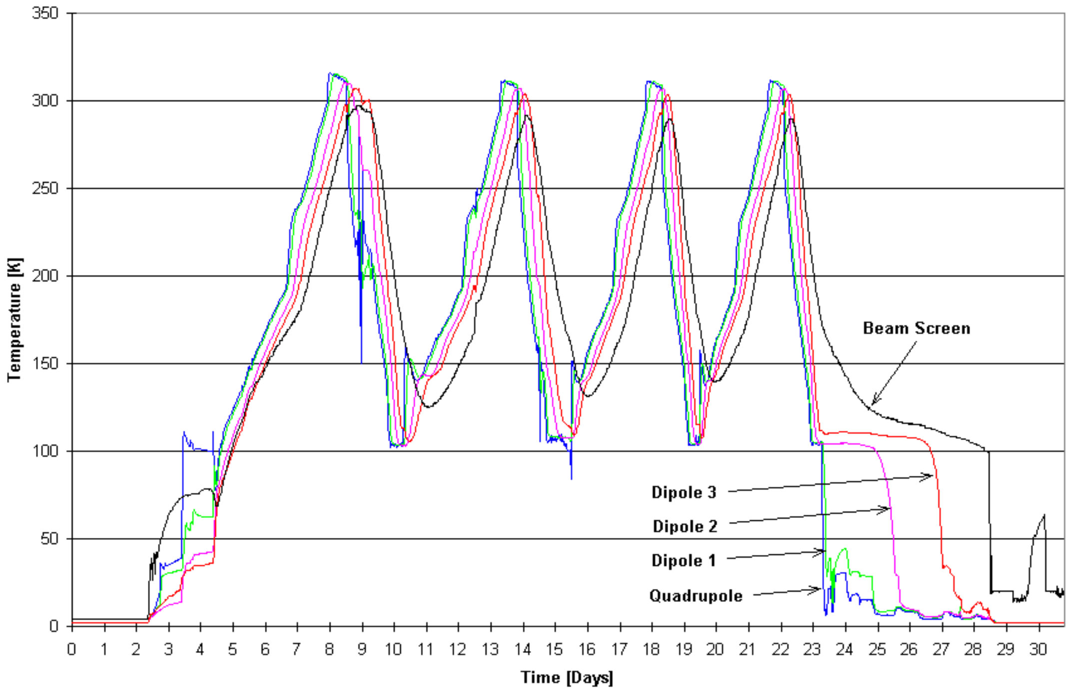

Figure 1 Thermal cycles

In order to investigate eventual fatigue-related flaws of components, 10 years of operation of the future collider were simulated by executing 3275 powering cycles (from 800 A up to the nominal current of 12.5 kA). The cryogenic system, during ramping and de-ramping that corresponds approximately in doubling of the heat load, was able to maintain the magnets well below their operating temperature of 1.9 K with a total temperature excursion of less than 10 mK (figure 2).

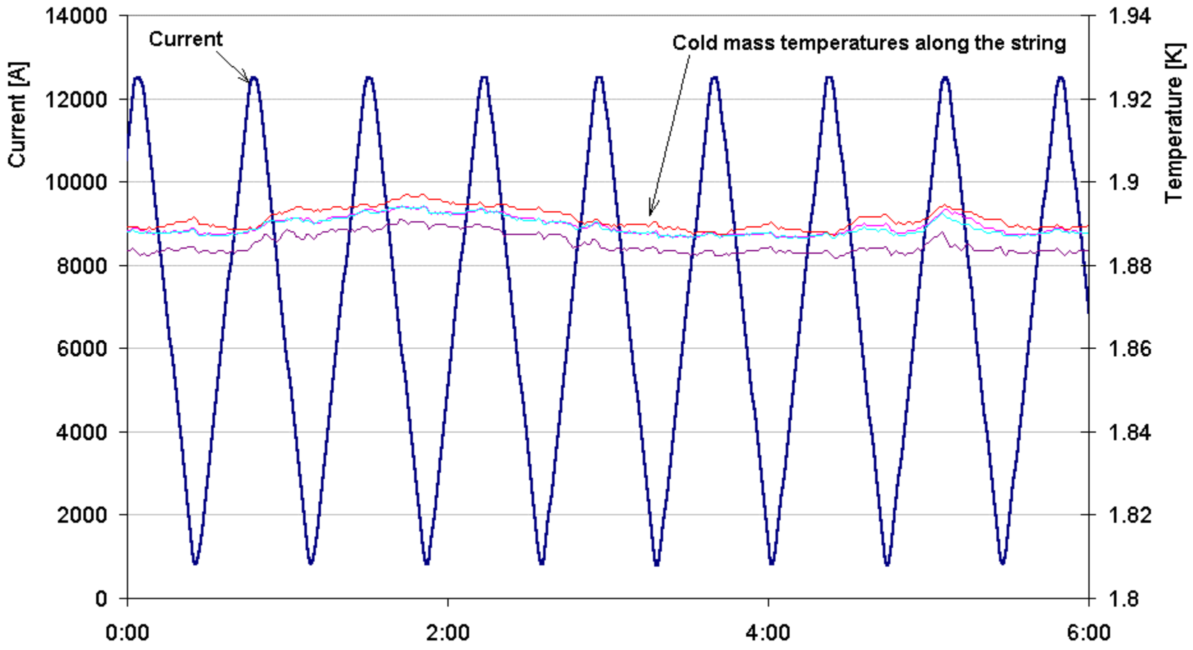

Figure 2 Powering cycles

We consider the time the cryogenic system has been operational sufficiently representative of the future machine lifetime operation. In order to complete the study, several thermal cycles and recoveries from 150, mainly provoked, magnet resistive transitions were performed.

All components have been operated in an industrial environment with no major interventions required. The cryogenic valves have, in average, performed half of the 10,000 stroke cycles for which the manufacturer designs them. Some of them have gone as far as 30,000 stroke cycles.

During this whole period there was no major incident excepted for the bursting of a recovery balloon following a quench and the breaking of the glued glass-fibre stem of an industrial valve used experimentally as quench relief valve. The first incident was due to an operator mistake that left the recovery line open to the high flow of helium discharged from the cold mass. A mechanical restriction for the flow discharged to the balloon and an electrical interlock are now taking care of possible human errors. The second one was probably due to a faulty construction of the valve.

3 EXPERIMENTS

Since 1994 the main goals of the experimental runs were the validation of the basic technical choices of the LHC design and the exploration of possibilities to optimise the cryogenic distribution scheme. Cryogenic experiments were performed during each of the four runs and the required cryogenic nominal operating conditions were ensured during non cryogenic-related experimental programs.

Co- and counter-current flow operating modes of the superfluid helium cooling loop were explored. Flow capacity limitations have led us to abandon the counter-current mode. The intensive testing on the superfluid helium cooling loop permitted to validate the performance and sizing rules of the bayonet heat exchanger for transporting linear heat loads in the W m^{-1} range over the distance of several tens of meters [5].

The introduction of two Pitot tubes in the quench recovery line as high flow flowmeters enabled us to confirm the results of the thermohydraulic experiments (figure 3) [6] and validated their extrapolation for a discharge from a 100-m long magnet string, as well as confirming the basic design choices of the quench recovery system [7]. The discharged flow of first superfluid, then normal liquid followed by supercritical helium is within 20 % of the calculated mass flow rate, as shown in figure 4.

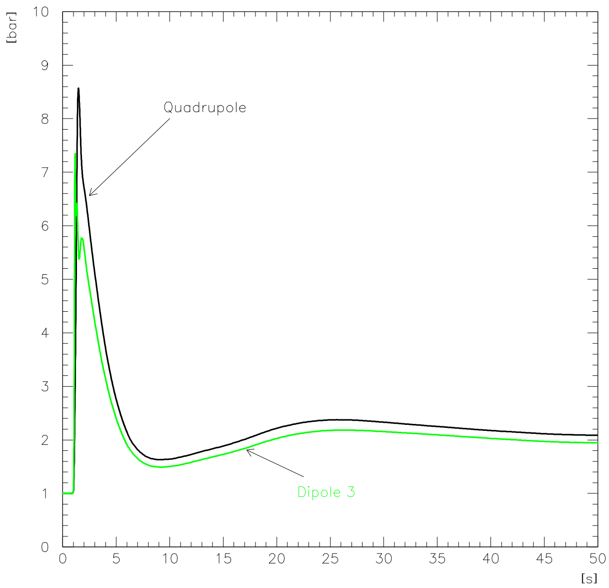

Figure 3 Pressure development in the cold mass after a quench

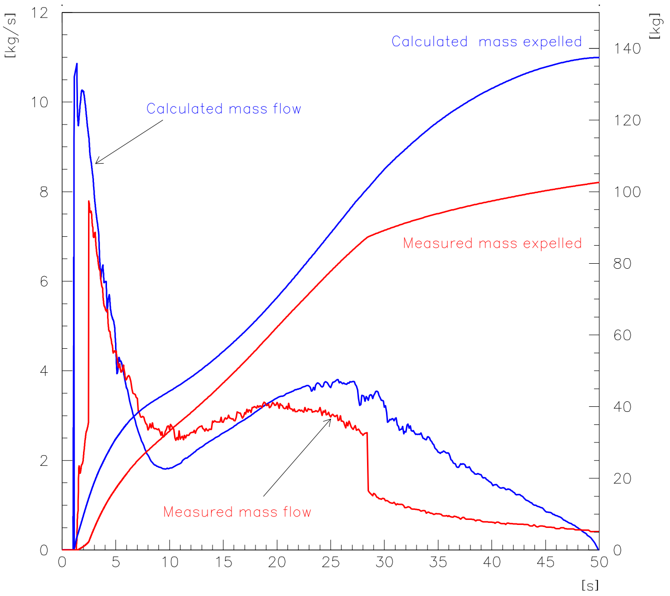

Figure 4 Calculated and measured discharged mass flow

Experiments on thermohydraulic quench propagation experiments from dipole-to-dipole magnets enabled us to identify the mechanism of heat propagation through the helium to dominate over the quench propagation by solid conduction via the bus-bars [8]. Following the results obtained, we expect the number of magnets to which a quench can propagate to be limited to few units, thus having no significant impact on the cryogenic recovery time, the helium inventory and exergy recovery. Furthermore, the thermohydraulic propagation through the helium can be slowed down by increasing the opening pressure of the quench relief valves.

4 INSTRUMENTATION AND PROCESS CONTROL

The test string has also been a test bed for cryogenic instrumentation and process control [9]. The PLC program is adapted to the constant evolution of the string test, in particular new routines for automatic thermal cycling, quench recuperation and additional closed control loops have been implemented. Studies concerning aging of temperature sensors have been conducted. The temperature sensors that have been investigated include Allen-Bradley, CERNOX and Russian TVO. Within the accuracy of the in-situ measurements it is difficult to conclude that a given type of thermometer has better long-term stability characteristics.

5 CONCLUSIONS

The LHC cryogenic system and the collective behaviour of all regular arc LHC systems (cryogenic, magnet protection and vacuum) have been fully validated and their design optimised during the extensive testing performed on the LHC test string facility. Valuable information has been gathered on the processes and on how to efficiently commission and operate a half-cell of the machine lattice.

This version of a half-cell will be dismantled next year to be replaced by the new test string facility that incorporates the final version of the LHC systems. This new facility will be operational in the year 2000 and will include a separate cryogenic distribution line external to the magnet cryostat to feed every 107-m the cooling circuits of the string of magnets.

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