EXPERIMENTS AND CYCLING AT THE LHC PROTOTYPE HALF-CELL

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1 INTRODUCTION

The first version of the LHC Prototype Half-Cell [1,2] has been in operation since February 1995. It consists of one quadrupole and three 10-m twin aperture dipole magnets which operate at 1.9 K. One electrical circuit powers all the magnets in series. This experimental set-up has been used to observe and study phenomena which appear when the systems are assembled in one unit and therefore influence one another.

2 EXPERIMENTS

Two experimental runs have been performed in the two years since commissioning began in December 1994 [2]. RUN2 started with the addition of a third dipole and a structural modification to the cryogenic system [3]. The LHC half-cell systems, the experiments and their results have been described and reported in detail in specialized conferences [4,5,6]: what follows is a concise report of the experiments carried-out with the facility.

The 1.9 K superfluid helium cooling scheme was experimentally validated in steady state conditions and during transients [7]. The thermohydraulic effects of a resistive transition of a string of magnets have been investigated. A model was developped and was extrapolated to a full-cell of LHC [8]; this allowed the reduction the number of valves and definition of their technical characteristics. Heat loads on the cryogenic system have been measured in steady state and with degraded insulation vacuum [9]. They confirmed the calculated heat loads and in some cases highlighted possible improvements.

The quench detection and magnet protection system [10,11] was experimentally validated. Quench propagation between magnets has been studied by provoking a quench in the quadrupole and observing its propagation to the adjacent dipole [12].

Experiments to determine the upper limit on pressure in the insulation vacuum enclosure prior to cool-down have confirmed that positive displacement pumps achieving a pressure of 1 Pa are sufficient [13]. The limited propagation speed of a helium leak along a cryogenically cooled tube has been measured on the 1.9 K cold bore beam tube [14] showing agreement within 20% of the theoretical model. Accidental loss of insulation vacuum has been studied by venting the cold LHC Prototype Half-Cell to atmospheric pressure.

The displacements of the magnet cold masses relative to their cryostats, for long term stability measurements, during quenches and during electrical cycles were monitored [15].

3 THE CYCLING EXPERIMENT

The cycling experiment was performed in order to reveal eventual flaws of components of the half-cell which could only be seen after some time of operation of the collider.

After 18 months of routine current ramping to 12.5 and 13.1 kA, the half-cell was electrically cycled from 800 A to 12.5 kA repeatedly in a cycle that lasted approximately 43 minutes. The ramp rates (10 A/s) were similar to those which will be experienced by the magnets during the acceleration phase. Assuming 200 days of operation per year and one injection per day, the experiment simulated 10 years of operation of the collider.

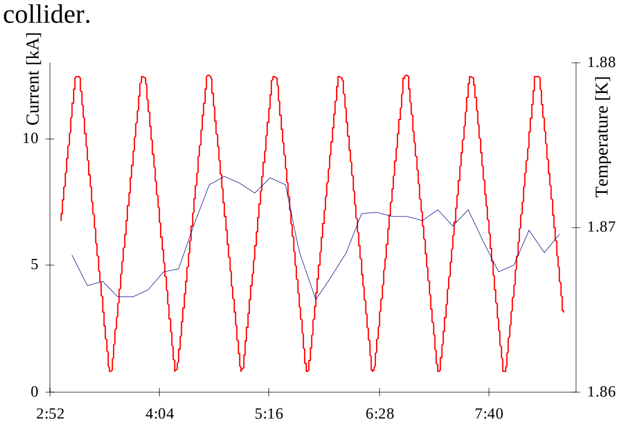

Figure 1: Current and temperature stability

3.1 Conditions of the experiment

The experiment was conducted from the accelerator control room under the supervision of the operators who are involved in the running of SPS and LEP. Therefore, the procedures for cycling the LHC Prototype Half-Cell had to be simple, secure and efficient to be executed by non-specialised personnel.

The area was closed with fences and video cameras were installed for remote visual inspection of the site. Two X-terminals were used to monitor the cryogenics, the vacuum and the power converter. Only limited control of the cryogenics system was available to prepare for cycling or put the cryogenic system in stand-by mode.

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The program controlling the power converter allowed the operator to start, stop or interrupt the continuous cycling. A completely linear downwards ramp at -10 A/s was achieved despite the inverse voltage limitation set by the free-wheeling diodes of the power converter. Authorization for powering was granted only by the magnet protection team at the beginning of a cycling period or after the interlocks had been broken.

All the systems (vacuum, cryogenic, magnet protection, power converter, general mains) were hardware interlocked. Depending on the gravity of a failure of any of the systems, the string was either slowly discharged or the magnets were quenched by firing the protection heaters.

The experiment, which lasted eleven weeks, was conducted 24 hours a day and seven days a week; it was only interrupted by access requirements to the restricted area of the LHC Prototype Half-Cell or the unavailability of peripheral systems (e.g. central refrigeration plant). The access procedure was remotely controlled by the accelerator control room operators: it mainly involved the lowering of the current to 50 A. The power converter was rarely turned-off because the operation would break the interlock chain.

3.2 Incidents

Although a number of minor incidents occurred during the cycling experiment, all were adequately handled either by the emergency systems which had been engineered for this purpose, or by the control room operators.

3.2.1 Interruption of the Cryogenic Supply

On several occasions, the liquid helium level in the main dewar supplying the LHC Prototype Half-Cell among other users, fell below a threshold. The operators were informed by an alarm signal and were advised to stop cycling in order to avoid quenching the magnets due to loss of nominal cryogenic conditions.

3.2.2 Quench Heater Power Supply Failure

Capacitor banks which are discharged in the protection heaters when a quench occurrs are continuously monitored. Two different internal power supplies failed on two occasions when the magnets were at 12.5 kA and 1.8 kA. As a result, the interlock chain was broken and the magnets slowly discharged.

3.2.3 Mains Failure

A mains failure on the electricity grid occurred during the falling phase of the cycle when the magnets were excited at 9.8 kA. The protection heaters were fired and the magnets were quenched. The emergency procedure during the cycling experiment foresees this in order to simplify the recovery.

3.3 Observations

Before the experiment started, the highest current level attained without quenching any of the magnets on two occasions was 13.5 kA. A number of cycles were executed and then the current raised to the same value: if a magnet quenched before 13.5 kA, a degradation of the quenching magnet was assumed.

After a relatively low number of cycles (184), the 13.5 kA limit could not be attained; the third dipole quenched just below 13.5 kA. Instead of trying to confirm this quench level, it was decided to double the number of cycles (300) before the second dipole was quenched at 13.2 kA. The number of cycles were increased first to 500 then to 1000 before the test quench. They all confirmed a degradation in the quench level of the second dipole. The cycling experiment was ended after 2152 cycles.

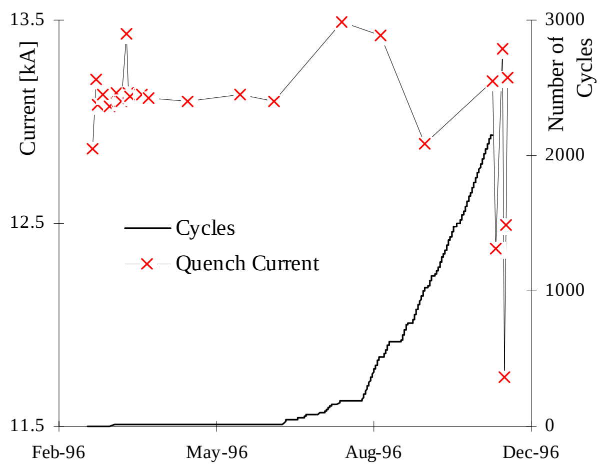

Figure 2 : Quench Current and Number of Cycles versus time

The degradation of the second dipole was investigated by repeatedly pushing the LHC Prototype Half-Cell to its highest natural quench. All the quenches which were observed during this campaign occurred in the first pole of the first aperture of the second dipole. The most salient pattern is the erratic quench behaviour characterized by quenches approaching the highest limit (13.2 kA) followed by quenches at much lower level (11.7 kA). In some cases, during the raising phase, intermediate higher current levels were attained; this wrongly suggested a retraining of the dipole (see Figure 3). The highest difference in current for two consecutive quenches was 1.6 kA. In total 10 natural quenches were caused during this campaign.

In the course of the campaign it was suggested that the quenches might be caused by a non-uniform current distribution in the superconducting cable [16]; this would start a persistent current loop which could saturate one of the strands and cause the quench. A number of attempts to highlight this effect were made, but all failed.

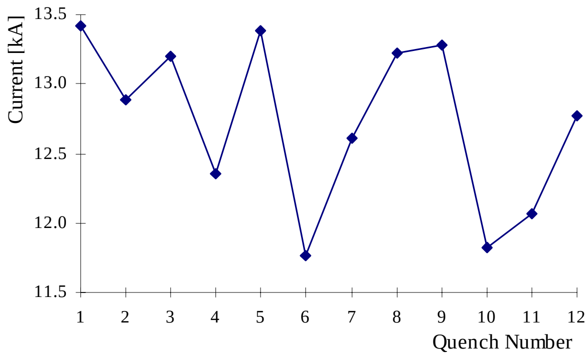

Figure 3 : Quench pattern after the cycling experiment

It was decided to remove the second dipole from the LHC Prototype Half-Cell during the shutdown following the cycling experiment. The dipole (MBL1A2) was exchanged with a spare (MBL1N1) which had been recently re-assembled and measured on the LHC Magnet Test Bench.

MBL1A2 has been since then measured on the LHC Magnet Test Bench [17]. Preliminary data, which has not yet been thoroughly analyzed, confirm what has been observed after the cycling experiment: the quenches are almost always localized to the same region of pole 1. Any attempt to identify the effects of cycling on MBL1A2 remains, so far, speculative.

Other than the degradation of the second dipole, no other effect of the cycling experiment has been identified. In the coming run, cycling will be resumed both to continue the artificial ageing of the components and, to eventually reveal other effects which might be hiding behind the degradation of the second dipole.

It is worthwhile mentioning that 85 natural or provoked quenches were performed during the two experimental runs: 45 of these were at nominal current or above. Another 15 quenches at nominal current or above were experienced by the magnets of the LHC Magnet Test Bench. This is far more than any dipole is expected to experience in the lifetime of LHC.

4 RUN3A

RUN3A will start in early June 1997. Following the shutdown which lasted five months, the LHC Prototype Half-Cell is now equipped with additional cryogenic instrumentation: wetting indicators in the longitudinal heat exchanger, level meter in the phase separator, flow meters in the discharge line and additional thermometers. The first beam screen [1] has been installed in the third dipole. The installation of diode directly on the bus-bars entering the third dipole will permit investigation of quench propagation between dipoles.

5 THE SECOND GENERATION TEST FACILITY

After RUN3, the present LHC half-cell will be dismantled. The construction of a second generation test facility will commence beginning 1999. It will include the separate cryogenic supply line and new generation 15-m dipoles with all the corrector magnets. For the year 2000 it is planned to start experimenting with a full 106-m LHC cell including three 12.5 kA circuits: one for the main dipoles, one for the focussing quadrupoles and one for the defocussing quadrupoles. Twelve additional 600 A circuits will power the multipole corrector and lattice magnets attached to the main magnets of the regular cell of an LHC arc.

6 ACKNOWLEDGMENTS

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