CONCEPTUAL DESIGN OF THE CRYOGENIC SYSTEM FOR THE LARGE HADRON COLLIDER (LHC)

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Abstract

The high-field superconducting magnets to be installed on the 26.7 km circumference of the Large Hadron Collider at CERN will operate below 1.9 K in pressurised superfluid helium, thus requiring the development and implementation of a cryogenic system unprecedented in size, refrigeration capacity and complexity. After recalling the basic features of LHC cryogenics, which allow to make full use of the peculiar properties of superfluid helium as a technical coolant for accelerator devices, we present recent updates in performance requirements and changes in architecture of the system, discuss their technical impact, and review the status of development of the key technologies involved.

1. INTRODUCTION

The Large Hadron Collider is the next high-energy particle physics instrument being built by CERN. This machine is basically a proton collider with a centre-of-mass energy of 14 TeV and with luminosity in the 10^{34} cm^{-2} s^{-1} range, providing the experiments with high interaction rates. In order to keep costs down the LHC is to be installed on the floor of the 26.7 km circumference LEP tunnel, and be fed by existing particle sources and pre-accelerators. The LHC uses the most advanced superconducting magnet, cryogenic and accelerator technologies ever employed and it is thoroughly described in the so-called "Yellow Book" [1].

The LHC employs high-field twin-aperture superconducting magnets operating in static baths of pressurised superfluid helium below 1.9 K. This low operating temperature is dictated by the high-field operation of the superconducting cable, based on the well-developed and mass-produced Nb-Ti alloy. Moreover it allows to benefit from the peculiar thermophysical properties of helium II (large effective thermal conductivity and heat capacity as well as low viscosity) for heat transport and conductor stabilisation.

The technology of pressurised superfluid helium chosen for the LHC was first pioneered by the "Commissariat à l'Energie Atomique" (CEA) in Grenoble (France) and implemented industrially for the Tore Supra fusion tokamak at Cadarache and a few other projects [2]. It allows kilowatts of refrigeration to be transported over the 3.3 km length and across elevation differences of up to 46 m of an LHC sector with a temperature drop of less than 0.1 K. The total LHC refrigeration capacity is equivalent to over 150 kW at 4.5 K distributed around the ring, circumference.

2. GENERAL ARCHITECTURE

Acknowledging that the even-numbered areas of LEP are much more accessible, developed and already equipped with technical buildings and infrastructure, we decided to group together, as much as possible, all the active cryogenic equipment at these four points, and to transport the refrigeration power over the complete length of a sector, i.e. 3.3 km, instead of the previous 1.7 km half-octant [3]. This results in the four-point cryogenic feed scheme that is sketched in Figure 1, instead of the previous eight-point feed scheme. This requires larger diameter pipes for distributing the cryogenic fluids, making impractical the previously designed integrated cryostat housing both the superconducting magnets and the cryogenic lines. Therefore the cooling power is now distributed by a separate Cryogenic Distribution Line (CDL) running alongside the magnets cryostats, with cryogenic interconnections at every half-cell cooling loop of 53.5 m. Two split-coldbox (Upper and Lower Cold Boxes, UCB - LCB) helium refrigerators of the LEP type [4] with an equivalent refrigeration power of 18 kW at 4.5 K serving adjacent sectors are installed in each even point. Partial redundancy is obtained by using a Cryoplant Interconnection Box (CIB) allowing distribution of the cryogenic power of each sector to either or both plants. Refrigeration at 1.8 K is provided by two Cold Compressor Boxes (CCB) installed at the level of the tunnel, each requiring four to five stages of centrifugal

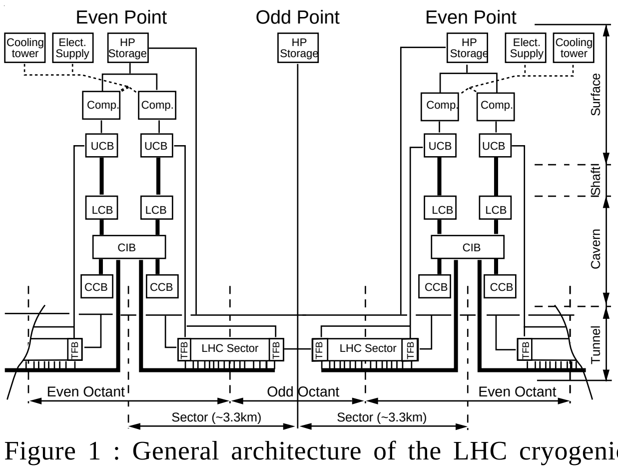

Figure 1 : General architecture of the LHC cryogenic scheme

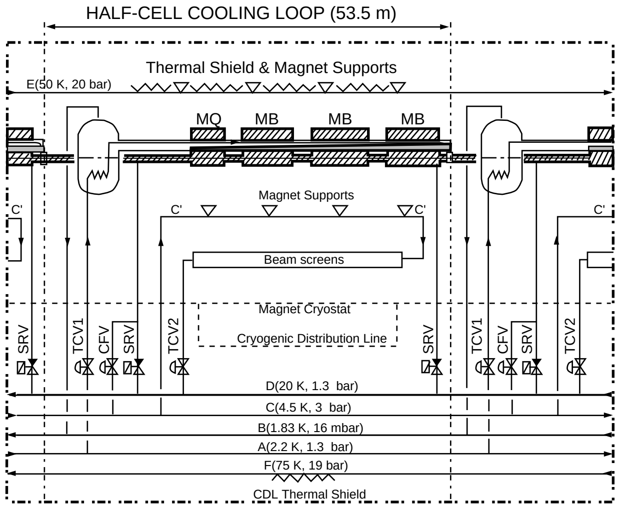

Figure 2: Cryogenic flow-scheme of an LHC half-cell

compressors in series. Two monostage centrifugal compressors, supplied by European industry and featuring novel ideas in wheel design, as well as bearing and drive technology, are being investigated [5,6]. Studies are also under way for possibly using volumetric cold compressors in the CCBs [7]. The string of magnets is terminated by Tunnel Feed Boxes (TFB) on each end of a sector that is used mainly for electrical feed of the LHC, by means of high-temperature superconductor (HTS) current leads [8]. 1000 m^3 and 1500 m^3 storage vessels at 2 MPa are used in the odd and even points respectively for recovery of gaseous helium after a generalised resistive transition of the superconducting magnets in the sector concerned. The total helium inventory in the LHC amounts to 93500 kg, most of which is stored in the cold mass of the magnet system during operation. For periods of shutdown partial storage in liquid form is envisaged in standard 11000 gallon (about 40 m^3) industrial containers compatible with liquid helium handling by European distributors.

3. RING OPERATION AND HEAT LOADS

The cryogenic flow scheme of an LHC half cell is shown in Figure 2. The pressurised superfluid helium bath at 1.9 K in which the superconducting magnets are immersed is cooled by saturated two-phase liquid helium flowing in heat exchanger tubes extending along the string of magnets and supplied by line A through the expansion valve TCV1. The performance and efficiency of this cooling loop, that are key factors in achieving the required magnet performance, have been assessed in the LHC test string [9]. The low saturation pressure is maintained by pumping the vapour through line B. Cool-down and warm-up is achieved by forced circulation of high-pressure gaseous helium supplied at variable temperature by line C, tapped through valve CFV and returned to the refrigerator by valve SRV and line D. In case of magnet resistive transitions, the resulting pressure rise is contained below the 2 MPa design pressure by discharging the liquid helium inventory of a half-cell into line D through the SRV valves. The low hydraulic impedance of this 150 mm diameter pipe, normally maintained at 20 K, proves very helpful in containing the helium discharge and buffering the gas storage vessels.

The temperature levels are:

- thermal shielding between 50 K and 75 K as a first major heat intercept, lines E and F;
- distribution of supercritical helium at 4.5 K by line C for initial filling of the magnets; during operation it provides the lower heat intercept and cryogen for the non-isothermal cooling of the beam screen by using the control valve TCV2;
- quasi-isothermal superfluid helium cooling the superconducting magnets at a maximum temperature of 1.9 K and transporting the heat loads across the length of a sector (3.3 km) to the CCBs operating at 1.8 K;
- saturated liquid helium (between 4.5 K and 4.7 K) cooling special superconducting magnets, superconducting acceleration cavities and the lower sections of HTS current leads;
- gaseous helium cooling the resistive upper sections of HTS current leads in forced flow of gaseous helium between 20 K and ambient.

As the heat loads depend strongly on the energy and intensity of the circulating beams, we use hereafter the values of the dynamic loads estimated for nominal (7 TeV, 2 x 0.536 A) and ultimate (7 TeV, 2 x 0.848 A) operating conditions. The estimated heat loads deposited in the magnet cold mass through several processes are given below, respectively for the nominal and ultimate cases:

- synchrotron radiation mostly absorbed by the beam screens amount to 0.41 W/m and 0.65 W/m;
- resistive heating due to image currents result in a 0.33 W/m and 0.83 W/m;
- continuous loss of particles results in a distributed heat load in the helium II baths of 0.06 W/m. This value should decrease with time due to improvement of the vacuum by beam cleaning;
- continuous loss of particles escaping the collimation sections may result in localised heat loads of 55 W and 92 W over a length of a few tens of metres, at one location around the ring;
- absorption of secondaries in the regions close to the high luminosity experimental areas:
  - at the 1.9 K level 500 W to 1250 W in the inner triplets of low-β quadrupoles and 54 W to 134 W in the dispersion suppressor magnets, for the whole machine;
  - at the 4.7 K level 240 W to 600 W in the beam separation and recombination dipoles for the whole machine.

Table 1 Refrigeration capacity demands of LHC sector cryoplants

Sector	Temperature levels				
	50-75 K [kW]	4.5-20 K [kW]	4.7 K [kW]	1.8 K [kW]	20-300 K [g/s GHe]
High-load	31	4.3	0.80	2.80	35
Low-load	30	4.3	0.65	2.45	23

On the basis of the heat load estimates for the LHC sectors, and allowing for some spare capacity, the refrigeration capacity to be simultaneously fulfilled by the cryogenic plants in each sector are listed in Table 1. The sectors which house high-luminosity insertions are subject to the largest 1.9 K heat loads, while sectors which feature the strings of superconducting acceleration cavities, exhibit the largest 4.7 K heat loads. Apart from fulfilling the demands listed in Table 1, the refrigeration plants have to be capable of operating in wide ranges of variation in the cooling power requirements at 1.9 K (up to two-fold variation) and 4.5 - 20 K (up to five-fold variation) that depend strongly in the operational mode of the LHC.

4. TECHNICAL VARIANTS UNDER STUDY

The system described above fully meets the design constraints and technical requirements established for LHC cryogenics, and may therefore be implemented with confidence. However, several technical variants, compatible with the basic design principles and presently under study, exhibit a strong potential for simplifying the layout, improving efficiency and performance, as well as reducing costs. Examples of such variants are given below.

Operating the two-phase helium II heat exchanger tube in counter-current as well as in co-current flow of liquid and vapour would bring complete symmetry in the cryogenic layout of the half-cell cooling loop, independent of the tunnel slope. This mode of operation is being tested in the second phase of the LHC prototype string [10], and its limits investigated in the thermohydraulic test loop at CEA in Grenoble (France).

Grouping all cryogenic headers in the CDL separately from the magnet cryostats, opens the way for finer sectorization of the LHC, an issue which could greatly shorten time spans for warm-up and cool-down of limited stretches of magnets to be replaced or repaired, and thus contribute to improving the availability of the LHC for physics.

Developing technology and establishing the performance and efficiency of several competing solutions for key cryogenic components, such as helium heat exchangers and compressors, over the useful ranges in the pressure and temperature domains, will allow the optimisation of the thermodynamic cycles for large-capacity refrigeration at 1.8 K. This could lead to solutions based on cold, warm, or mixed compression schemes, which may prove more economical or easier to operate and interface with the 4.5 K refrigerators. This topic constitutes the subject of an ongoing R&D programme conducted in collaboration with CEA (France) [7].

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