THE LHC TEST STRING: FIRST OPERATIONAL EXPERIENCE

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1 INTRODUCTION

The LHC prototype half-cell, alias *The String,* consists of a string of three 10m twin-aperture dipoles and one 3m twin-aperture quadrupole. It follows an earlier design [1,2] with the cryogenic lines traversing the magnet cryostats and is equipped with dipoles shorter than those foreseen for LHC.

2 OPERATION

After a shutdown, the LHC half-cell is warm and the insulation vacuum enclosure vented with air or nitrogen at atmospheric pressure; it is first evacuated to establish the insulation and beam vacua: this operation takes approximately one week.

The LHC half-cell is then cooled down in three phases, the total of which takes just over a week. In the first phase, the temperature is lowered from room temperature to 80 K by forced flow of gaseous helium at progressively decreasing temperatures. A fixed gradient of 60 K between the quadrupole inlet and last dipole outlet limits the mechanical stresses experienced by the structure. The next phase, 80 to 4.5 K, is achieved by filling the magnets either with liquid or with supercritical helium. The last phase, 4.5 to 1.9 K starts when the coldmasses of the magnets are filled with 800 liters of liquid helium; the temperature is then lowered by pumping on saturated helium flowing and evaporating in a longitudinal heat exchanger. This heat exchanger traverses the complete string of magnets and is thus coupled to the pressurized helium bath permeating the yoke, collars and superconducting windings of the magnets [3,4]. For the whole duration of the run, the LHC half-cell is maintained at 1.9 K with temperature excursions of short duration caused by quenches or other tests.

Insulation of the superfluid helium bath of the magnets from ambient is achieved by evacuated cryostats featuring several levels of thermal shielding and heat interception.

The electrical circuit consist of a 20 kA, 14V power converter, mechanical and thyristor switches together with their associated de-excitation resistors. Each magnet is equipped with a cold diode assembly which by-passes the magnet coils during a quench. A quench detection system monitors and compares the voltage differences between magnet poles and apertures: when a threshold is exceeded, protective action, which results in a fast discharge procedure, is taken. The magnet protection system, which is built around a hardwired logic unit, has a reaction time of the order of milliseconds.

The powering and magnet protection system [5] of the LHC half-cell is interlocked to the cryogenic system: when magnet temperatures reach 1.9 K and peripheral systems (current leads, thermal screens, etc.) are adequately cooled, powering is authorized. Should these conditions disappear while the magnets are powered, a programmable logic controller triggers the power system to initiate a de-excitation procedure.

Cryogenics, vacuum and powering are controlled by a system based on an industrial model. It makes use of commercially available hardware and software [6]. Industrial programmable logic controllers (PLC) are networked via Ethernet™; they control the process by regulating steady state operation or driving the system in automatic control modes, for example, through the cool-down phases. Operators control and monitor the process in the String Control Room via workstations running a commercial supervision package. Remote control and monitoring is also possible via X-terminals across the CERN site and WWW applications on the site and from home.

2.1 Thermal Cycles and Training

The three thermal cycles experienced by the LHC half-cell have uncovered an aspect of training behaviour in the superconducting magnets: following a thermal cycle, one of the magnets naturally quenches at a current level lower than that previously attained.

2.2 Quench History

75 natural or provoked quenches were performed during the two experimental runs: 35 of these were at nominal current (12.4 kA) or above.

While the LHC half-cell is routinely powered and subsequently quenched at 13.1 kA, the highest natural quench observed occurred at 13.4 kA.

2.3 Incidents

Three notable incidents are reported. All occurred during the last few month of operation.

An industrial control valve, which had been modified to study the use of commercially available valves as quench relief valves, broke down. The epoxy resin rod, connecting the closing inset with the actuator, disconnected from the latter. Preliminary studies suggest that the glueing had not been carried out properly. Fortunately, the valve could be exchanged while the string was kept at 100 K.

An instrumentation feedthrough enclosing the voltage sensing and quench heater powering wires exhibited a helium leak large enough to be visually observed. Interim measures (local potting with epoxy resin) have been taken to reduce the leak: a new feedthrough will be installed during the coming shutdown.

During a provoked quench, the wires from the external connectors to the voltage taps of Aperture B of the quadrupole were interrupted somewhere in the coldmass. The redundancy existing in the quench detection system permitted an alternative to be set-up.

2.4 Organization

The organization of the operation and of the experiments is performed by the *String Team*. It consists of 10 engineers and scientists from different groups. The String Team is helped by the operators of the cryogenic plant for routine operations such as the preparation for, and the recovery from a programmed quench. The String Team meets once every two weeks and the minutes of the meetings are widely distributed.

3 EXPERIMENTAL PROGRAM

Two experimental runs have been organized in the two years since commissioning began in December 1994 [7]. RUN2 started with the addition of a third dipole and a structural modification to the cryogenic system [4]. The LHC half-cell systems, the experiments and their results have been described in detail in specialized conferences [3,4,5,6,7,9,10,11]. What follows is a summary.

3.1 Cryogenics

The 1.8 K *cooling scheme* was experimentally validated through extensive experimentation in steady state conditions and during transients. A temperature excursion of 6 mK was observed during ramping at nominal LHC rate (10 A/s). De-excitation at nominal rate (130 A/s) results in a temperature increase of 50 mK allowing the string to be discharged from nominal current without quenching the magnets. This fast response does not compromise the long term stability: in fact, temperature oscillations of only a few mK were observed in a 48 hour run. Proton losses in LHC were simulated applying heat loads of up to 1 W/m: temperature excursions less than 30 mK were observed.

The study of the thermohydraulic effects of a resistive transition of the magnets allowed to reduce the number of quench relief valves to at most two per half-cell. Furthermore, by delaying the opening of the valve, the performances of commercially available industrial valves were evaluated.

3.2 Quench Propagation

Quench propagation between magnets has been studied by provoking a quench in the quadrupole and observing its propagation to the adjacent dipole. Results of these ongoing studies suggest a thermal propagation of the heat generated in the quadrupole diode assembly to the neighbouring dipole via a quench of the linking bus-bar [9] but no quench propagation due to helium.

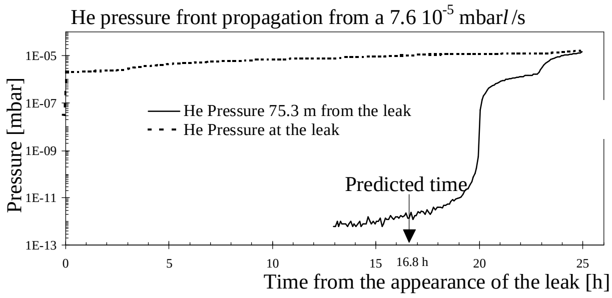
3.3 Vacuum

LHC cryostats must be pre-evacuated to achieve both rapid and efficient cooldown. Experiments to investigate the upper pressure limit to begin cooldown, show an initial pressure of 10^{-2} mbar as acceptable. Positive displacement pumps thus satisfy the needs for pre-evacuation of the insulation vacuum enclosure.

Efficient cryogenic operation at 1.9 K can only be achieved if the insulation vacuum remains below 10^{-6} mbar. The LHC may require in situ turbomolecular pumping on the cryostats to deal with large helium leaks which cannot be cryopumped and, in addition, to minimise warming by residual gas conduction during interuptions of the cryogenic plant when cryosorbed gases are released. For the latter case, warmup data with the turbomolecular pumps on and off, show good agreement with theoretical models.

Accidental loss of insulation vacuum has been studied by venting to atmospheric pressure, with the String cold [10]. Results will be used to optimise the LHC cryostat design.

Experiments have been made to quantify the speed at which helium from a leak will propagate along the 1.9 K cold bore beam tube. At 1.9 K it took over 20 hours for a helium leak of $7.6 \cdot 10^{-5}$ mbar*l*/s to be detected at the other end of the ∅ 43 mm 75.3 metre long cold bore tube and 5 hours for a leak of $9.3 \cdot 10^{-5}$ mbar*l*/s at 4.25 K. The measurements agree within 20% with a theoretical model. The figure below shows the evolution of the He pressure for this experiment with the cold bore at 1.9 K.



3.4 Positioning Metrology

A capacitive sensor system was used on the String to measure the movements of the cold mass relative to the cryostat, for long term stability measurements, during quenches and during electrical cycles. Measurements of the position of the String were taken for over one year [11] with the String at atmospheric pressure, under vacuum, at 1.9 K, etc.

The vertical movements of the String are due to the contraction of the support posts which differ either in the material and/or in the manufacturing process: the contraction of the fixed post of the quadrupole, for example, was 250 µm while the one on its mobile post was 450µm. In the radial plane, very small movements, in the range of 40 µm, were observed. An elongation of 150 µm per magnet proportional to the square of the current was measured in the longitudinal direction when the string was powered. During electrical cycles, the elongation and contraction of the cold masses follow exactly the current.

It is important to notice that after one year of operation, three thermal cycles and 75 quenches later the String has changed position: longitudinally, displacements of up to 377 µm and vertically up to 140 µm have been measured.

3.5 Support to Experiments

A 600 channel data acquisition system continuously monitors (1 Hz) temperature, pressure, position, vacuum parameters; the system also implements the functionality of a transient recorder to observe the string systems during a quench [6] with frequencies of up to 1 kHz. The system was completely specified [8] and purchased from industry as a turn-key commercial product.

The data from the acquisition system is made available for analysis immediately after the experiment in the String Control Room either on the SUN™ workstation, or via direct calls to the system from another workstation, or via a WWW application or, for later analysis from an ORACLE™ database.

4 CONCLUSIONS

The program carried-out in the past 18 months has experimentally validated the basic design choices and yielded a number of results that in some cases have simplified the design of subsystems of the LHC. The large number of quenches observed have also initiated a degradation of some components which has highlighted some known and other less known weaknesses.

The present LHC half-cell, in the coming summer, will be cycled in current to undergo the same mechanical stress experienced when the LHC will be ramped-up after injection. This is expected to yield information on the ageing of key components of the LHC.

In autumn 1996, a cryogenically cooled beam screen will be fitted into the vacuum chamber and will constitute the centerpiece of RUN3 starting in January 1997. In November 1997, the present LHC half-cell alias String 1 will be dismantled to be replaced by String 2 which is scheduled for commissioning in August 1998.

5 REFERENCES

[1] Design Study of the Large Hadron Collider (LHC), CERN 91-03, May 1991

[2] The Large Hadron Collider, Conceptual Design, CERN 95-05, October 1995

[3] A.Bézaguet, J.Casas-Cubillos, B.Flemsaeter, B.Gaillard-Grenadier, T.Goiffon, H.Guinaudeau, Ph.Lebrun, M.Marquet, L.Serio, A.Suraci, L.Tavian, R. van Weelderen, The Superfluid Helium Cryogenics System for the LHC Test String: Design, Construction and First Operation, paper presented at the Cryogenics Engineering Conference, Columbus, Ohio, July 1995.

[4] A.Bézaguet, J.Casas-Cubillos, H.Guinaudeau, B.Hilbert, Ph.Lebrun, L.Serio, A.Suraci, L.Tavian, R. van Weelderen, Cryogenic Operation and Testing of the Extended Prototype Magnet String, paper presented at the ICEC16, Kitakyushu, Japan, May 1996.

[5] F.Rodriguez-Mateos, L.Coull, K.Dahlerup-Petersen, D.Hagedorn, G.Krainz, A.Rijllart, A.McInturff, Electrical Performance of a String of Magnets Representing a Half-Cell of the LHC Machine, Fourteenth International Conference on Magnet Technology, Tampere, Finland, June 1995.

[6] D.Brahy, J.Casas-Cubillos, M.Grippeling, D.Lavielle, G.Leo, L.Madaro, A.Rijllart, R.Saban, M.Skiadelli, The Control and Data Acquisition of the LHC Test String, International Conference on Accelerator and Large Experimental Physics Control Systems, Chicago, Illinois, November 1995.

[7] P.Faugeras for the String Team, Assembly and Commissioning of the LHC Test String, 1995 Particle Accelerator Conference, Dallas, Texas, May 1995

[8] Specification for a Data Acquisition System for the LHC String, CERN-AT Group Note 94-02 (IC)

[9] L.Coull, D.Hagedorn, G.Krainz, F.Rodriguez-Mateos, R.Schmidt, Quench Propagation Tests on the LHC Superconducting Magnet String, this conference.

[10] P.Cruikshank, N.Kos, G.Riddone, L.Tavian, Investigation of Thermal and Vacuum Transients on the LHC Prototype Magnet String, paper presented at the ICEC16, Kitakyushu, Japan, May 1996.

[11] D.Missiaen, Metrology of Superconducting Magnets, Fourth International Workshop on Accelerator Alignment, Tsukuba, Japan, November 1995.