FINAL DESIGN AND EXPERIMENTAL VALIDATION OF THE THERMAL PERFORMANCE OF THE LHC LATTICE CRYOSTATS

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Abstract

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Measurements of the total helium vaporization rate in String 2 gives, after subtraction of supplementary heat loads and end effects, an estimate of the total thermal load to a standard LHC cell (107 m) including two Short Straight Sections and six dipole cryomagnets. Temperature sensors installed at critical locations provide a temperature mapping which allows validation of the calculated and estimated thermal performance of the cryostat components, including efficiency of the heat interceptions.

Accelerator Technology Department

Presented at the 2003 Cryogenic Engineering Conference and International Cryogenic Materials Conference
CEC/ICMC 2003

22-26 September 2003, Anchorage, Alaska

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 29 January 2004

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ABSTRACT

The recent commissioning and operation of the LHC String 2 have given a first experimental validation of the global thermal performance of the LHC lattice cryostat at nominal cryogenic conditions. The cryostat designed to minimize the heat inleak from ambient temperature, houses under vacuum and thermally protects the cold mass, which contains the LHC twin-aperture superconducting magnets operating at 1.9 K in superfluid helium. Mechanical components linking the cold mass to the vacuum vessel, such as support posts and insulation vacuum barriers are designed with efficient thermalisations for heat interception to minimise heat conduction. Heat inleak by radiation is reduced by employing multilayer insulation (MLI) wrapped around the cold mass and around an aluminium thermal shield cooled to about 60 K.

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INTRODUCTION

The Large Hadron Collider (LHC), whose installation is due to start in April 2004 at CERN, will accelerate two proton beams up to 7 TeV energy for head-on collisions in 4 points around the circumference. The machine is subdivided in octants of approximately 2.7 km length, comprising two dispersion suppressors and a standard arc of 23 optical cells, composed of 6 two-in-one 8.3 T dipoles of 15 m length, and two Short Straight Sections (SSS) each housing a two-in-one quadrupole and a set of corrector magnets.

Dispersion suppressors and standard arc magnets are enclosed in a common cryostat (arc cryostat) of 914 mm external diameter. The superconducting magnets operate in a bath of pressurized 1.9 K superfluid helium, and are cooled via a separate cryogenic distribution line (QRL) running parallel to the main cryostat, to which is linked every cell, as shown on Figure 1 [1] and [2]. The LHC machine comprises 8 arc cryostats. An arc cryostat comprises 154 cryodipoles (32 tons and 15 m in length), 54 SSS (8 tons- length 6 m), 570 magnet support posts, 14 insulating vacuum barriers, and 208 instrumentation capillaries housing more than 10000 instrumentation wires.

The LHC main cryostat has been designed to mechanically support and position precisely the superconducting magnets and minimize the static heat inleak to the cold masses at 1.9 K in the most efficient and cost effective way, while having to house, sectorise and interconnect a number of utilities such as vacuum, electrical distribution, magnet instrumentation and cryogenic distribution [3, 4]. During the course of the development of the LHC cryostat system and components, systematic laboratory heat load measurements were performed to validate designs, concepts, manufacturing and assembly methods, with, in addition, full scale cryostat thermal performance assessments [5, 6]. These allowed a reference thermal load budget to be established and used to size the cryogenic plant and cryogenic distribution system, of which the static arc cryostat contribution (i.e. no beam, no current) is 514 Watts/arc (0.19 Watts/m) at 1.9 K, 353 Watts/arc (0.14 Watts/m) at 5-20 K, 12160 Watts/arc (4.5 Watts/m) at 50-70 K.

Recently, the thermal performance at 1.9 K of the LHC arc cryostat system was validated in the spring of 2003 on the full scale LHC 107 m long prototype arc cell, the so-called String 2 [7].

FIGURE 1: Artist view of the LHC in the LEP tunnel.

REVIEW OF THE MAIN FEATURES AND COMPONENTS OF THE LHC ARC CRYOSTAT

LHC Main Cryostat Cross-Section

FIGURE 2: Standard schematic cross-section of the LHC Arc Cryostat.

The LHC cryostat main constituents (Figure 2) contributing to the static heat load at 1.9 K are the carbon steel vacuum vessels, the Glass Fiber Reinforced Epoxy (GFRE) magnet support posts, the 60 K Thermal Shielding, the Multi Layer Insulation (MLI), and the residual gas conduction and radiation shielding MLI wrapping the 1.9 K magnets. To these are added the magnet Instrumentation Feedthrough systems (IFS) and the 20 K beam screens present in each magnet, the insulating vacuum sectorisation barriers (VB) and QRL jumpers every in every second SSS, corrector magnet current feedthroughs (DCF), 20 K-cooled Beam Position Monitors (BPM) supports, beam vacuum feedthroughs and technical service modules (QQS) at each SSS.

The vacuum vessels consist of long cylindrical industrial standard tubes (outer diameter 914 mm, wall thickness 12 mm) made from alloyed low carbon steel, and equipped with end flanges in AISI 304 L stainless steel for vacuum-tight connection (10^{-3} Pa) via elastomer seals to adjacent units. After welding of lower cast steel supports, reinforcement rings and alignment target supports, they are stress relieved by vibration to ensure long term mechanical stability. They are then sand blasted and simply cleaned to HV standards with no other inner wall treatment. The thermal shield assembly (TSA), intercepting radiant heat at 50-65 K, is composed of a lower extruded profile in series 6060 aluminium alloy onto which are fitted cylindrical upper sheets in high purity aluminium alloy over its entire length and welded in place. The TSA is supported on the lower aluminium flanges of the magnet support posts and thermalized to these same flanges via

two aluminium multi-foil flexible straps welded at each end to ensure good thermal contact.

The magnet support posts are composed of moulded (RTM: Resin Transfer Moulding) monolithic 4 mm-thick tubular columns in Glass Fibre Reinforced Epoxy resin (GFRE) material, chosen for its low thermal conductivity-to-stiffness ratio at reasonable cost. They comprise a top and a bottom flange, which serve as mounting interfaces to the cold mass and the vacuum vessel, respectively. Each support post is equipped with two external aluminium heat intercepts and with internal stainless steel rings, glued to the composite column. Aluminium anti-radiation disks and reflective coating complete the assembly. To ensure efficient thermalisation, the lower aluminium heat intercept operating at 50-65 K is equipped with two aluminium multi-foil flexible straps welded to the Bottom Tray Assembly, whereas the upper intercept operating at 4.5-10 K integrates a low-thermal-impedance stainless steel tube insert to be later welded into the corresponding cryogenic supply line.

Sets of MLI blankets including all blankets and pads needed to equip one magnet cryostat and its cold mass, are obtained from industry as an installation kit. The blankets are manufactured with a layered structure of sheets of 6 μm thick reflective polyethylene terephthalate (PET) film, coated with 400 $\text{\AA}$ minimum aluminium on each side, perforated with open areas of minimum 0.05 % and maximum 0.15 % of their total area and interleaved with polyester net spacing sheets of very low weight ($< 5 \text{ g/m}^2$). The thermal shield is equipped with two superimposed blankets of 15 layers each. The cold masses and the diodes are equipped with single blankets of 10 layers. The outermost layer of each blanket is a 6 μm reflective film reinforced with a polyester net. All blankets, for ease of installation, are equipped with Velcro^{TM} fasteners assembled on the cold inner side of the blankets and stitched to their edges. Adequate performance of the blankets requires their overall thickness not to be less than 2 mm for the 10 layers and not less than 3 mm for the 15 layers. To avoid direct intrusion of room temperature black body radiation, all holes, slits and component feed-throughs through the thermal shield are masked by MLI pads overlapping with the blankets. Interconnect zones between magnets are wrapped in the same way as the magnet cryostats and interfaced via Velcro^{TM}fastened overlaps. The developed length of each blanket is adjusted to compensate for their thermal contraction being superior to that of aluminium alloy.

All LHC arc cryostat components have seen their thermal design validated by laboratory measurements. Table 1 gives the static thermal budget for a standard arc cell of length 107 m [8]:

TABLE 1: Standard 107 m arc cell heat loads at the 3 cryostat temperature levels			
Source of heat load	50-75 K [W]	4.6-20 K [W]	1.9 K LHe [W]
Magnet support posts	157	9.78	1.07
Thermal shield	301.3	-	-
Radiative insulation	-	0.854	11.3
Beam Screen	-	-	1.618
Instrumentation feedthrough system (IFS)	-	-	4.254
Beam vacuum feedthrough	2.40	-	0.420
Dipole corrector feedthrough (DCF)	10.4	2.44	0.534
Beam position monitor (BPM)	-	0.928	0.604
Service Module QQS	-	0.013	0.210
Longitudinal Vacuum Barrier VB	11.6	0.029	0.424
TOTAL	482	14.0	20.4

THE PROTOTYPE LHC STANDARD CELL (STRING 2)

The LHC Test String 2 is a 107.5-m long superconducting magnet string representative of a full-cell of the LHC machine (Figure 3) in the middle of an arc, with exception of its extremities which contribute to an additional heat load (electrical distribution feedbox DFBS and magnet return box MRB). It was designed and commissioned at CERN in order to validate the final design choices and investigate the collective behaviour and operation modes of the LHC machine systems. It has been operated since May 2001 in three main successive phases and has accumulated more than 8000 hours at its nominal operating temperature of 1.9 K under near machine-like conditions.

FIGURE 3: The LHC prototype arc cell String 2.

The LHC prototype cell String 2 - phase 2 whose heat load at 1.9 K had been measured at 44 W, i.e. with an excess of 23 W with respect to nominal, was heavily instrumented in order to assess the performance of its various systems. Temperature sensors were installed on the various cryostat components in order to verify the operating temperatures of the shields and the heat intercepts, i.e. the efficiency of the thermalisation. In its so-called phase 3 in January 2003, String 2 was modified to represent more closely the LHC standard cell, with the aim to assess its thermal performance at 1.9 K. A large amount of excess instrumentation was removed and repairs were made to the thermal shielding. However a few anomalies, i.e. not representative of the nominal LHC cryostat, could not be repaired. These concerned prototype MLI blankets of poorer than nominal performance on 3 prototype magnets, and excess instrumentation wires on 6 IFS systems.

STRING 2 – PHASE 3 THERMAL PERFORMANCE AT 1.9 K

During the first running phases of the string and before the removal of the cryostat thermometers, temperatures on thermal shields and heat intercepts were recorded on a representative number of cryomagnets (SSS) and components (VB, IFS and magnet supports). Measurements confirmed the nominal system and component temperatures, thus validating the design of the thermalisation and the efficiency of the all-welded aluminium thermal shield structure, with the noteworthy exception of the insulating vacuum barrier, for which a defect could be traced to a poor aluminium to copper brazing of a thermalisation strap. A detailed account is given in reference [9].

The heat load measurements at 1.9 K in String 2 were performed by measuring either the boil-off of gaseous helium or the supplied supercritical helium mass flows with precise flowmeters and hence the enthalpy difference between the liquid inlet and gaseous outlet of the 1.9 K string heat exchanger [10]. Various measurements were performed, with nominal and off nominal temperatures on the cryostat cryogenic lines. Heat load values were corrected from measured and calculated extra heat loads not representative of a standard LHC cell (amounting to 3.2 W) and end effects such as the DFBS lambda plate and the MRB with its extra jumper (amounting to 8 W) [11]. Table 2 summarises the results of the measurements.

TABLE 2: String 2 heat load measurements vs estimates at 1.9 K at nominal insulating vacuum pressure $P < 10^{-3}$ Pa.		
Heat intercept temperature settings	Measured thermal load at 1.9 K	Heat load estimates assessed from design models and laboratory measurements
Line C' (cold feet intercepts) at nominal 7 K- Line E (thermal shield) at nominal 60 K average temperature	21.2 +/- 1.9 W	20.7 W
Line C' at 5-20 K, Line E (thermal shield) at nominal 60 K average temperature	23.2 +/- 1.9 W	22.3 W
Line C' at nominal 7 K - Line E (thermal shield) at 100 K average temperature	46.8 +/- 1.9 W	40.8 W, upper estimate

As can be inferred from additional experiments performed with off-nominal thermalisation temperatures, no gross thermal anomaly could be identified. In particular the near to nominal performance of the LHC MLI between 1.9 K and 60 K is confirmed (~ 0.06 Watts/m²), even though some experimental values obtained with a full scale dipole cryostat could have nourished the hope of a better-than-nominal performance [5]. The dismantling of the string at the end of 2003 will be the occasion to scrutinize the tightness of the thermal shielding, in particular in prototype cryostats, to fully confirm the results obtained and possibly diagnose paths of parasitic heat inleak.

CONCLUSIONS

The value of the thermal heat load at 1.9 K measured on the String 2 experimental cell with nominal temperature settings validates the arc cryostat design and its technical choices. Within the uncertainties of the measurements and extrapolations, the nominal LHC value lies within the range of the String 2 – Phase 3 thermal load measured at 1.9 K.

REFERENCES

1. J.C. Brunet et al, *Mechanical design and layout of the LHC standard half-cell*, CERN-LHC-Project-Report-111
2. P. Lebrun, *Superfluid helium cryogenics for the LHC*, ICEC 15, 1994, CERN AT/94-18
3. *The Large Hadron Collider, Conceptual Design*, CERN/AC/95-05 (LHC), 20 October 1995 (update being prepared)
4. *Design of the second series 15 m LHC dipole magnet cryostats* – CERN-LHC Project Report 133
5. L. Dufay, *A Large-scale Test Facility for Heat Load Measurements down to 1.9 K*, CERN-LHC-Project-Report-510, 19 Oct 2001
6. G. Vandoni et al, *Heat Flow Measurements on LHC Components*, CERN-LHC-Project-Report-329, 1 Dec 1999
7. F. Bordry et al, *The Commissioning of the LHC Test String 2*, CERN-LHC-Project-Report-480, 6 Aug 2001
8. Heat Load Working Group (HLWG), CERN, Reference tables on: <http://lhc-mgt-hlwg.web.cern.ch/lhc-mgt-hlwg/>
9. N. Bourcey et al, *Thermal performance of SSS3 and SSS4 in the LHC string 2*, LHC-CRI Technical Note 2002-19, EDMS No. 363872
10. E. Blanco et al, *Experimental validation and operation of the LHC Test String 2 cryogenic system*, this conference
11. A. Poncet, *Assessment of excess heat loads measured on string 2-phase 3 from known non-nominal configurations*, AT-CRI Technical Note 2003-04, EDMS No. 402418