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COMMISSIONING THE CRYOGENIC SYSTEM OF THE FIRST LHC SECTOR

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L. Ronayette[2], L. Serio[1], M. Soubiran[1], L.Tavian[1]

Abstract

The LHC machine, composed of eight sectors with superconducting magnets and accelerating cavities requires a complex cryogenic system providing high cooling capacities (18 kW equivalent at 4.5 K and 2.4 W at 1.8 K per sector produced in large cold boxes and distributed via 3.3-km cryogenic transfer lines). After individual reception tests of the cryogenic subsystems (cryogen storages, refrigerators, cryogenic transfer lines and distribution boxes) performed since 2000, the commissioning of the cryogenic system of the first LHC sector has been under way since November 2006.

After a brief introduction to the LHC cryogenic system and its specificities, the commissioning is reported detailing the preparation phase (pressure and leak tests, circuit conditioning and flushing), the cool-down sequences including the handling of cryogenic fluids, the magnet powering phase and finally the warm-up. Preliminary conclusions on the commissioning of the first LHC sector will be drawn with the review of the critical points already solved or still pending. The last part of the paper reports on the first operational experience of the LHC cryogenic system in the perspective of the commissioning of the remaining LHC sectors and the beam injection test.

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ABSTRACT

The LHC machine, composed of eight sectors with superconducting magnets and accelerating cavities requires a complex cryogenic system providing high cooling capacities (18 kW equivalent at 4.5 K and 2.4 kW at 1.8 K per sector produced in large cold boxes and distributed via 3.3-km cryogenic transfer lines). After individual reception tests of the cryogenic subsystems (cryogen storages, refrigerators, cryogenic transfer lines and distribution boxes) performed since 2000, the commissioning of the cryogenic system of the first LHC sector has been under way since November 2006.
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KEYWORDS: LHC, large scale cryogenic system, refrigeration, superfluid helium.

INTRODUCTION

After the procurement and installation phases of cryogenic equipment, the individual reception tests (cryogen storage, 4.5 K refrigerators, 1.8 K refrigeration units, cryogenic transfer lines and distribution cold boxes) have been performed since 2000. At the end of 2006, the cryogenic commissioning of the first LHC sector started, including cool-down to 1.9 K, powering and quench tests in magnets, and warm-up to 300 K. The global behavior (equipment and controls) of the cryogenic system has to be validated during magnet powering to prepare the beam injection scheduled in 2008 after commissioning of all LHC sectors.

DESCRIPTION OF THE LHC CRYOGENIC SYSTEM

The LHC machine [1], composed of eight 3.3-km sectors with superconducting magnets and accelerating cavities requires a complex cryogenic system grouped in five cryogenic islands providing high cooling capacity at different temperature levels. The cryogenic islands are located all around the LHC machine and mainly at the even access points to the underground tunnel, as shown in FIGURE 1.

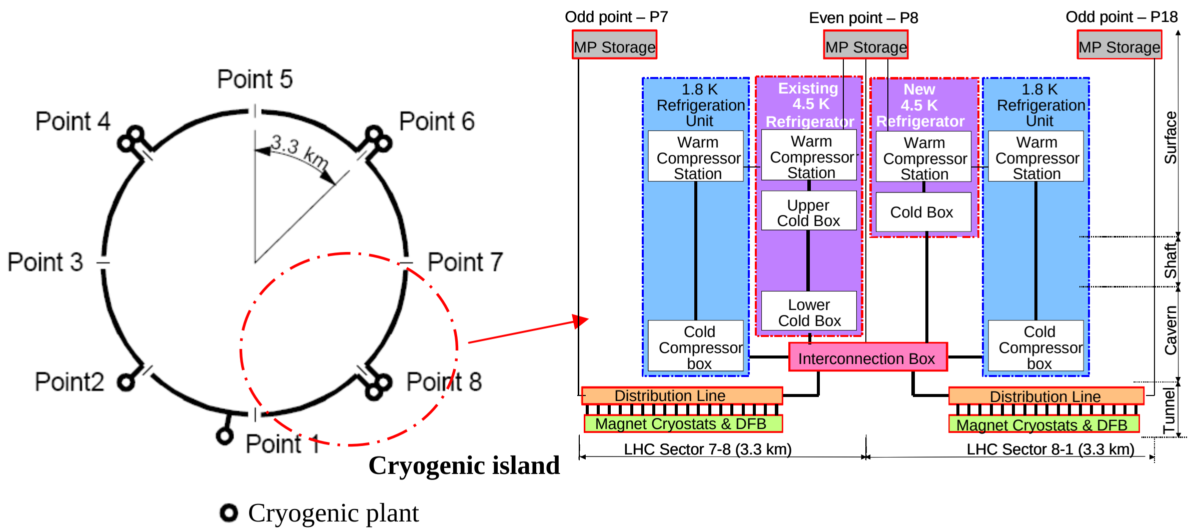

FIGURE 1. General layout of LHC cryogenic system (a) and details of Point 8 cryogenic island (b)

The cryogenic system required for the cooling of a sector comprises the following subsystems:

- cryogen storage composed of vertical dewars (100 m^3) for liquid nitrogen (LN2) and horizontal medium pressure tanks (2 MPa, 3000 m^3) for gaseous helium,
- 4.5 K refrigerator (18 kW equivalent at 4.5 K) [2] including a 600 kW LN2 pre-cooler,
- 1.8 K refrigeration unit (2.4 kW at 1.8 K) with cold compressors [3],
- cold box interconnecting the different cryogenic subsystems via a network of warm and cryogenic transfer lines and containing 600 kW electrical heaters for sector warm-up. This box allows for redundancy between two adjacent cryogenic systems,
- 3.3-km long cryogenic distribution line [4] coupled to the machine component strings. FIGURE 2 shows the generic flow scheme of a standard cell,
- several electrical feed boxes (DFB) [5] allowing for electrical supply of superconducting magnet circuits through high temperature superconducting (HTS) current leads.

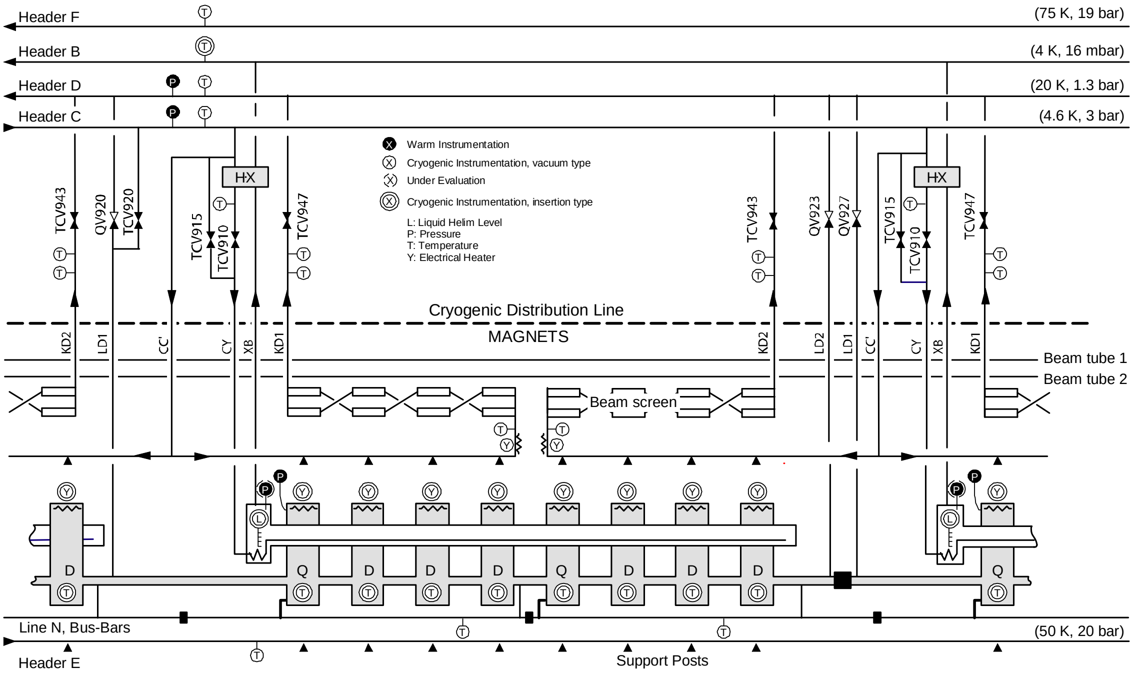

FIGURE 2. Cryogenic flow-scheme of a LHC standard cell

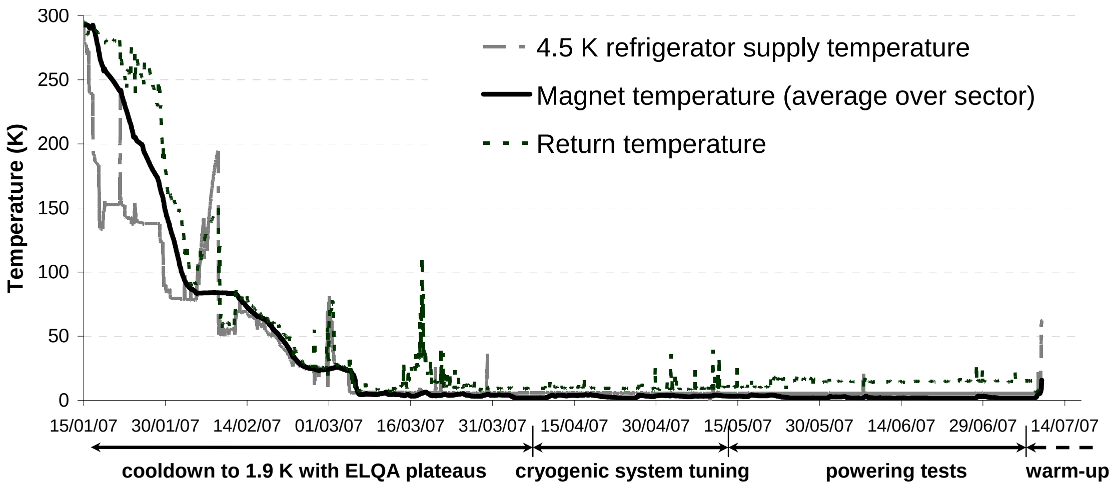

FIGURE 3. Temperature evolutions during the commissioning of sector 7-8

FIRST LHC SECTOR COMMISSIONING DESCRIPTION

The commissioning of the cryogenic system of the first LHC sector (sector 7-8) has been under way since November 2006. FIGURE 3 shows the temperature evolution of the system during the different phases:

- preparation phase including pressure tests for mechanical design validation, helium leak tightness tests, conditioning and flushing of the helium circuits,
- cool-down to 80 K with a plateau required for electrical quality assurance (ELQA),
- cool-down from 80 K to 20 K with a plateau for ELQA,
- cool-down from 20 K to 4.5 K and partial magnet filling,
- magnet filling and cool-down to 1.9 K,
- cryogenic system tuning,
- powering test and quench of magnets,
- warm-up to 300 K including magnet emptying.

Preparation Phase

In November 2006, the installation of the sector was completed and all circuits were ready for the global pressure test. Pressurization of all helium circuits (300 m^3) was therefore performed up to 1.25 times the design pressure corresponding to 2.75 MPa for the thermal shield circuits, 2.5 MPa for the magnets and their supply-return headers, 0.5 MPa for the 1.5 kPa pumping header and 0.44 MPa for the liquid helium baths and current leads in DFBs. The pressure test was successfully achieved except for the inner triplet quadrupole magnets where a copper heat exchanger tube inside the cold mass collapsed at 1.2 MPa. The magnets were then isolated from the other circuits to allow for the cool-down of the sector in parallel with the analysis and repair of these magnets.

Most of the leaks towards atmosphere or inside the vacuum enclosure were identified and repaired during the preparation phase. The accurate localization and repair of internal leaks in 200-m long vacuum sub-sectors were difficult and time consuming. Not to delay the cool-down start-up, a few leaks in the range of 10^{-4} mbar.l/s at room temperature have not been repaired and additional vacuum pumping groups have been installed to guarantee the required insulation vacuum at cryogenic temperature.

Following the leak detection and repairs, a complete conditioning of the helium circuits with repetitive purge and filling cycles, has been performed during one week. Following this operation, the level of impurities (water and nitrogen in helium) was lower than the required criterion to start the cool-down (< 10 ppm).

The preparation phase was concluded with the flushing operation necessary to minimize the dust quantity which could remain after the installation. Forced-flow circulation was provided at the maximum possible velocity in all circuits to remove any solid particles. Metallic powders, pieces of metal, wood, rubber and pieces of electrical insulation foil were recovered in a demountable filter (see FIGURE 4) installed in the interconnection cold box. This filter was regularly demounted to check the cleaning effect of the flushing. Two weeks (twice the foreseen time) of flushing were required to clean all the circuits. The flushing operation has also allowed to drain water contained in magnets thanks to a dryer (adsorber with molecular sieves) installed at the outlet of the warm compression station of the 4.5 K refrigerator. About eight liters of water were removed from the machine during the flushing operation. At the beginning of the cool-down phase, the dryer system continued to remove water (about 50 l) until all magnets reached a temperature below 273 K.

FIGURE 4. Filters after (grey) and before (white) flushing and dusts collected in the filter

This preparation phase finished at the beginning of January 2007 and included one week for pressure test, one week for leak detections and repairs, one week for conditioning and two weeks for flushing. In parallel, interlocks, instrumentation and control logic were also progressively checked.

Cool-down to 80 K

This phase started on January 16, 2007. The cool-down from 300 K to 80 K is produced by a helium flow which is cooled using the 600 kW LN2 pre-cooler. About 1250 tons of LN2 were required to cool down to 80 K the 4600 tons of the sector. During 20 days, 64 trucks (about 20 tons each) have filled the vertical LN2 dewars with a delivery rate of 3 to 6 trucks per day. The cooling capacity was progressively increased and then adjusted to cope with the cool-down activities with reduced operation during nights and week-ends as well as with utility stops (electrical power cut) or truck delays (snow on roads during winter).

The maximum cooling capacity produced by the LN2 pre-cooler is 600 kW with a helium flow of 800 g/s and a maximum temperature difference of 150 K between the magnet inlet and outlet. Distribution of the total cooling mass-flow was manually adjusted in the different cooling loops of the LHC sector (about 30 magnet cell and thermal shield loops in parallel) to obtain homogenous cool-down along the 3.3-km sector. This first cool-down has pointed out an unbalanced cooling of neighboring cells together with, in some cases, back-flow due to the high pressure drop in the return header [6]. To settle this issue, it was decided to cool down alternatively half of the magnet cells with a periodic switch-over every 30 hours.

During the first cool-down of a sector, to cope with risks linked to thermal contraction of cryogenic equipment, the access to the tunnel was not allowed until 80 K was reached. The access doors could be unlocked only if the cool-down was temporarily stopped. In parallel, at ground level, a safety perimeter (50 m x 50 m) was defined around the nitrogen vent exhaust of the pre-cooler to prevent oxygen deficiency hazard due to the large venting of nitrogen (up to 0.5 to 1.5 kg/s).

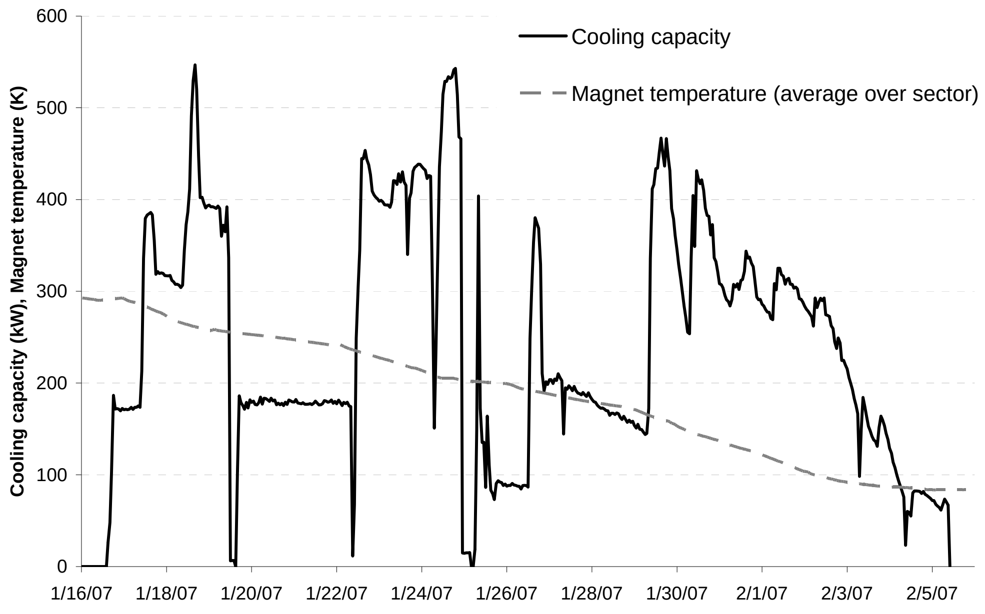

FIGURE 5. Nitrogen cooling capacity and magnet average temperature during the cool-down to 80 K

Cool-down to 20 K

Following ELQA tests, the cool-down to 20 K was started using the turbo-expanders of the 4.5 K refrigerator. Adjustments of cooling mass flow in magnet cells were done daily including the periodic switch-over, thus avoiding unbalanced cooling. Daily inspections in the tunnel were carried out to check the equipment. Two helium leaks to atmosphere were detected and rapidly repaired (joint on level gauge feed-through and uncompleted welding of small instrumentation tube). For the first time, one electrical distribution feed box was cooled and controlled at its nominal operating conditions. Water condensation was observed on the top of current lead chimneys and operating conditions were adapted to avoid such phenomena before consolidation.

After 15 days, 20 K temperature was established in magnets and ELQA tests at 20 K were carried out. The longer cool-down time is mainly due to the reduced cooling capacity produced by the 4.5 K refrigerator which was not fully optimized and to the unequal flow distribution applied for this first sector cool-down. No operational difficulty was observed during this phase except for the plugging of a turbine filter which required a mechanical intervention.

Cool-down to 4.5 K and Partial Magnet Filling

During this phase, the 4.5 K refrigerator produced and supplied supercritical helium at 0.3 MPa and 5 K which was distributed and expanded at 0.13 MPa through the inlet valves of the different cooling loops for liquid helium production. Before leaving the refrigerator, this helium was sub-cooled in a LHe phase separator. Mass-flow distribution adjustments in each cell were performed manually every four hours. In less than two days, all magnets were at 4.5 K and partially filled with liquid helium. About 7 tons of helium were liquefied and transferred from ground storage to LHC sector. This phase performed as expected despite the fact the phase separator of the sub-cooler, which had been designed for other duty, did not supply the specified supercritical helium as low as 4.6 K. This sub-cooler will be re-designed and then consolidated in the coming months.

Magnet Filling and Cool-down to 1.9 K

The completion of the filling of the magnet dead-volumes was performed by using the 1.8 K refrigeration unit. During this phase, about 11 tons of helium were liquefied and transferred to the magnets giving a total amount of 18 tons. The status of the helium inventory available on site or to be delivered was permanently followed up.

Due to the late upgrade and short reception of the 4.5 K refrigerator recovered from LEP, specific consolidation and adaptation were mandatory, especially in the cold part (new turbine working parameters, flow restriction suppression…) to achieve the magnet filling in parallel with the operation of the 1.8 K refrigeration unit. The latter has also to be adapted to sector specifics, such as 3.3-km length and 200 m^3 volume which introduce long response time. This phase has also pointed out that the rangeability of the 1.8 K Joule-Thomson valves was lower than specified creating additional control complications. New valve poppets with the required characteristics have been validated and will be installed after the sector warm-up.

Finally on April 5, 2007, after three weeks (including few pumping stops) all magnets of the first LHC sector were filled and cooled below 2 K.

Cryogenic System Tuning

As pointed out during the cool-down phases, the cold compressors, the DFBs and the control logic required additional consolidation before authorizing the powering tests. The drive system of a cold compressor has shown erratic behavior; after unsuccessful replacement of its frequency drive and voltage transformer, the motor itself and cabling were then suspected. At nominal operating conditions, water condensation was still present on top of current lead chimneys of the DFBs; plastic bags permanently filled with dry air and conduction strips were installed on the chimneys to prevent condensation (see FIGURE 6). The supercritical helium supplied by the refrigerator was too warm and generated excessive gas fraction during its final expansion and could produce instabilities in level controls.

Due to the above mentioned difficulties still existing at the end of April 2007, it was decided to operate sector 7-8 with the adjacent cryogenic plant normally dedicated to sector 8-1. This plant contains a new 4.5 K refrigerator able to supply supercritical helium at 4.6 K and of a 1.8 K refrigeration unit without suspicious cold compressor. Two additional weeks were needed for tuning this new configuration and to obtain stable conditions at 2 K. In particular, the new cold compressor system required additional consolidation with the supplier to settle instrumentation and control algorithm issues.

Powering Tests and Quenches

At the beginning of May 2007, after about 50 days of cool-down and final cryogenic tuning, cryogenic conditions for powering tests were obtained both in magnets and electrical feed boxes. First, standalone magnets operating at 4.5 K were powered and underwent quench training before reaching their nominal operating currents. Finally, in mid-June 2007, the 2-K magnets were powered to their maximum allowable currents. A few quenches were also provoked to check the quench protection system. The cryogenic system was in fully automatic mode and quench recoveries were performed in less than one to three hours depending on the deposited energy (see FIGURE 7). Powering tests were concluded with a long overnight run.

Warm-up to 300 K

Due to the inner triplet issue and to repair several non-conformities detected in sector 7-8, a complete warm-up was scheduled. The first phase of the warm-up was the complete emptying of the liquid helium contained in the magnets; the helium was then recovered in the surface storage tanks after active warm-up by using the electrical heaters (about 200 kW). The final warm-up to 300 K started on July 12, 2007.

FIGURE 6. Plastic bags with dry air and conduction strips around current lead chimneys

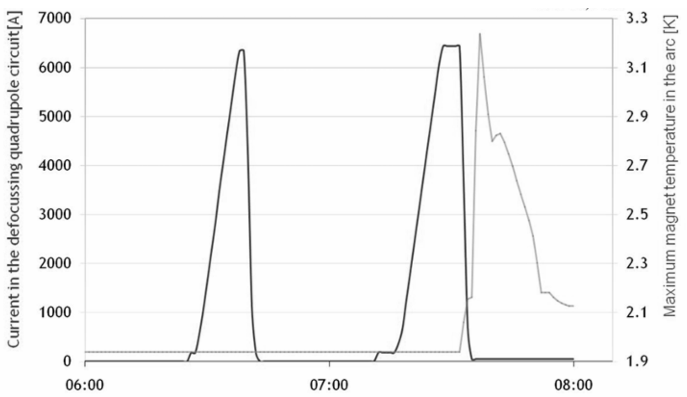

FIGURE 7. Powering tests and quench in quadrupole circuits

PRELIMINARY CONCLUSIONS OF THE FIRST SECTOR COMMISSIONING

Handling of cryogen was an important issue which required a permanent follow-up due to the large amount of LN2 (1250 tons) needed for the sector cool-down and to the high helium inventory (18 tons) to fill a LHC sector and its cryogenic system. The basic design of the cryogenic system for the cool-down to 1.9 K and the powering operation has been validated. Nevertheless, some consolidations on equipment and controls have been identified. The achieved time for first cool-down was larger than predicted due to the available cooling capacity which was reduced and due to the time required for the tuning of this system of unprecedented size and complexity.

However after intensive tuning, cryogenic operation for powering was fully automatic. Some transient modes (recovery after quench or re-cool-down after utility stops) need additional efforts to reach the required automation level. More than 50 major operating stops occurred along this six-month commissioning, half of them provoked by utility stops (electrical, water, communication) and the remaining half provoked by cryogenic faults (instrumentation, cold compressor, turbine, relay). The experience gained during this first LHC sector commissioning will be applied for the next sector (Sector 4-5) where the cool-down started on 4^{th} of July 2007.

ACKNOWLEDGEMENTS

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REFERENCES

1. LHC Design report, CERN-2004-003
2. Gruehagen, H. and Wagner, U., “Measured performance of four new 18 kW@4.5 K helium refrigerators for the LHC cryogenic system”, *Proceedings of ICEC20*, Beijing, China, 2004,
3. Millet F., Claudet S., Ferlin G., Tavian L., “1.8 K refrigeration units for the LHC: performance assessment of Pre-series units”, *Proceedings of ICEC20*, Beijing, China, 2004,
4. Brodzinski K. *et al*., “Reception tests of the cryogenic distribution line of the LHC”, Cryo-Prague 2006
5. Perin, A,. *et al*, "Design, Production and First Commissioning Results of the Electrical Feed Boxes of the LHC ", paper presented at this conference
6. Liu, L., *et al*, "Cool-down of the First Sector of the Large Hadron Collider: Comparison between Mathematical Model and Measurements", paper presented at this conference