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VALIDATION AND PERFORMANCE OF THE LHC CRYOGENIC SYSTEM THROUGH COMMISSIONING OF THE FIRST SECTOR

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Abstract

The cryogenic system [1] for the Large Hadron Collider accelerator is presently in its final phase of commissioning at nominal operating conditions. The refrigeration capacity for the LHC is produced using eight large cryogenic plants and eight 1.8 K refrigeration units installed on five cryogenic islands. Machine cryogenic equipment is installed in a 26.7-km circumference ring deep underground tunnel and are maintained at their nominal operating conditions via a distribution system consisting of transfer lines, cold interconnection boxes at each cryogenic island and a cryogenic distribution line.

The functional analysis of the whole system during all operating conditions was established and validated during the first sector commissioning in order to maximize the system availability. Analysis, operating modes, main failure scenarios, results and performance of the cryogenic system are presented.

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ABSTRACT

The cryogenic system [1] for the Large Hadron Collider accelerator is presently in its final phase of commissioning at nominal operating conditions. The refrigeration capacity for the LHC is produced using eight large cryogenic plants and eight 1.8 K refrigeration units installed on five cryogenic islands. Machine cryogenic equipment is installed in a 26.7-km circumference ring deep underground tunnel and are maintained at their nominal operating conditions via a distribution system consisting of transfer lines, cold interconnection boxes at each cryogenic island and a cryogenic distribution line.

The functional analysis of the whole system during all operating conditions was established and validated during the first sector commissioning in order to maximize the system availability. Analysis, operating modes, main failure scenarios, results and performance of the cryogenic system are presented.

KEYWORDS: Large scale refrigerator, cryogenic distribution, superfluid helium, cold compressor, superconducting device.

INTRODUCTION

The refrigeration capacity for the LHC is produced using eight large cryogenic plants and eight 1.8 K refrigeration units installed on five cryogenic islands. Machine cryogenic equipments are installed in a 26.7-km circumference tunnel deep underground and are maintained at their nominal operating conditions via a distribution system consisting of transfer lines, cold interconnection boxes at each cryogenic island and a cryogenic distribution line. The first 3.3-km long sector (Sector 7-8) was successfully commissioned at nominal operating conditions during the first semester of 2007. The magnets were cooled down to the nominal operating temperature of 1.9 K during the first two months [2]. The whole cryogenic system was then fully commissioned [3] together with the magnet electrical circuits.

The cool-down of the second sector of the LHC has now been started and the whole machine is expected to be at nominal cryogenic operating condition at the beginning of 2008.

MAIN FUNCTIONS AND REQUIREMENTS

The cryogenic system has been designed to fulfill a certain number of main functions and to meet the requirements set by the operating conditions of the LHC machine.

It must cool superconducting magnets in arcs, dispersion suppressors and inner triplets which will be immersed in a pressurized bath of superfluid helium at about 0.13 MPa and a maximum temperature of 1.9 K. This cooling requirement applies during both ramping and stored-beam operation. In the case of fast current discharge, the temperature excursion must remain below the helium II/helium I phase transition (lambda line). In the long straight sections, with the exception of the inner-triplet quadrupoles and the recombination superconducting dipoles, the field strength and heat extraction requirements are such that operation at 1.9 K is not necessary. These magnets will have their superconducting windings immersed in a bath of saturated helium at 4.5 K.

It must cope with load variations and large dynamic range induced by operation of the accelerator. It has been estimated that the distributed static heat inleaks in the arcs and dispersion suppressors (including the distribution) are of the order of 0.21 W/m without contingency. To reach this level, active thermal shielding is needed with a corresponding estimated distributed heat inleak (without contingency) of 7.7 W/m between 50 K and 75 K.

It must be able to cool down and fill the huge cold mass of the LHC, 4.6×10^6 kg per sector in a maximum time of 15 days. This time also applies to the forced emptying and warm-up of the machine prior to shutdown periods.

It must be able to cope with the resistive transitions of the superconducting magnets, which occasionally will occur in the machine, while minimizing loss of cryogen and system perturbations. It must handle the resulting heat release and its consequences, which include fast pressure rises and flow surges. It must limit the propagation to the neighbouring magnets and recover in a time that does not seriously detract from the operational availability of the LHC. A resistive transition extending over one magnet cell (107 m) should not result in a down time of more than a few hours.

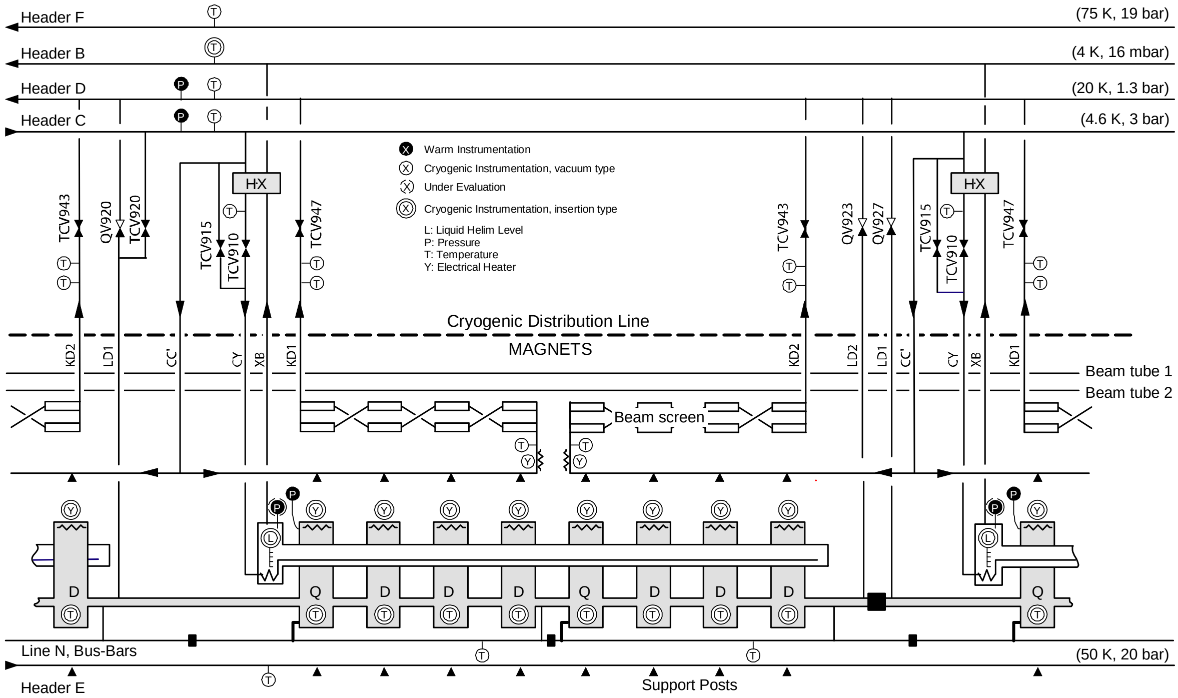

FIGURE 1. Cryogenic flow-scheme of a standard LHC cell (107 m).

It must also cool a large number of high temperature superconductor (HTS) current leads by keeping the lead foot in liquid helium within +/- 15 mm and by controlling the warm end of the HTS part at 50 K +/- 2 K. The lead heads must remain dry to guarantee the good insulation to ground of the electrical circuits.

Finally, to ensure reliable operation and high availability, it should provide some redundancy among its components and sub-systems.

FIGURE 2 shows the cryogenic flow-scheme of a standard LHC cell.

SECTOR COOL-DOWN

The parallel cool-down of adjacent magnet cells was not possible because of back-flow in one of the cells due to the pressure drop over the return line [2]. The alternate switch of the cooling of the cells solved the problem with limited impact on the cool-down time. Nevertheless, a longer cool-down time has been observed. FIGURE 2 shows the measured average temperature evolution of the magnets and the corresponding cool-down power. A total of 50 days, including two plateaus of 7 days for electrical quality assurance (ELQA), were required to cool down the sector, i.e. 36 days of effective cool-down to be compared with the theoretically possible time of 15 days. The difference in time is mainly explained by the reduced cooling power available for this first cool-down.

During the first cool-down phase from 300 K to 80 K, where large amounts of liquid nitrogen are used, the capacity was limited on average by about a factor 2 due to reduced LN2 truck deliveries during nights and weekends and due to the learning and tuning of the process during working hours. However, cooling peaks close to the installed capacity (600 kW) have been reached, thus giving confidence to keep this phase within the 10 predicted days.

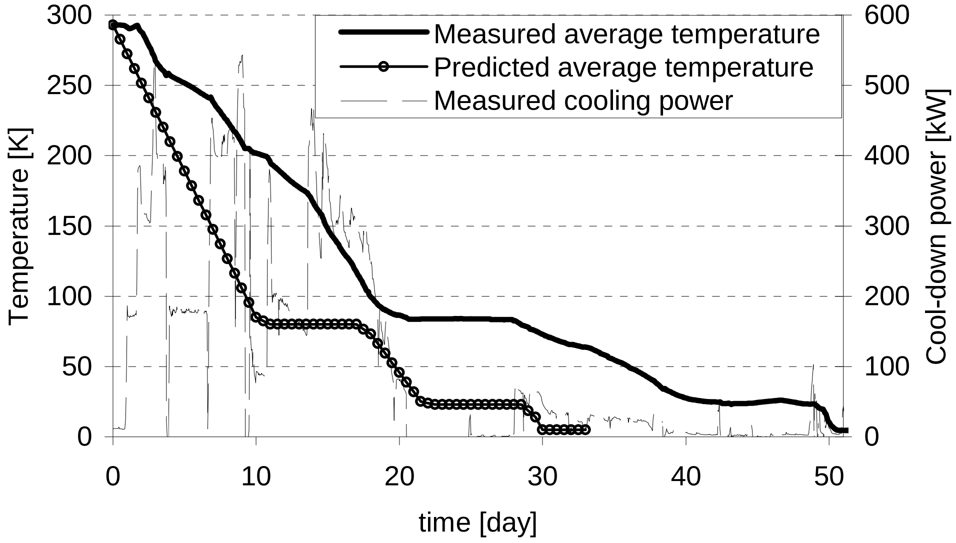

FIGURE 2. Evolution of average magnet temperature and cool-down power.

During the second cool-down phase from 80 K to 4.5 K, the average capacity was limited by the refrigerator turbo-expanders producing the cool-down power. During this phase, the turbo-expanders were not working at their nominal operating temperature and consequently it was not possible to extract their nominal capacity, limiting in average the cool-down capacity by about a factor 3. For the next cool-down, it is foreseen to change the refrigerator temperature profile and to maintain the turbo-expanders close to their nominal operating conditions for keeping this phase within the predicted 5 days.

STEADY-STATE

Superconducting Magnet Cooling

Under steady-state conditions, fine tuning and accurate operation of the system was required to cope with the inherent time constants of several hours caused by the cooling flow distribution along the sector. The 1.9 K cool-down and subsequent temperature stability of the magnet cells was difficult to achieve due to the cooling valve (TCV910) characteristics and rangeability not fulfilling the specifications as well as to the static heat inleaks which were lower than expected (see below), making the valve operating outside the available rangeability. Nevertheless the magnets could be controlled at 1.9 K within 20 mK. This shall be further improved together with the control robustness in the next sectors where new modified valve poppets are being installed. FIGURE 3 shows the stability in steady-state of the temperature of the magnet cold-masses in two adjacent cells.

The first graph corresponds to the standard cooling of a cell, i.e. with saturated superfluid helium flowing inside its bayonet heat exchanger. The second graph corresponds to the adjacent cell in which the feeding of the bayonet heat exchanger was not possible due to the interruption of its supply pipe (missing interconnection during installation). Consequently the bayonet heat exchanger of this cell cannot be fed and the heat deposited has to be extracted from the adjacent cell by conduction in the pressurized superfluid helium creating an extra temperature increase. Nevertheless, this temperature increase remains limited to 20 mK, keeping the non-conforming cell below 1.9 K and validating the cooling redundancy from adjacent cells.

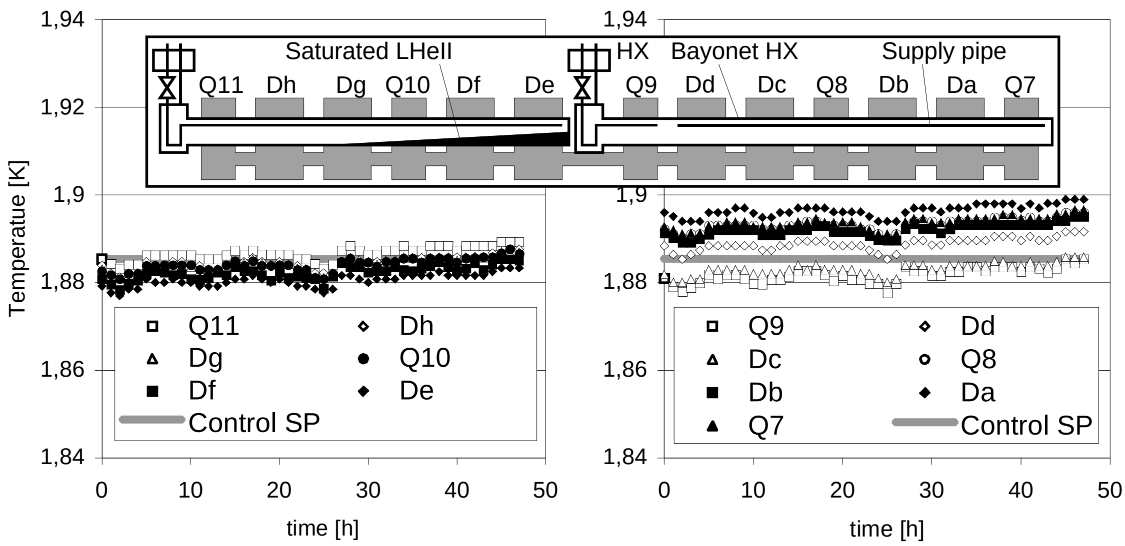

FIGURE 3. Steady-state stability of magnet cold-mass temperatures in two adjacent cells.

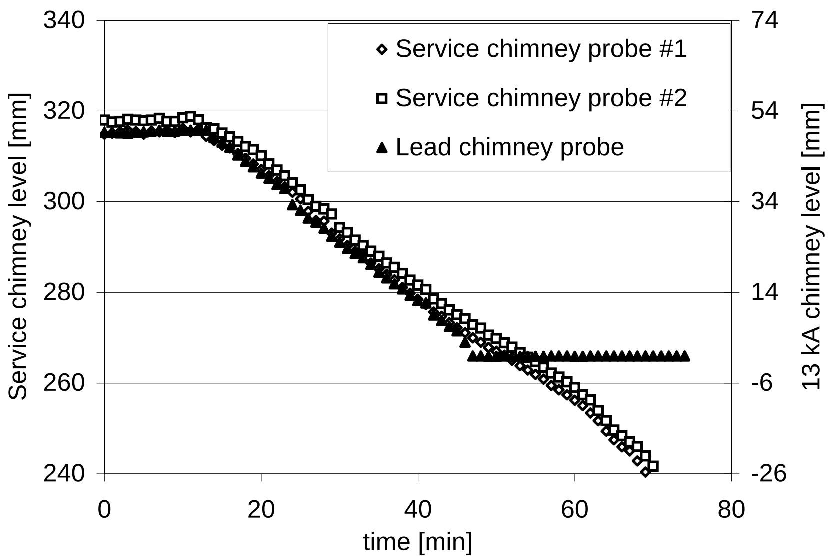

FIGURE 4. Agreement of liquid level measurements in a 5-m long electrical feed box.

Current Lead Cooling

The electrical feed boxes [5] containing the current leads were successfully commissioned. An extensive program of liquid level gauges in-situ calibration was required to correctly and precisely control the level. In addition, some gauge readings were perturbed by direct spraying of liquid helium. In the future, short calibrated level sensors as well as protecting casing will be installed for fine control and verification. FIGURE 4 shows the agreement, after in-situ calibration, of the liquid level measurements at the two ends of a 5-m long electrical feed box, confirming the correct filling by gravity of the different current lead chimneys.

Due to the high dew-point temperature (~12 ºC) in the tunnel, water condensation has been observed on the current lead heads and chimney top-flanges. Dry-air (-40 ºC dew-point temperature) plastic bags and/or conduction strips around the lead chimneys were provisionally installed to allow powering. A more robust anti-condensation system must be implemented in the future and is presently under study.

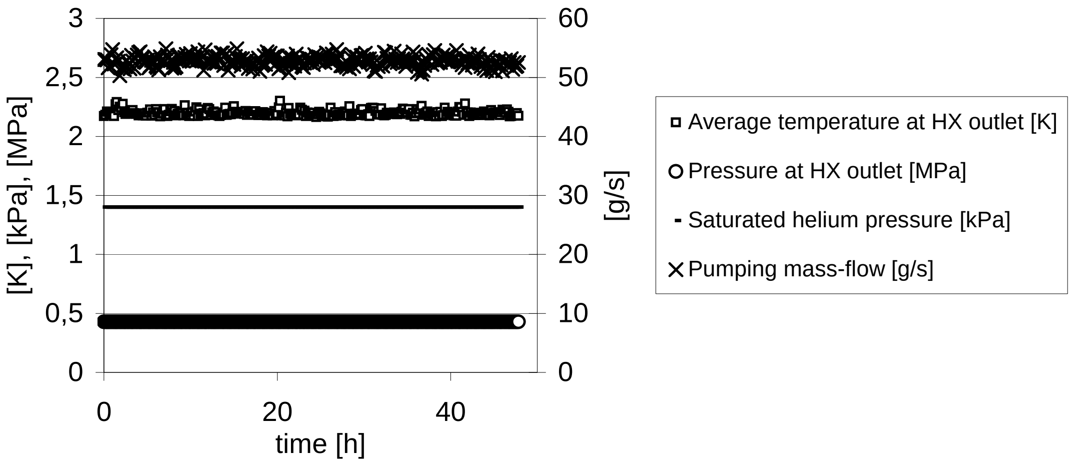

FIGURE 5. Evolution of the 1.9 K cooling loop parameters in steady-state conditions.

HEAT INLEAKS

Heat inleaks at the 1.9 K temperature level were globally estimated by measuring the total sub-atmospheric pumping mass-flow. FIGURE 5 shows the evolution of the 1.9 K cooling loop parameters needed to calculate the total heat deposition. The total measured heat deposition was 961 W including a permanent electrical heating of 401 W added to the cold masses, i.e. a total heat-inleak value of 560 W, slightly below the design estimation of 600 W for the sector 7-8 (without the inner triplet). Taking into account a total length of 2.8 km at 1.9 K, the average distributed heat inleak is therefore 0.2 W/m. Nevertheless, it must point out that 5 cells (i.e. about 20% of the total length) were operated with degraded insulation vacuum due to the presence of cold helium leaks. It was estimated, comparing valves opening, that the corresponding heat inleaks were larger by a factor 2 to 3.

Heat inleaks at 1.9 K on some specific arc cold-masses and the corresponding liquid helium content were also estimated with dedicated tests performed by measuring the internal-energy rise during a natural warm-up of the cold-masses in superfluid-helium and close-volume conditions with different known applied heating power. An average heat inleak of about 0.14 W/m, 33% below the design estimation, was measured for three different sub-sectors (two cells) operating at nominal insulation vacuum conditions. This low value could be partly explained by the lower operating temperature of the thermal shields and heat intercepts. The corresponding average helium content is about 26 l/m in accordance with calculation and warm measurements.

The thermal-shield heat inleaks (including the cryogenic distribution) were estimated by enthalpy balance at the refrigerator interface. A total value of 19.8 kW has been measured corresponding to an average distributed heat inleak of 6.6 W/m which is about 15% below the design estimation.

CURRENT RAMPING, FAST DISCHARGE AND RESISTIVE TRANSITION

FIGURE 6 shows the evolution of the magnet cold-masses of a cell during current ramping, fast current discharge and resistive transition. During a current ramping, thanks to the thermal buffering of the helium content of the cold-masses, the temperature of the cold-masses remains stable. During a fast current discharge, the temperature increases but the helium remains in the superfluid state as expected.

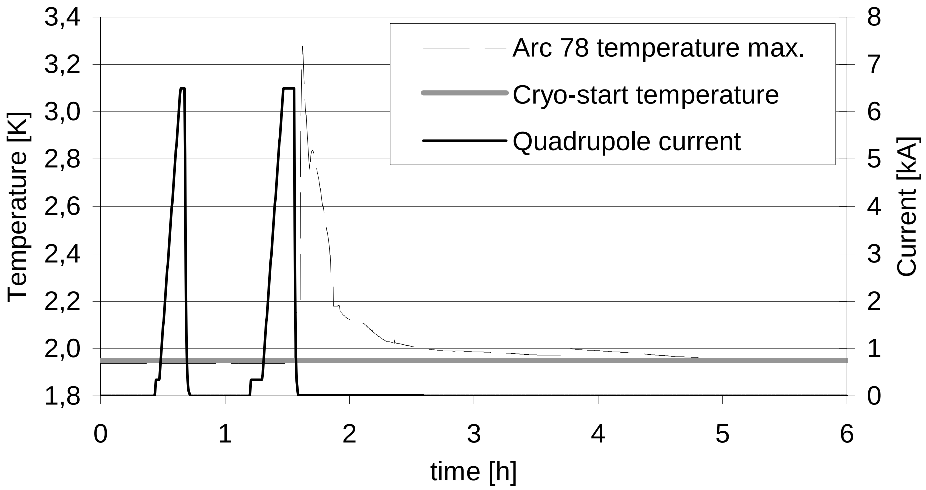

FIGURE 6. Evolution of cell temperatures during current ramping, fast discharge and resistive transition.

Resistive transitions have also been provoked but at reduced current, i.e. with limited temperature and pressure build-up in the magnet cold-masses and without propagation to the adjacent magnets. Consequently, additional tests will be needed to validate the recovery times of a full cell resistive transition as well as the propagation to neighboring cells.

RELIABILITY AND AVAILABILITY

Availability and Cryogenic Plant Redundancy

During the commissioning, the cryogenic plant dedicated to sector 7-8 has shown several limitations such as an undersized liquid helium sub-cooler giving low quality supercritical helium distribution to the cooling loops and an erratic behavior of the driving system of a cold compressor producing untimely stop. The successful use of the adjacent sector cryogenic plant to provide the required refrigeration capacity has validated the redundancy functions. This redundancy possibility will increase the overall availability of the system in the case of major problems on a plant.

Reliability and Untimely Stops

More than 50 major operational stops, provoked by utility failures (electrical, water, communication…) or by cryogenic faults (instrumentation, cold compressor, turbine, relay…), occurred during the six-month commissioning period. Consequently, the robustness of the overall system and the corresponding reliability were not at the required level and must be improved.

Availability and Electrical Powering of Magnets

The cryogenic system has a hardwired link to the magnet powering system. To avoid unnecessary magnet resistive transitions, interlocks are set for each powering sub-sector (long straight section, arc and dispersion suppressor) to authorize powering (“Cryo-start” interlock) or request a slow current discharge (“Cryo-maintain” interlock) when the magnets are powered.

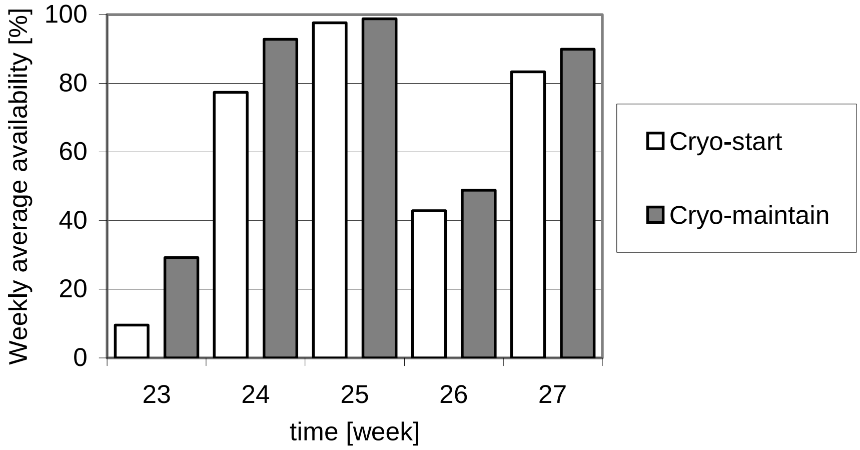

FIGURE 7. Status of "Cryo-start" and "Cryo-maintain" for arc and dispersion suppressor sub-sector.

These interlocks are based on thresholds on the magnet temperatures, the helium level in the electrical feed boxes and stand-alone magnets, the current-lead temperatures and the general status of the cryogenic plant. FIGURE 7 shows the status of the interlocks for the arc and dispersion suppressor sub-sector during the powering tests. The overall availability of the cryogenic system for powering, including the quench recovery time for the calculation of the downtime, has reached weekly averages above 85%, except for two weeks (weeks 23 and 26) when major teething problems on the instrumentation and the control system hardware were encountered. Furthermore during week 23 the cryo-start was triggered overnight to avoid untimely powering. Several magnet resistive transition recoveries were performed during week 27 further decreasing the overall availability. This gives confidence for the future sector commissioning to reach availabilities above 90%.

CONCLUSIONS

The first sector of the LHC machine has been successfully commissioned and validated to nominal operating conditions. The performance and availability of the whole cryogenic system has reached satisfactory levels after an initial period of adjustments in order to overcome obvious and expected teething problems of sub-systems working for the first time altogether.

After this first experience and profiting from the consolidations and lessons learned, we are confident of the systems, functionalities and control logics for the future cool-down and operation of the remaining 7 sectors of the LHC machine.

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