EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 960

DESIGN, CONSTRUCTION, INSTALLATION AND FIRST COMMISSIONING RESULTS OF THE LHC CRYOGENIC SYSTEM

S. Claudet

Abstract

The cryogenic system of the Large Hadron Collider (LHC) will be, upon its completion in 2006, the largest in the world in terms of refrigeration capacity with an equivalent to 144 kW at 4.5 K, about 400’000 litres of superfluid helium with 25 km of superconducting magnets below 2 K leading to a cryogen inventory of 100 tons of helium. The challenges involved in the design, construction and installation, as well as the first commissioning results will be addressed in this talk. Particular mention will be made of the problems encountered and how they were or are being solved. Perspectives for LHC will be presented. General considerations for future large cryogenic systems will be briefly proposed.

CERN, Accelerator Technology Department, Geneva, Switzerland

Presented at the Tenth European Particle Accelerator Conference (EPAC'06)
26-30 June 2006, Edinburgh, UK

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 4 August 2006

DESIGN, CONSTRUCTION, INSTALLATION AND FIRST COMMISSIONING RESULTS OF THE LHC CRYOGENIC SYSTEM

S. Claudet, CERN, Geneva, Switzerland

Abstract

The cryogenic system of the Large Hadron Collider (LHC) will be, upon its completion in 2006, the largest in the world in terms of refrigeration capacity with an equivalent to 144 kW at 4.5 K, about 400'000 litres of superfluid helium with 25 km of superconducting magnets below 2 K leading to a cryogen inventory of 100 tons of helium. The challenges involved in the design, construction and installation, as well as the first commissioning results will be addressed in this talk. Particular mention will be made of the problems encountered and how they were or are being solved. Perspectives for LHC will be presented. General considerations for future large cryogenic systems will be briefly proposed.

INTRODUCTION

The Large Hadron Collider (LHC) is a 26.7 km circumference superconducting accelerator equipped with high-field magnets operating in superfluid helium below 1.9 K. One of the early design constraints for the accelerator has been to use the former LEP tunnel and associated infrastructure. This also applies to the cryogenic system [1], which re-uses the four ex-LEP refrigerators. A direct consequence of the site constraints is the cryogenic layout of the machine, with five cryogenic "islands" where all refrigeration and ancillary equipment is concentrated. Each cryogenic island houses one or two refrigeration plants that feed one or respectively two adjacent tunnel sectors, requiring distribution and recovery of the cooling fluids over distances of 3.3 km underground. Some equipment is located at ground level (cryogen storage, electrical sub-station, cooling towers, warm compressor stations QSC-A,B,C, cold boxes QSR-A,B) and underground (lower cold boxes and 1.8 K refrigeration unit cold boxes QUR-A,C, interconnection boxes QUI-A,B,C, interconnecting cryogenic lines). For limiting environmental impact as well as the pressure build-up during helium discharge in case of generalized resistive transition of magnets, cryogen storage infrastructure is provided at all eight access points

The design phase took place mostly during the 90ies with start-up of the procurement phase in 1998. Most of the equipment of the cryogenic system will be installed by end of 2006, with progressive commissioning activities going on.

DESIGN

For a distributed system such as that of the LHC, the most important consideration for design is that there be a strong and early involvement of the cryogenic team together with teams in charge of magnets, beam vacuum and beam dynamics. This work has been essential in checking cooling capacities at various temperature levels, verifying the assumptions and data to get a globally optimised system.

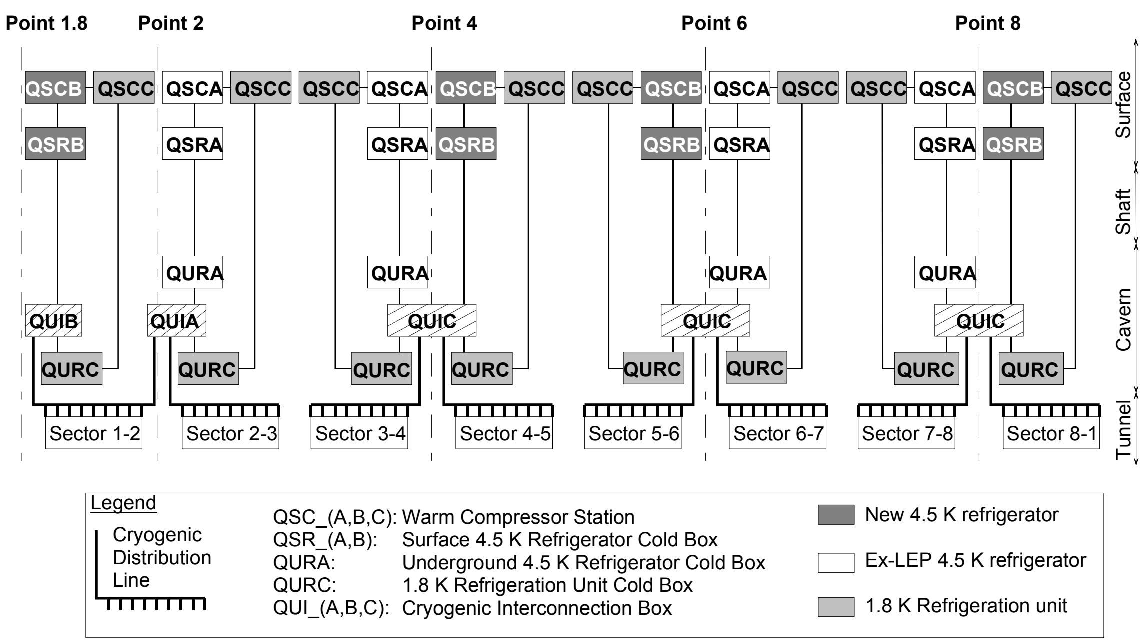

Figure 1: General architecture of LHC cryogenic system

A "heat load" working group was created at the project level with the aim at registering all possible heat loads without margins. Depending on the type of heat loads (static or dynamic) and beam parameters, they were converted into required capacity with multiplication factors varying from 1.5 to 2.0 [2]. The cryogenic architecture and associated sub-systems were periodically revised until procurement phase, to cope with capacity and distribution requirements.

In addition, the experience gathered from previous applications of cryogenics for accelerators at CERN was considered at an early stage. Major impacts were for process heat exchangers, bellows free vertical cryogenic lines or dryer units.

To proceed with detailed design of the cryogenic system, some general features were considered. In addition, specific R&D was conducted for overall behaviour or components identified as critical [3].

General features

Cooling down the huge cold mass of the LHC (37'000 t) has to be performed within 15 days, representing some 600 kW cooling capacity for most of the temperature range. The only economical way to do it is by using liquid nitrogen. For evident safety reasons, nitrogen is not used in all underground areas such as LHC tunnel. This implies pre-cooling helium at ground level with nitrogen-helium heat exchanger, in order to distribute only helium underground.

Another safety related issue reflected in the design concerns the restriction to small quantities of possible helium discharge in the tunnel. Therefore, a large acceptance cold recovery header has been implemented, with the foreseen possibility to recover all helium expelled in case of resistive transition of all cryo-magnets in a sector.

To simplify the magnet string design, the cryogenic headers distributing the cooling power along a machine sector as well as all remaining active cryogenic components in the tunnel are contained in a compound cryogenic distribution line (QRL). The QRL runs alongside the cryo-magnet strings in the tunnel and feeds in parallel, via a jumper connection, each 106.9 m-long lattice cell. The spacing of the jumper connections to one full cell length was the result of an optimisation effort [4].

The quest for highest availability considering present performance of refrigeration plants did not result in doubling all systems. A study of most frequent failures and corresponding effects on LHC availability resulted in avoiding single machines dealing with total flow, setting by-pass systems at different levels to allow operating LHC at lower intensity with a cryogenic sub-system down, and only doubling critical components such as oil pumps or filters at the warm compressor stations.

Such a distributed system including magnets is a high potential source of solid or gaseous impurities into the helium flow. It was therefore decided to accept the idea that there would be impurities, mostly dust, air and water, even though strong efforts were made to minimise the remaining levels. Impurities removal was then sized for full flow capacity, and located in the process stream before impurities could lead to process perturbation.

The total helium inventory of the machine is about 100 tons, mostly located in the cold mass and distribution headers during normal LHC operation. For reasons of limitations in investment cost and impact on the environment, it was decided to provide storage in gaseous form for only half of the inventory. The complement will be either via liquid storage or market based "virtual" storage. This is presently under investigation.

Specific system R&D

The cooling principle of the LHC magnets is based on a series/parallel arrangement allowing to cool kilometre-long strings of magnets within a narrow temperature range of about 0.1 K. The validity and performance of such a scheme depend critically on the thermo-hydraulic behaviour of two-phase helium II flowing in quasi-horizontal tubes. This has been the subject of theoretical modelling and experimental studies at CERN and CEA Grenoble (France). It was demonstrated that, over a large range of vapour quality, most of the tube cross-section is occupied by the vapour flow controlling the overall pressure drop, while the wetted area controls the heat transfer. Limitations in heat transfer and pressure drop were identified [5,6].

In view of the high thermodynamic cost of refrigeration at 1.8 K, the thermal design of the LHC cryogenic components was an issue. The cryostats and cryogenic distribution line combine several low-temperature insulation and heat interception techniques. These include low-conduction support posts made of non-metallic glass-fibre/epoxy composite, low-impedance thermal contacts under vacuum for heat intercepts and multi-layer reflective insulation wrapping the some 80'000 m^2 of cold surface area below 20 K. Precision experimental measurements confirmed the soundness of the adopted design and its suitability for industrial construction [7].

Coping safely with magnet resistive transition is a must for applications based on cryo-magnets, as stored magnetic energy of several hundreds of kJ/m will be dissipated in the resistive windings within a second. A set of buffers (cryostat helium enclosure, cold recovery line, medium pressure tanks) with increasing volume and temperature allows to contain the resulting pressure rise within the 2 MPa design pressure of the helium enclosure without venting helium to atmosphere. Specific cold safety relief valves had to be developed by industry following CERN specification and including performance assessment on a specially designed test facility. The thermo-hydraulics associated with quench propagation and collective behaviour were extensively tested on a 106.9 m full scale LHC test string [8,9].

Specific component R&D

A series of components were identified as critical at an early stage of the project, both for their technical and cost impacts.

Efficient production of large capacity in the kW range at 1.8 K may only be achieved practically through combined cycles making use of sub-atmospheric cryogenic compressors and heat exchangers. To foster the development of these technologies, CERN has procured from industry prototype low-pressure heat exchangers and small scale hydrodynamic cryogenic compressors. Thorough test campaigns permitted to investigate technology and efficiency issues. Design and optimisation studies were performed in liaison with industry on refrigeration cycles meeting the requirements and boundary conditions of the project, and matched to the expected performance of full-size machinery [10,11,12].

Powering the different magnet circuits of the LHC will require feeding about 3.4 MA into the cryogenic environment. The advantages of the high-temperature superconductors (HTS) combined with the favourable cooling conditions provided by the 20 K level in the LHC cryogenic system renders the use of HTS-based current leads very attractive. After conducting tests on material samples, CERN has procured from industry prototypes of such leads based on several alternative choices of material and manufacturing techniques. Upon completion of the test programme, final specification for the LHC current leads were established and procurement undertaken [13].

The tight temperature margins allowed along the cryo-magnets strings in the LHC require implementing precision cryogenic thermometers (several thousand channels at +/- 10 mK) and associated signal conditioning tolerating the radiation levels foreseen. Several types of sensors were tested as regards their performance including effects of neutron irradiation at cryogenic temperature and thermal cycling. Dedicated calibration facilities of metrological class were established at CERN and CNRS Orsay (France) where calibration of series sensors was performed [14]. In order to facilitate mounting of the delicate sensors and associated thermalisation blocks into the cryogenic piping manufacturing process, dedicated pre-assembled pipe-elements were fabricated and shipped to integrators for welding assembly.

PROCUREMENT

The procurement strategy has been to place contracts for sub-systems by type of functionality for which CERN was defining the interfaces, boundary conditions and required performance. A great majority of sub-systems were procured from industry, after competitive tendering based on functional technical specifications. Contracts included detailed studies, manufacturing, site installation, commissioning and performance assessment. According to CERN purchasing rules and to ease the industrial supply chain for the manufacturing process, there has been no specific standardization constraints for valves and instruments, but only recommended products to illustrate the required quality level. This resulted in a large variety of item references. Maintenance aspects will have to be assessed in the long term.

For standardisation reasons aiming at simplifying installation and future operation/maintenance, CERN decided to manage separately general services such as interconnecting piping or controls for which specific interfaces were defined: maximum equivalent pressure drop for the piping, and input/output signals switches for controls. For the latter, the specifications requested direct protection of the supply hardware by electrical interlocks, and logic sheets defining the proposed algorithms to be implemented under CERN responsibility [15].

A few sub-systems were procured through in-kind contributions agreements with research institutes. The whole technical performance was met, but interface clarification and follow-up has not always been as strict as for industrial contracts, thus leaving some additional adjustment work necessary at site.

In order to monitor and anticipate possible effects of series production, a set of dashboards showing progress of manufacture and installation were established for the entire LHC project

Construction

The manufacturing process can be analysed by using the following different categories:

- Industry available products: equivalent products have already been supplied (Storage, piping, 4.5 K refrigerators). Functional technical specifications are adapted as it is usually possible to measure the performance and react in case of problems. Follow-up of such contracts requires experienced teams able to anticipate what is being proposed as a standard by industry in order to preserve at best future operation and maintenance features.
- Extension of existing products: Relevant experience to fulfil the requirements exists, but there is a significant change of complexity or scale for the concerned supply (1.8 K units, cryogenic distribution line, electrical feed boxes housing the current leads). Whatever the type of contract, a strong involvement of CERN staff for complementary design and support to fabrication is mandatory. The frontier for responsibility for the supply is not always easy to define, as all parameters defining the overall performance might be difficult to assess or with very complex technical or schedule impact in case of necessary consolidation.

- Totally new products: there are no equivalent products on the market (radiation tolerant cryogenic thermometry, superconducting links) and CERN teams had to take full responsibility for developments and "built to print" fabrication contracts.

Installation

The main difference for installation activities is directly linked to the location of the supply. Except for the tunnel cleared from previous equipment, some difficulties were due to installation activities being held in zones with existing equipment and continued operation. For all teams, the inherent distributed work sites around the accelerator contributed to the heavy load associated to its guidance and follow-up.

To allow installation activities while other sub-systems were being tested with possible pressure and low temperature circuits, a specific procedure was set-up to physically separate the test/installation zones by either blind flanges or two valves in series.

- Ground level: nothing specific.
- Shaft and caverns: there was not much space available, handling means were delicate, and dealing with co-activity across different platform levels was rather limited for safety reasons
- Tunnel: there is increased complexity due to very tight technical and schedule interfaces, requiring a huge coordination effort that was established in the course of the project. As for other LHC tunnel sub-systems, special logistics for components delivery and teams has been setup.

FIRST COMMISSIONING

After delivery and installation at CERN, each sub-system is individually commissioned with relevant performance assessment. It always includes mechanical pressure test, helium leak test, and input/output signal tests. It is followed by operational tests aiming at demonstrating all functions specified and finally performance measurements (e.g. refrigeration capacity, thermal losses). Once commissioned and qualified for operation, sub-systems are used in a cascade way to commission subsequent sub-systems, progressively allowing testing and tuning collective behaviour of the LHC cryogenic system. This gives the possibility to the operation team to progressively get experience and define or adapt corresponding procedures and qualification of personnel.

From magnets to various refrigerators and cryogenic transfer lines, all test performed so far confirmed the expected functionalities and performances, sometimes after few temporary limitations were removed.

A specific working group established at LHC project level was established to coordinate the overall hardware commissioning with series of procedures. For cryogenics, documents defining concerned flow-schemes and circuits are being produced together with final control logic requirements [16]. Due to past delays with accelerator components and construction, it has not yet been possible to cool-down and test cryo-magnets already installed in the tunnel. The first LHC hardware commissioning of a sector is foreseen by end 2006. It is a crucial test for many systems including cryogenics. A staging exists for commissioning the eight sectors before beam commissioning.

MAIN PROBLEMS ENCOUNTERED

Design concerns

As indicated earlier, the thermal design of LHC distribution systems was an issue, with a tendency to focus on very low heat leak levels. However, this has only a practical interest if the lines can sustain the concerned mechanical loads. At least three different lines ranging from 10 m to several km required part or complete redesign supported by CERN staff for basic mechanical design of internal and external supports. The main cryogenic distribution line suffered as well from weak quality assurance. Lack of control for sub-contracted components or configuration changes for the industrialisation phase are typical examples. As regularly done at CERN for the procurement of refrigerators, double sourcing may have helped reducing the impact on the project.

Electrical heaters for cryogenic flows are rather commonly deployed, giving interesting design studies combining heat exchange, flow patterns, electrical and integration analysis. Probably due to the supply strategy of integration companies, some of these components were treated as simple electrical devices. At least three items over a 20-600 kW range did not fulfil their requirements and had to be consolidated.

Sub-system or general concerns

Our strategy for impurities was developed to protect the cryogenic system from outside contaminations. For at least three sub-systems, impurities (dust) originated in the cryogenic supply, leading to leaks across valves and longer commissioning periods. Probably due to the large quantity of cryogenic components to be supplied for the LHC, new fabrication sites were established in Europe but without enough guidance or control concerning the required cleanliness.

For cryogenic controls, CERN has a long experience with industrial systems and object oriented software. This was retained for LHC and completed by an Ethernet-based backbone network allowing more open access to local controllers and data servers. This distributed system is indeed open, but suffers for the time being from communication reliability and availability of programming tools. Possible remedies are being evaluated.

Project related items

Such a large project as LHC requires adapted tools for quality assurance, 3D models for machine configuration management, logistic and handling issues. All this was developed during the course of the project and gradually operational. The availability at an earlier stage would have provided a global benefit.

Another aspect is linked to the change of management strategy for LHC project, from "Time is Contingency" to "take decisions and actions to keep on schedule". Whatever one's feeling on the subject, it took some time to be converted into reinforced teams with validated procedures.

CONSIDERATIONS FOR NEW PROJECTS

An impressive documentation with public notes and reports describes LHC systems including cryogenics, and all published papers are available on-line [17]. Each new project has its own specificities and constraints that need to be assessed, with particular evaluation of boundary conditions and technological evolution. Establishing a partnership is an efficient way to catch-up faster, with dedicated R&D and validation of components as a complement. From design to installation phase, a solid reference scenario is required as guideline, while keeping some flexibility to cope with unforeseen events.

Take advantage of experienced teams while they exist!

CONCLUSION

The installation of various sub-systems will be mostly completed by end of 2006, with some remaining tasks until mid 2007. All sub-systems commissioned so far fulfil their requirements. The first LHC sector cool-down and commissioning is foreseen end 2006. We are confident that the LHC cryogenic system will meet the requirements and provide expected availability for LHC, and we are also aware that it represents an enormous challenge!

ACKNOWLEDGEMENTS

The work and experience reported here is that of many colleagues at CERN and laboratories of the contributing countries as well as specialised industry.

REFERENCES

[1] LHC Design Report, CERN Report 2004-003 Vol.1, Cryogenics, pp. 309-337, www.cern.ch/lhc/

[2] Ph. Lebrun, G, Riddone, L. Tavian & U. Wagner, Demands in refrigeration capacity for the Large Hadron Collider, ICEC16, Elsevier science, Oxford, UK (1997) pp. 95-98, LHC-Project-Report-18

[3] P. Lebrun, "Cryogenics for the Large Hadron Collider", IEEE Trans. Appl. Superconductivity10 1 (2000) pp 1500-1506, LHC-Project-Report-338

[4] M. Chorowski et al., A simplified cryogenic distribution scheme for the Large Hadron Collider, Adv. Cryo. Eng. 43A (1998) pp. 395-402, LHC-Project-Report-143

[5] J. Casas, et al., Design concept and first experimental validation of the superfluid helium system for the Large Hadron Collider, Cryogenics 32 ICEC Supplement (1992) pp. 118-121.

[6] A. Gauthier, L. Grimaud, B. Rousset, A. Bézaguet & R. van Weelderen, Thermohydraulic behaviour of He II in stratified co-current two-phase flow, Proc. ICEC16, Elsevier Science, Oxford, UK (1997)

[7] V. Benda et al., Measurement and analysis of thermal performance of LHC prototype cryostats, Adv. Cryo. Eng. 41A (1996) 785-792.

[8] M. Chorowski, Ph. Lebrun, L. Serio & R. van Weelderen, Thermohydraulics of quenches and helium recovery in the LHC prototype magnet strings, Cryogenics 38 (1998) pp. 533-543.

[9] L. Dufay, A. Perin & R. van Weelderen, Characterisation of prototype superfluid helium safety relief valves for the LHC magnets, CEC-ICMC'99 Montreal (1999), LHC-Project-Reports-318

[10] N. Gilbert et al., Performance assessment of 239 series helium sub-cooling heat exchangers for the Large Hadron Collider, CEC-ICMC'05, LHC-Project-Report-860

[11] A. Bézaguet et al. , Performance assessment of industrial prototype cryogenic helium compressors for the Large Hadron Collider, Proc. ICEC17, IoP, Bristol, UK (1998) 145-148, LHC-Project-Report-213

[12] F. Millet, P. Roussel, L. Tavian & U. Wagner, A possible 1.8 K refrigeration cycle for the Large Hadron Collider, Adv. Cryo. Eng. 43A (1998) 387-393, LHC-Project-Report-140

[13] A. Ballarino, HTS Current Leads for the LHC Magnet Powering System, LHC-Project-Report-608.

[14] E. Chanzy et al., Cryogenic thermometer calibration system using a helium cooling loop and a temperature controller, Proc. ICEC17, IoP, Bristol, UK (1998) 751-754.

[15] P. Gayet, C-H Sicard, Deployment and integration of industrial controls: the case of LHC cryogenics controls, ICALEPCS'03, Gyeongju October 2003, CERN-AB-2003-107(CO)

[16] L. Serio et Al., "Commissioning of the LHC cryogenic system: sub-systems cold commissioning in preparation of full sector tests", Adv. Cryo. Eng. (2006) pp. 1599-1606, LHC-Project-Report-862

[17] LHC Project Reports, www.cern.ch/lhc/