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Advances in Cryogenics at the Large Hadron Collider

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Abstract

After a decade of intensive R&D in the key technologies of high-field superconducting accelerator magnets and superfluid helium cryogenics, the Large Hadron Collider (LHC) has now fully entered its construction phase, with the adjudication of major procurement contracts to industry. As concerns cryogenic engineering, this R&D program has resulted in significant developments in several fields, among which thermo-hydraulics of two-phase saturated superfluid helium, efficient cycles and machinery for large-capacity refrigeration at 1.8 K, insulation techniques for series-produced cryostats and multi-kilometre long distribution lines, large-current leads using high-temperature superconductors, industrial precision thermometry below 4 K, and novel control techniques applied to strongly non-linear processes. We review the most salient advances in these domains.

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After a decade of intensive R&D in the key technologies of high-field superconducting accelerator magnets and superfluid helium cryogenics, the Large Hadron Collider (LHC) has now fully entered its construction phase, with the adjudication of major procurement contracts to industry. As concerns cryogenic engineering, this R&D program has resulted in significant developments in several fields, among which thermo-hydraulics of two-phase saturated superfluid helium, efficient cycles and machinery for large-capacity refrigeration at 1.8 K, insulation techniques for series-produced cryostats and multi-kilometre long distribution lines, large-current leads using high-temperature superconductors, industrial precision thermometry below 4 K, and novel control techniques applied to strongly non-linear processes. We review the most salient advances in these domains.

1 INTRODUCTION

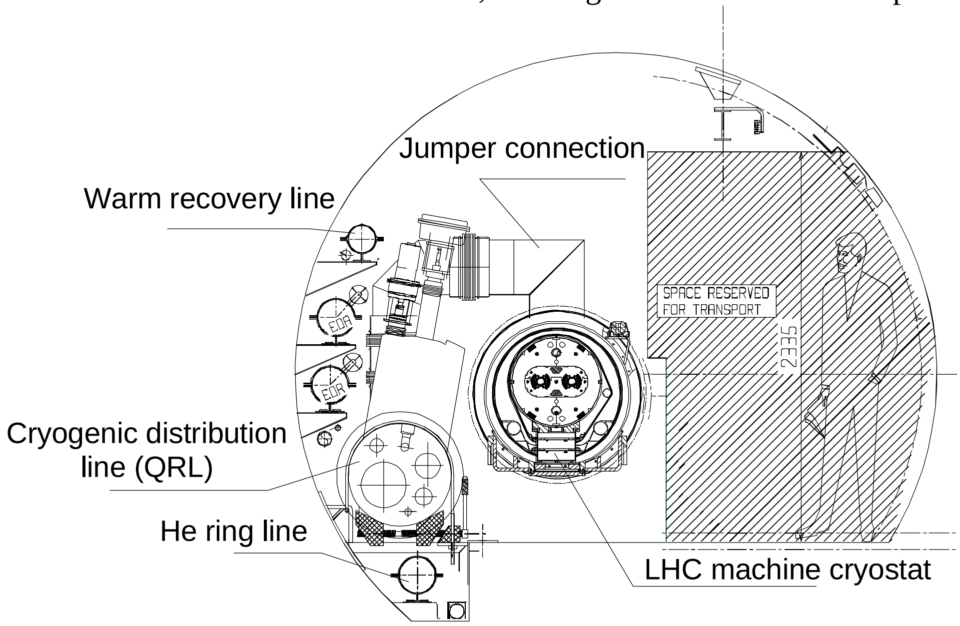
The Large Hadron Collider (LHC), presently under construction at CERN, will be, upon its completion in 2005, the largest scientific instrument in the world. It will accelerate and bring into collision intense beams of protons and ions, in order to study the structure of matter and basic forces of nature on an unprecedentedly fine scale. To achieve this goal at an economically acceptable cost, the LHC is based on the generalised use of high-field superconducting magnets, using Nb-Ti conductor operating in superfluid helium at 1.9 K, around most of its 26.7-km circumference.

The sheer size and technical sophistication of the LHC cryogenic system have demanded a dedicated development program, conducted over the last decade in collaboration with national laboratories and specialised industry, which has resulted in significant technical advances. The LHC project and cryogenics have already been presented in plenary sessions of ICEC15 [1] and ICEC16 [2]. In the following, we therefore only recall the main parameters (Table 1) and relevant features (Figure 1) of the LHC, and review its major contributions to progress in cryogenic engineering.

Table 1 Main technical parameters of the LHC with proton beams

Circumference	26.7	km
Beam energy in collision	7	TeV
Beam energy at injection	0.45	TeV
Bending field	8.3	T
Coil aperture	56	mm
Luminosity	10^{34}	$cm^{-2}.s^{-1}$
Beam intensity	0.53	A
Beam stored energy	332	MJ
Radiated power per beam	3.7	kW
Critical radiated photon energy	45.6	eV
Operating temperature	1.9	K
Cold mass	31×10^6	kg

Figure 1 Transverse cross-section of the LHC tunnel, showing the main machine components

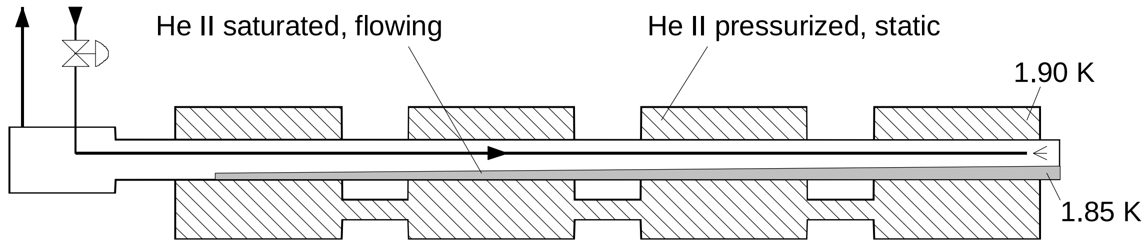


2 MAGNET COOLING SCHEME

The large, but finite bulk thermal conductivity of static pressurised superfluid helium has been successfully used for cooling large superconducting magnets and transporting their heat loads over distances up to few tens of meters [3]. Cooling strings of superconducting devices in high-energy accelerators, however requires to transport heat over kilometer distances under minute temperature differences, beyond the practical capability of helium-II thermal conduction alone.

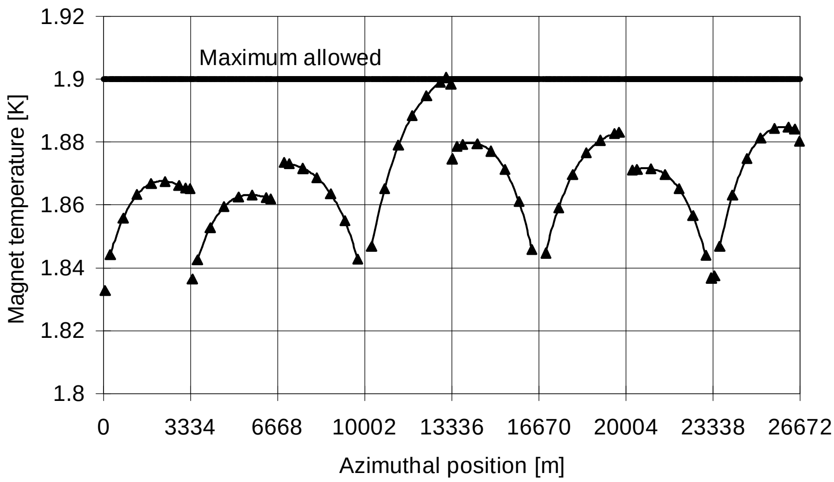
Alternative cooling schemes based on forced convection of pressurised helium II are plagued by pressure drop and Joule-Thomson heating along the flow path, as well as by the limited efficiency and reliability of circulator pumps [4]. In order to maintain below 1.9 K the furthest magnet of each sector, located 3.3 km away from the 1.8 K refrigeration plant, the LHC uses a quasi-isothermal heat sink running through the magnet string, constituted by a bayonet heat exchanger [5] in which a stratified two-phase flow of saturated helium II absorbs the linear heat load, about 0.4 $W.m^{-1}$ in the LHC arcs (Figure 2).

Figure 2 String cooling by two-phase helium II bayonet heat exchanger



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, which has been the subject of theoretical modelling and experimental studies at CERN [6] and CEA Grenoble [7,8] since the beginning of the decade. The heat transfer across the heat exchanger wall, dominated by Kapitza resistance, has also been investigated experimentally on industrial tube samples [9]. This research, finally validated on a 35-m long prototype magnet test string which has accumulated more than 10'000 hours operation at 1.9 K [10], permitted to establish practical sizing rules for the cooling loops in the LHC arcs, thus bringing significant simplification to the overall system [11] without loss of performance (Figure 3). A similar cooling scheme, using larger-diameter heat exchanger tubes, is also envisaged for cooling the final-focus magnets in the interaction regions of the LHC, subject to much higher heat loads in the 10 $W.m^{-1}$ range [12].

Figure 3 Calculated temperature profiles of LHC magnets in nominal operation

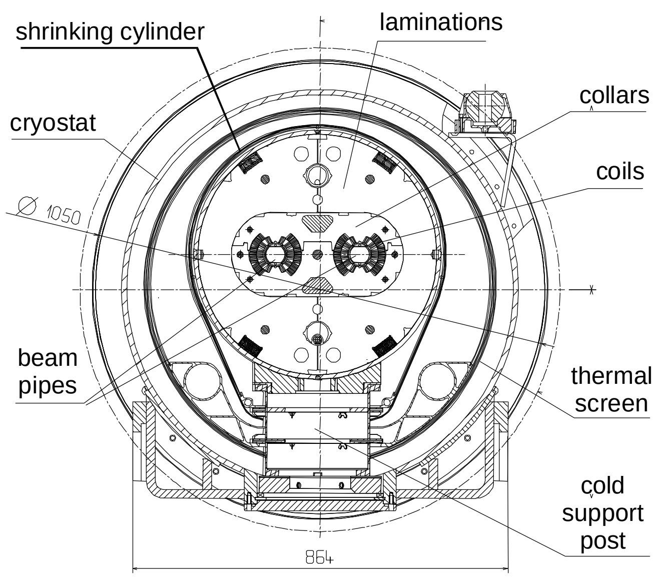


The dynamic behaviour of the two-phase helium II cooling loop is characterised by strong non-linearities – including initial inverse response – and long time delays, due to the low velocity of the liquid flow. To cope with this, we have been investigating the potential of advanced control techniques for improving the temperature regulation of the superconducting magnets. First results using a predictive model-based controller appear promising [13].

3 THERMAL DESIGN AND INSULATION

The cryostats housing the huge cold mass of the LHC, extending over more than 24 km, require efficient low-temperature insulation to be reliably implemented on an industrial scale. In view of the high thermodynamic cost of refrigeration at 1.8 K, the design of the cryostats (Figure 4) aims at intercepting the largest fraction of the incoming heat loads at higher temperature [14]. Critical components in this endeavour, such as low-conduction support posts made of non-metallic glass-fibre/epoxy composite [15], low-impedance thermal contacts for heat intercepts and multi-layer reflective insulation wrapping the some 80'000 m^2 of cold surface [16], as well as beam screens cooled at 5 to 20 K by supercritical helium [17], have been developed and investigated thoroughly in the laboratory. Based on these results, the cryostats were modelled by thermal network analysis, and optimised in standard as well as off-design operation [18]. Precision experimental measurements confirmed the soundness of the adopted design and construction [19]. Similar insulation and heat interception techniques will be applied in the compound cryogenic distribution line which parallels the cryomagnets in the LHC tunnel.

Figure 4 Transverse cross-section of LHC dipole cryomagnet



4 LARGE-CAPACITY REFRIGERATION AT 1.8 K

The refrigeration demands of the LHC sectors [20], listed in Table 2, require mixed-duty operation of the cryogenic plants, amounting to a total equivalent entropic capacity of 120 kW/4.5 K. Previous experience at CERN with similar plants delivered by European industry, has demonstrated good efficiency and reliability [21]. CERN has recently adjudicated contracts for the delivery of four new plants which will feed the "high-load" sectors, as well as for the upgrade of four existing plants for the "low-load" sectors.

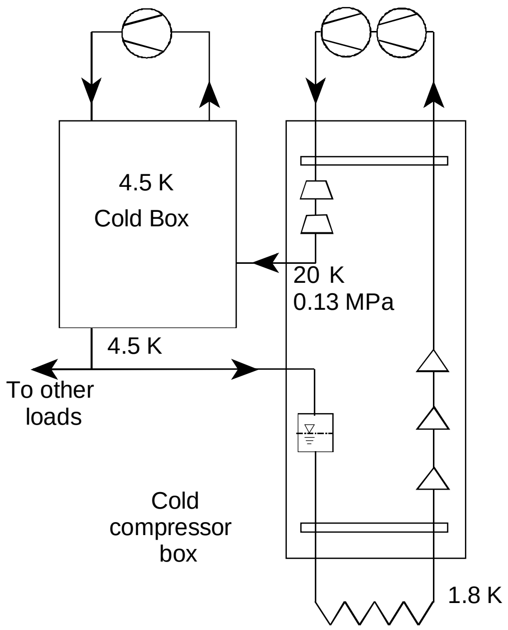
Table 2 Installed refrigeration capacity in the LHC sectors

Temperature Level	50-75 K	4.5-20 K	4.6 K	3-4 K	1.8 K	20-300 K
	W	W	W	W	W	g/s
High-load sector	33'000	7'700	300	430	2'400	41
Low-load sector	31'000	7'600	150	380	2'100	27

A specific demand of the LHC concerns efficient 1.8 K refrigeration in the kW range, which may only be achieved practically by means of sub-atmospheric cryogenic compressors [22]. To stimulate development of this technology, CERN has procured from industry and tested three prototype hydrodynamic compressors, each handling 18 $g.s^{-1}$ at 1 kPa with a pressure ratio of 3 [23]. This program has permitted to investigate impeller and diffuser hydrodynamics, mechanical and thermal design, drive and bearing technology, as well as their impact on overall efficiency.

Design and optimisation work has also been performed, in liaison with industry, on 1.8 K refrigeration cycles meeting the requirements and boundary conditions of the LHC, and matched to the performance of available machinery. A mixed-compression 1.8 K refrigeration cycle [24], such as schematised in Figure 5, could achieve a COP of about 900 W/W.

Figure 5 A possible 1.8 K refrigeration cycle matched to the 4.5 K cryogenic plants



5 CURRENT LEADS USING HIGH-TEMPERATURE SUPERCONDUCTORS

Powering the different magnet circuits of the LHC will require feeding about 3.6 MA into the cryogenic system, which would result in a heavy liquefaction burden when using conventional vapour-cooled leads. The advent of quasi-industrial HTS materials, combined with the favourable cooling conditions provided by the 20 K level in the LHC cryogenic system [25], makes the use of HTS-based current leads very attractive. After conducting tests on material samples, CERN is now procuring from industry and will be testing prototypes of such leads for 13 kA and 0.6 kA, based on several competing choices of material and technology [26]. The long-term performance of HTS materials remains an important pending issue.

6 COPING WITH MAGNET RESISTIVE TRANSITIONS

Following a transition, the 500 kJ.m^{-1} stored magnetic energy will be dissipated in the resistive coils, and part of it eventually released to the 15 l.m^{-1} static helium in the cold mass. The resulting pressure rise, partly accommodated by the 2 MPa design pressure of the helium enclosure, will nevertheless result in mass discharge to the cold recovery header, and later to the gas storage vessels at ambient temperature [27]. These phenomena were investigated on the prototype magnet string, and simulated by means of simple thermo-hydraulic models in order to size discharge piping and relief valves [28].

7 INDUSTRIAL PRECISION THERMOMETRY BELOW 4 K

The tight temperature margins allowed along the LHC magnet strings require precision cryogenic thermometry (+/- 10 mK) on an industrial scale (several thousand channels) with long-term robustness and reliability. Following the establishment of a cryogenic thermometer calibration facility of metrological class [29], several types of sensors have been tested on statistically significant ensembles, as regards their performance in LHC-type environmental conditions. In particular, the effect of neutron irradiation at superfluid helium temperature has been investigated on several hundred thermometers [30], in view of selecting adequate solutions for the project.

8 CONCLUSION

After a decade of pluri-disciplinary R&D in the domains usually associated with cryogenic engineering, but also in some less conventional niches, the principles of the LHC cryogenic system have been validated, and its construction is progressing. The LHC case confirms that large projects in "big science" and technology, besides generating industrial markets by themselves, also provide opportunity, drive and resources for R&D in related domains. Beyond the immediate technological results, it is in fact the training of young professionals and the development of team competence in academia and industry, which generate the main long-term returns to society.

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