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COMMISSIONING OF THE LHC CRYOGENIC SYSTEM: SUBSYSTEMS COLD COMMISSIONING IN PREPARATION OF FULL SECTOR TESTS

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Abstract

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ABSTRACT

The cryogenic system for the Large Hadron Collider accelerator is presently in its final phase of installation and commissioning at nominal operating temperatures. The refrigeration capacity for the LHC will be produced using eight large cryogenic plants installed on five technical sites and distributed around the 26.7-km circumference ring located in a deep underground tunnel. The status of the cryogenic system commissioning is presented together with the experience gained in operating and commissioning it.

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

The layout of the cryogenic system for the LHC accelerator is based on five feed points located around the 26.7-km circumference ring. Each plant of 18 kW at 4.5 K equivalent refrigeration power is connected to a 2.4-kW at 1.8 K refrigerator unit and associated infrastructure (helium tanks, nitrogen dewars, piping and cryogenic transfer lines, interconnection valve box), supplying a LHC machine sector of about 3.3 km via a compound cryogenic distribution line [1] (FIGURE 1). Equipment is installed as much as possible above ground level and active components are concentrated in the feed-points.

Refrigeration plants have already been commissioned and are progressively going into operation to commission other cryogenic subsystems. Among these subsystems are the 1.8-K refrigeration units, the transfer lines, the interconnection boxes and the cryogenic distribution lines.

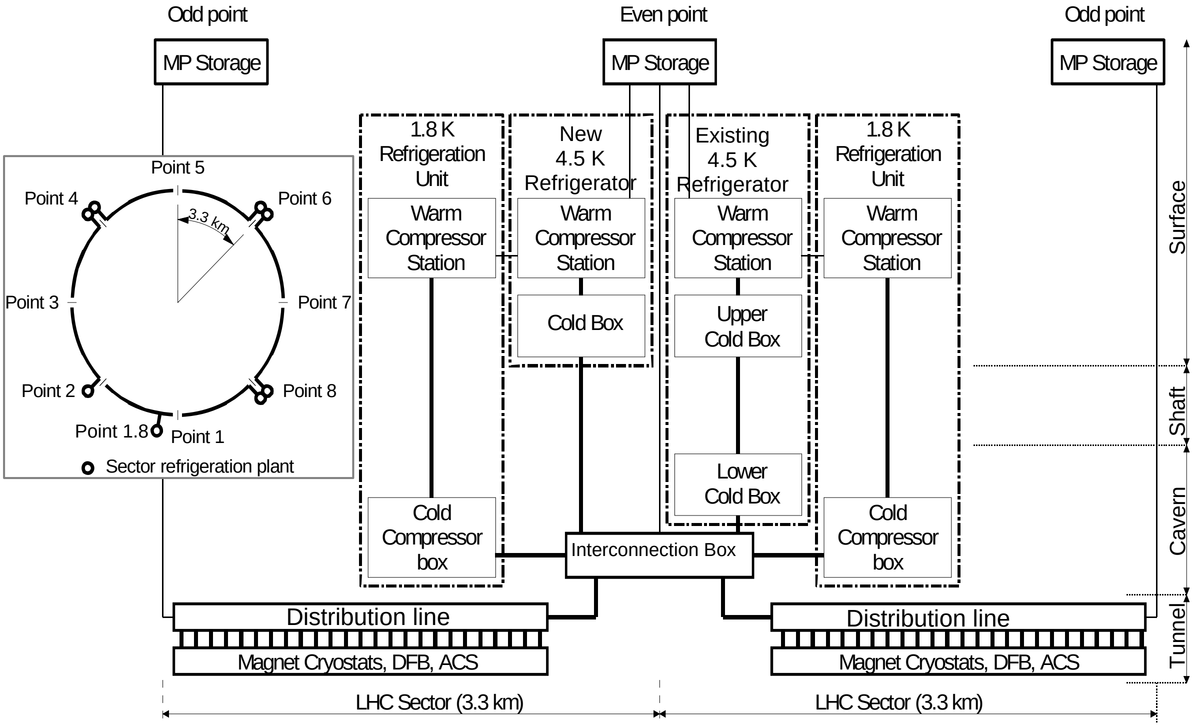

FIGURE 1. The cryogenic system layout and its architecture at an even numbered point.

The cold test of the first 3.3 km sector of the LHC will provide the final verification of the collective behavior and operation modes of all the units that have already been individually tested. It will complete and validate results obtained with the LHC Test String 1 and 2 [3], and it will provide a valuable tool to define control strategies, procedures and operator training for the full machine operation.

SUB-SYSTEMS COMMISSIONING

The individual components and sub-systems of the LHC cryogenic system are manufactured in industry on the basis of functional and interface specification written by CERN. For some components such as heat exchangers, cold compressors and quench relief valves, an extensive R&D program and a prototype-test phase has been conducted before issuing the final specification [2]. The superfluid-helium bayonet heat exchanger and the tunnel cryogenic system collective behavior and overall performances have also been extensively tested and validated during more than 20’000 hours of operation of the LHC Test Strings at nominal temperature [3].

After delivery and installation at CERN each sub-system is individually commissioned and accepted for operation. The already commissioned and qualified sub-systems are then used in a cascade way to commission dependent sub-systems. The collective behavior of the cryogenic sub-systems is therefore progressively tested and the overall process established and at the same time consolidation work or adaptation of the system to real operating conditions takes place.

4.5 K Refrigerators

A total equivalent entropic capacity of 144 kW at 4.5 K will be required to cool the LHC machine. The refrigerators are constituted of a compressor station and a cold box.

Each compressor station with an installed electrical input power of about 5 MW has five to eight oil-lubricated screw compressors, water cooling for helium and oil as well as a final oil-removal system. The vacuum-insulated cold boxes house the aluminium plate-fin heat exchangers and up to 10 turbo-expanders to provide the cooling capacity. A 600-kW liquid-nitrogen pre-cooler is used for the cool-down to 80 K of the magnets sectors. Up to 50 ppm of air and remaining traces of hydrogen and neon, can be removed by 80-K and 20-K adsorbers. Switchable dryers are connected at the ambient-temperature cold box inlet.

To feed the low-load sectors of the LHC, four existing refrigerators, each with an average of 35,000 accumulated hours of operation, are currently being upgraded in capacity. These will shortly be commissioned after a major overhauling of the compressor stations (compressors and electrical motors), and will be ready for operation during 2006. Two compressor stations have already been overhauled without any major faults detected apart from some oil pump damage requiring the change of the couplings, the rotors and stators, and the light polishing of a compressor rotor.

Four new refrigerators were installed in the high-load sectors and successfully commissioned [4]. During the first few years of operation, in addition to preventive and corrective maintenance, additional consolidation work has taken place mainly on the compressor stations (vibration, machine fixation, replacement of oil injection valves, modification of shaft-seal lubrication piping, improvement of filter robustness, blocking of internal volume-ratio slide valves for all compressors as well as modification of the low-pressure oil pumps). The cold box control system was improved to adapt the refrigeration capacity to the varying loads by changing the high pressure of the cycle depending on the electrical heaters power applied in the cold-box liquid helium phase separator and adjusting the turbine flow depending on their output temperatures.

Recently the liquid-nitrogen pre-cooler has been successfully tested with the cryogenic interconnection box 600-kW heater. It reached the design values of 600-kW cooling capacity at 770 g/s of helium flow with a temperature difference of 150 K by vaporization of 1500 g/s of liquid nitrogen. The results confirm that the 36,800 tonnes of the LHC machine can be cooled down to 80 K in less than 10 days.

Interconnection Boxes

The central node of the cryogenic distribution system is the interconnection box situated in the underground caverns. At each of the five feed-points, it connects the different cryogenic sub-systems: surface 4.5-K cold boxes, underground 4.5-K lower cold-boxes, 1.8-K refrigeration unit and the cryogenic distribution line (QRL). Operational redundancy is also possible by connecting any of the two refrigerators of the point to the left or right sector. The interconnection box also houses two 600-kW heaters for the sector warm-up and a filtering system (50 micron) on the main gas return from the magnets to avoid contamination of the refrigerator components (compressors, turbines, etc.).

A total of 5 boxes are installed in the LHC machine. The first box in Point 8 has already been commissioned and accepted for operation of the connected sub-systems. Three other boxes have been installed, pressure and leak tested (Points 2, 4, 6). The remaining box at Point 1.8 is under installation.

The commissioning of the first interconnection box has shown some flaws in the 600-kW heater design that limits the transfer of the heating power to the helium flow and, in some operating conditions, the protection of the heating elements. A new design has been agreed with the manufacturer and the first modified heater has already shown better results. Further improvements have also been identified to optimize it. At the same time it was discovered that the filtering system was undersized and difficult to access and handle.

A new filtering system is under design with increased dimensions, improved handling and guaranteed redundancy. Several temperature sensors were broken during the welding of components and have required replacement.

The cryogenic system was designed (in particular the filtering system in the interconnection box) to protect the refrigerator from impurities mainly coming from the magnets. The experience gained during the LHC magnet testing, the LHC Test String tests and the commissioning of the cryogenic sub-systems has shown that the magnets are expected to be clean, while significant quantities of impurities originate mainly from the cryogenic distribution system (piping not sufficiently cleaned during installation). Additional efforts and flushing procedures have been implemented prior to the cool down on all connected systems to reduce the downtime required by the filter replacement.

Helium Transfer Lines

Four new vertical transfer lines [5] and twelve new local transfer lines [6] distributed among five LHC points in the technical pits and in underground caverns are being manufactured and installed by industry to connect the 4.5-K refrigerator cold boxes and the 1.8-K refrigeration units to the cryogenic interconnection boxes. The vertical lines are bellows-free in the long vertical part and are between 90 m and 190 m in length. The local lines have a maximum of 30-m length and may possess either small or large shuffling units to allow connection to the interface ports. All lines consist of a vacuum jacket, a thermal shield and either three or four helium-process pipes. Two vertical transfer lines have been successfully tested, and their thermal performance measured, with a dedicated test cryostat; the remaining two lines have been installed and will be cooled down together with other sub-systems. Two local transfer lines have been successfully commissioned and are operational at Point 8. The local transfer lines are commissioned together with other sub-systems. Commissioning consists of verification of the insulation vacuum and possible cold spots while circulating helium in all process pipes at nominal operating temperatures.

1.8 K Refrigeration Units

The first 1.8-K refrigeration unit for the LHC [7] has been recently tested in its final configuration and location [8]. The aim was to confirm the complete system after the removal from the surface test bench [9], to validate the equipment with in situ constraints (layout and piping lengths) and finally to check the performance of the 1.8-K refrigeration unit for the specified mass flow range (from 41.5 to 125 g/s). During this test sequence, the 1.8-K refrigeration unit is simply coupled to the 18-kW plant (feed: supercritical helium at 4.6 K and 0.3 MPa; recovery: GHe at 20 K and 0.12 MPa) via the interconnection box. The pumped helium gas flow (temperature from 4.0 to 4.8 K) is generated by means of an electrical heater installed in a liquid-helium phase separator. The pump down to 1.5 kPa is performed with a steady mass flow of 85 g/s (+/- 10 g/s). Subsequently the mass flow is increased to 124 g/s (equivalent to 2400 W @1.8 K) and the overall system is verified at full capacity for a period of ~100 hours. Then the mass flow is reduced to other machine specified values with a transient rate of 6 g/s per minute and finally increased again to 124 g/s (transient rate of 6 g/s per minute). During all this sequence, the inlet pressure must remains below 1.7 kPa.

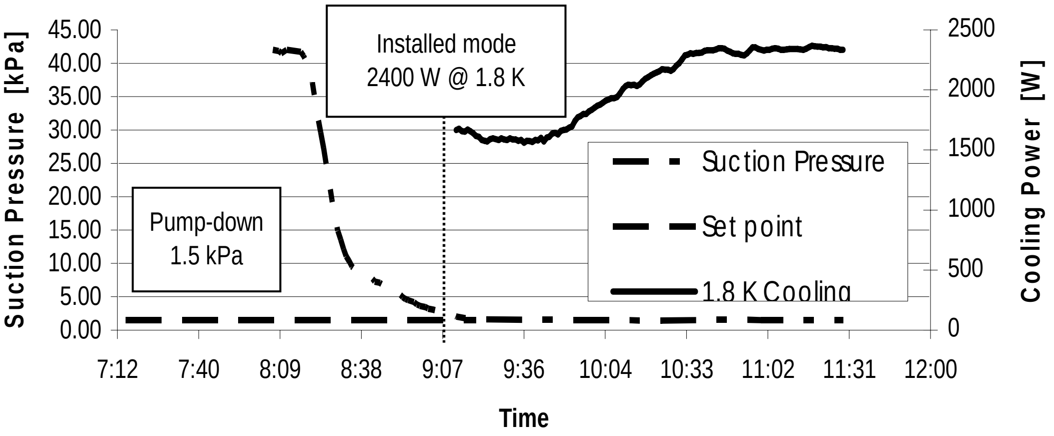

FIGURE 2. Pump down of the first 1.8K-refrigerator unit in the LHC underground cavern.

The coupling to the cryogenic infrastructure has required some days of tuning to reach the stability expected on the feed line (+/- 1 kPa). Thermo-acoustic oscillations were also detected and solved. The results of these acceptance tests (FIGURE 2) are consistent with the tests performed on the pre-series test bench despite some instrumentation (mainly thermometers) that requires improving in order to have a fully automatic control system. The first 1.8-K refrigeration unit reinstalled at its final location is now accepted and the equipment will go into operation in 2006 to cool down the first sector of the LHC accelerator.

Cryogenic Distribution Line

To distribute cryogenic refrigeration to the local magnet cooling loops in the form of helium flows at different values of pressure and temperature, the refrigeration power produced by the LHC refrigerators has to be transported over long distances via a cryogenic distribution line (QRL) [10]. This line houses the helium supply and recovery headers, and runs inside the machine tunnel parallel to the regular lattice of the superconducting quadrupole/dipole magnets with interconnections at every machine full-cell length of 106.9 m. These interconnections are made via a jumper, which is part of specific elements where the QRL instrumentation and operation valves are installed (so called service modules). Each QRL sector (8 in total), along a distance of 3.3 km, starts with an interconnection box and ends with a return module.

Specific acceptance tests will be performed after installation of each QRL sector in the tunnel in order to verify the thermal performance, the leak tightness, the functioning of components as well as the overall behaviour at cryogenic temperatures. To save time, precision heat load measurements should be carried out only on the first two sectors.

The installation of the cryogenic distribution line is in progress despite several technical and organizational problems encountered with the contractor. CERN is presently completing the repair and installation of the first sector. The reception tests on part of sector 7-8 and the full sector 8-1 will start shortly. If testing is successful the remaining sectors will be tested at the same time as the commissioning of the magnet strings.

OPERATIONAL PERFORMANCE

TABLE 1 summarizes the performance of the LHC refrigerators going into operation for subsystem commissioning in the LHC points or magnet testing in Point 1.8 [11].

TABLE 1. Statistics and availability of LHC refrigerators from 2002 to date.

	Production [h] or status [**C**-commissioning, **MO**-Major Overhauling] [performance in %]			
LHC point/sector/refr.	**2002**	**2003**	**2004**	**2005** *(1/2 year)*
Point 1.8 / 1-2 - new	**6469** [98.9%]	**5700** [99.4%]	**7620** [99.9%]	**3700** [99.6%]
Point 2 / 2-3 – ex-LEP	Stand-by	Stand-by	**MO, C**	**C**
Point 4 / 3-4 – ex-LEP	Stand-by	Stand-by	Stand-by	**MO**
Point 4 / 4-5 - new	**C**	Stand-by	**C**	**C**
Point 6 / 5-6 - new	Installation	**C**	**C**	Stand-by
Point 6 / 6-7 – ex-LEP	Stand-by	Stand-by	Stand-by	Stand-by
Point 8 / 7-8 – ex-LEP	Stand-by	Stand-by	**MO**	**C**
Point 8 / 8-1 - new	**C** NA	**~600** NA	**1150** [99.1%]	**1400** [98.2%]
On-call interventions [h]	**~220**	**~248**	**~100**	**~50** *(1/2 y)*

The cryogenic system is operated by a team of 2 engineers, 5 technicians and 12 operators working during normal working hours with 3 individuals performing on-call services.

The impact of impurity problems on production is minimized by the use of adsorbers and dryers and the possibility of using the nitrogen pre-cooler instead of the first stage turbines. This was not possible in 2003 when a significant leak prevented the use of the pre-cooler and required a full regeneration of the cold box. Early stage failures are mainly related to process settings, necessary consolidation of new equipment and controls (communication interface problems).

The automatic adaptation of the refrigerators to the load can be further improved. The redundancy and restart in case of a stop would be further optimized by means of software tools to manage major breakdown, improve diagnostics, procedures and, last but not least, provide continuous training of the operation team.

As the good performance is also due to the availability of spare cryogenic capacity and system redundancy, the future challenge is to maintain this performance while increasing the cryogenic power capacity and connecting all sub-systems for sector cool down and testing.

MAINTENANCE

The reliability and performance of the cryogenic system is highly dependent on the maintenance of the installations. Maintenance policy is based on a complete maintenance plan, taking into account equipment lists and their criticality, spare-parts list, preventive routines and major overhauls, corrective follow-up actions, history of interventions and performance indicators. This maintenance is being upgraded for the previously existing installations and established for the new LHC plants. It will be implemented in the CERN Computer Aided Maintenance Management System while the sub-systems go into operation. Maintenance tasks are outsourced to an industrial consortium and monitored via performance indicators and bonus or penalties applied to the downtime of the installations.

Extensive preventive-maintenance work is performed between commissioning periods. At a later stage, it will be done during the winter shutdowns. Additional constraints and subsequent staging of maintenance tasks could come from the request not to warm-up the magnets above 80 K to avoid re-commissioning the quench protection system.

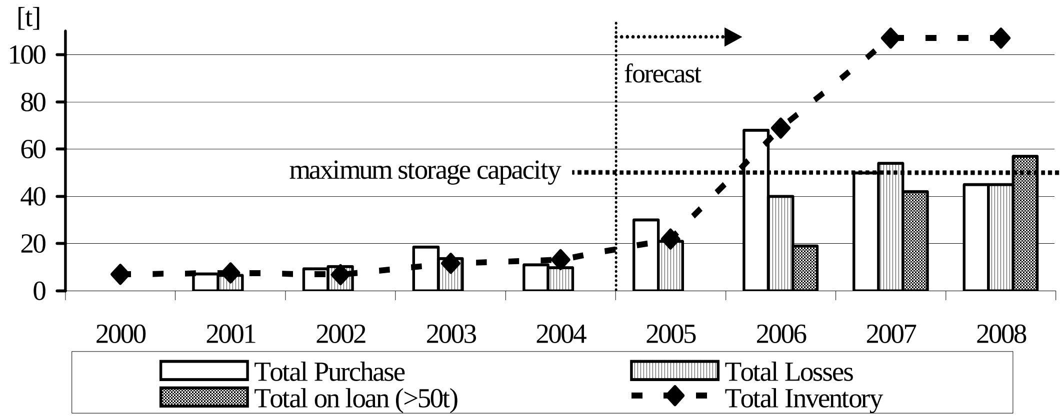

FIGURE 3. LHC machine overall helium management and future forecast.

The decision on the spare parts to stock is based on a criticality analysis method performed just after the commissioning of the installation (the average value of spares is on the order of 2.2% of the plant cost) to minimize capital costs and maximize system availability. Further improvements of the spare parts list would come after a few years' operational experience.

CRYOGENIC FLUID MANAGEMENT

The helium inventory is steadily increasing with the number of installations under commissioning or operation. It requires attentive management and continuous follow-up of local inventories and transfers in order to limit the losses. FIGURE 3 shows the measured losses and quantities of helium purchased to date (2005 extrapolated to the end of the year) and forecasts the needs and losses until the first few years of operation of the LHC machine. In order to cover future needs and storage constraints, CERN is in the process of placing a contract with recognized industrial suppliers of liquid helium and manufacturers of liquid helium storage facilities for the storage or recovery and distribution to other helium users of up to 60 t of liquid helium during machine shutdowns (when it cannot be stored in the LHC magnets or in the gas storage system). The release to atmosphere of this excess helium, would correspond to a loss of about 1.5 M CHF per shutdown and is therefore economically and operationally not acceptable.

Liquid nitrogen is mainly used to boost the refrigerators capacity during cool down. 1260 t of liquid nitrogen would be required during the 10-day cool down period of each sector of the machine. At present about 6000 t of liquid nitrogen are consumed per year to cool down magnets in the magnet test facility at Point 1.8 [11] and to assist in the operation of the refrigerators (adsorbers regeneration and back-up of the first stage turbines).

CONCLUSIONS

The cryogenic sub-systems will be individually tested, but the overall cryogenic system will certainly require complex and extensive commissioning prior and during powering in order to validate the collective behaviour and optimize operating modes. The availability and quench recovery performance of the LHC cryogenic system could be reduced by additional heat loads or non-conformities discovered during commissioning and magnet powering and would also depend on the organisation and efficiency of the maintenance activities.

The high number of on-call interventions required during the commissioning and the first years of operation are mainly due to the novelty of the installation, missing functionalities, required consolidations and reduced commissioning time. These interventions are progressively being reduced but require manning of the control room on shift in order to minimize the downtime of the installation and better manage and organize the operators' crew, at least until the overall process and the control system are fully debugged and optimized.

The results of the sub-system commissioning and experience of first years' operation of some sub-systems have validated the performance and robustness of the main cryogenic system components, but also has shown that the reliability and availability strongly depend on those of the utilities and of the control system. The training and knowledge acquired by the operator's crew during the commissioning will also permit rapid achievement of the expected performance.

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REFERENCES

1. Lebrun Ph., "Large Cryogenic Helium Refrigeration System for the LHC," Proceedings of the 3rd International Conference on Cryogenics & Refrigeration, ICCR'2003, Hangzhou, China, pp. 11-18.
2. Lebrun Ph, "Advanced Superconducting Technology for Global Science: the Large Hadron Collider at CERN," in *Advances in Cryogenic Engineering* 47A, edited by S. Breon et al., AIP, New York, 2002, pp. 3-14.
3. Blanco E. et al., "Experimental Validation and Operation of the LHC Test String 2 Cryogenic System" in *Advances in Cryogenic Engineering* 49A, edited by J. Waynert et al., AIP, New York, 2004, pp. 233-240.
4. Gruehagen H. and Wagner U., "Measured Performance of Four New 18 kW@4.5 K Helium Refrigerators for the LHC Cryogenic System," to be published in the proceedings of the 20th Int. Cryo. Eng. Conf., ICEC20, Bejing, China, 2004.
5. Gruehagen H. et al., "Long, Bellows-Free Vertical Helium Transfer Lines for the LHC Cryogenic System," Proceedings of the 19th Int. Cryo. Eng. Conf., ICEC19, Grenoble, France (2002), pp. 91-94.
6. Parente C. et al., "The Local Helium Compound Transfer Lines for the Large Hadron Collider Cryogenic System," this conference.
7. Claudet S. et al, "Specification of eight 2400 W / 1.8 K refrigeration units for the LHC", Proceedings of 18th International Cryogenic Engineering Conference, ICEC18, Mumbai, India (2000), pp. 215-218.
8. Millet F. et al, "Performance assessment of 35 cold hydrodynamic compressors for the 1.8 k refrigeration units of the LHC," this conference.
9. Claudet S. et al., "A cryogenic test station for the Pre-series 2400 W@1.8 K Refrigeration units for the LHC," Proceedings of the 19th Int. Cryo. Eng. Conf., ICEC19, Grenoble, France (2002), pp. 83-86.
10. Riddone G. and Trant R., "The Compound Cryogenic Distribution Line for the LHC: Status and Prospects," Proceedings of the 19th Int. Cryo. Eng. Conf., ICEC19, Grenoble, France, 2002, pp. 59-62.
11. Calzas C. et al., "Large Cryogenic Infrastructure for the LHC Superconducting Magnet and Cryogenic Components Testing: Layout, Commissioning and Operational Experience," Proceedings of the 19th Int. Cryo. Eng. Conf., ICEC19, Grenoble, France, 2002, pp. 217-224.