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LHC Note 347

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Cryogenic Engineering Conference and International Cryogenic Materials
Conference,
July 17-21 1995, Columbus - Ohio, USA

Geneva, Switzerland
18 September 1995

MEASUREMENT AND ANALYSIS OF THERMAL PERFORMANCE OF LHC PROTOTYPE CRYOSTATS

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ABSTRACT

The heat inleaks into the cryostats represent a significant fraction of the total heat loads to the Large Hadron Collider (LHC). In view of the large size of this machine and the high thermodynamic cost of low-temperature refrigeration, it is essential to maintain the heat inleaks within budgeted values. Following experimental validation of thermal design of critical components (e.g. multilayer reflective insulation, support posts, cold valves), thermal performance assessment of complete cryomagnets has been undertaken. Thermo-mechanical and cryogenic behaviour was measured on full-scale prototype units.

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Measured values have been compared to calculated values and to budgeted heat loads.

INTRODUCTION

The Large Hadron Collider (LHC) project, now approved, will represent a unique facility in high-energy physics research¹. To be installed in an existing 26.7 km circumference tunnel, it is based on the large-scale use of high-field twin-aperture superconducting magnets² and will operate below 1.9 K in pressurized helium II³. The high cost of low-temperature refrigeration imposes that heat loads are maintained within budgeted values and the search for a cryostat of economic thermo-mechanical design renders essential the evaluation of the heat loads into complete cryomagnets. This has been carried out on full-scale prototype units, in the course of single-magnet tests⁴, on a dedicated Cryostat Thermal Model (CTM)⁵ and during the recent string tests⁶.

In collaboration with European industry, CERN is running an accelerator magnet development program which includes the testing of prototype 10 m-long twin-aperture high-field superconducting dipole magnets. Since February 1994, the thermal, mechanical and magnetic behaviour of four of these dipole magnets has been evaluated.

The string test phase 1, comprising one quadrupole and two dipoles, connected to a refrigeration unit and powered to nominal LHC conditions, has been operating since March 1995 and has allowed basic choices concerning LHC cryogenics to be validated.

The sources of heat loads are the heat inleaks, the resistive dissipation in the non-superconducting cable splices and the beam-induced loads produced by synchrotron radiation, beam image currents and the loss of particles by nuclear inelastic scattering with residual gas. The heat inleaks constitute 19 % of the heat loads at 4.5-20 K and 53 % at 1.9 K. Precise calorimetric measurements are difficult to perform during single-magnet tests as additional heat loads due to the cryogenic plant, high-current feedthroughs and equipment for “warm” magnetic measurements in the apertures dominate. The CTM has been finely instrumented and exploited to provide precise measurements of heat inleaks at 1.9 K, 4.5-20 K and 50-75 K without the contribution of the interconnection regions and other equipment.

CRYOSTAT THERMAL DESIGN

The currently tested prototype dipole cryostats⁷ (Fig. 1a) house the cold mass of a twin-aperture dipole magnet, of 10.25 m length and 0.56 m outside diameter. Two cylindrical composite support posts maintain the cold mass in position. Top and bottom stainless steel flanges glued to each tubular column interface to the cold mass and the vacuum vessel. Two heat intercept plates in aluminium alloy are shrink-fitted and glued to the column to allow thermalisation at the two intermediate temperature levels. The cryogenic piping for helium distribution is fixed on both sides of the cold mass via low heat conduction supports. This cold mass and piping assembly is wrapped with 10 layers of reflective aluminized mylar superinsulation (MLI), thermally insulated from the cold mass at 1.9 K and in contact with the cryogenic pipes operating between 5 and 20 K.

The thermal shield, in commercially pure aluminium alloy consists of a 5 mm thick lower tray clipped and tack-welded to 3 mm-thick upper shell parts. This structure is wrapped with 30 layers of MLI.

The vacuum vessel, a 10 mm thick mild steel cylinder with stainless steel end flanges, several auxiliary ports and two reinforced load points for the cold mass and screens, contains an insulation vacuum in the 10^{-4} Pa range during normal operation. A bellows element attached to the vacuum vessel at one end houses the interconnect region to the adjacent magnet. The instrumentation feedthrough comprising two stainless steel tubes 8 mm and 12 mm-diameter by 3.5 m long, filled with instrumentation cables and rendered leak tight by epoxy impregnation, is welded to the cold mass and the vacuum vessel.

The cold mass of the CTM (Fig. 1b), which simulates that of a real magnet, is formed from a low-mass double-walled stainless steel cylindrical structure, spot-welded and pre-formed plastically to give adequate hydraulic resistance for the helium flow. A collector in stainless steel housing the copper heat exchanger and a dummy cold bore is placed on the bottom of the cylinder and is connected hydraulically in series with it. The two 1.9 K tubes are simulated by copper sheets approximating their shape and surface area and are fixed mechanically and thermally to the dummy cold mass. All other elements are identical to those in a real prototype dipole cryostat.

Figure 1. Cross sections of the prototype LHC dipole cryostat (a) and the Cryostat Thermal Model (b).

CRYOGENIC CIRCUITS

The simplified hydraulic circuit of the LHC half cell, the smallest repetitive LHC machine module, and of the string test, designed to simulate the behaviour of the half cell is shown in Fig. 2.

Magnets are cooled from ambient temperature to 4.2 K by forced circulation of gaseous helium tapped via the cooldown-and-fill valve (CFV) from line C and returned through the valve FV via line D.

Helium at 2.2 K and 1 bar from line A first passes through a heat exchanger and after expansion to saturation in a Joule-Thomson valve (TCV1) is expelled through the inner tube of the heat exchanger at 1.9 K. During its return through the outer heat exchanger tube, the helium vaporizes and cools the cold mass from 4.2 K to below 1.9 K.

The 4.5-20 K circuit, lines C (supply) and D (return), is cooled by forced flow of supercritical helium. It intercepts heat from the support posts and from the thermal shield through the radiative insulation. In the case of a superconducting magnet quench, helium is discharged from the cold mass into the recovery line D through the safety relief valve (SRV).

The circuit at 50-75 K, lines E (supply) and F (return), will be cooled in the LHC by forced flow of gaseous helium. Line E cools the support posts and line F cools the thermal shield which represents a first heat intercept of the heat inleak from room temperature.

The CTM maintains the temperature levels envisaged for the LHC cryogenic system. It is not equipped with the safety relief valve (SRV) and its flow scheme can be found in reference 5.

For single-magnet and string tests, the 50-75 K circuits are cooled by saturated nitrogen around 80 K.

The budgeted heat loads^{8,9} for the prototype cryostats under steady-state nominal conditions at the three temperature levels are listed in Table 1.

Figure 2. Flow-scheme of the LHC prototype half-cell

Table 1. Distributed heat loads under steady-state conditions at nominal beam energy and luminosity. [$\text{W}\cdot\text{m}^{-1}$]

Heat load	50-75 K	4.5-20 K	1.9 K
Heat inleak	6.27	0.17	0.19
Resistive and beam-induced heating		0.71	0.17
Total	6.27	0.88	0.36

TEST CONDITIONS AND HEAT LOAD MEASUREMENT METHODS

Cryostat Thermal Model

The heat inleaks under nominal LHC operational conditions have been measured and a parametric sensitivity study aimed at identifying the most critical cryostat components has been carried out. The parameters varied were temperature, mass flow and residual gas pressure in the insulation space.

The first evaluation of steady-state heat inleak to the CTM cryostat was made without the contributions from the end boxes and additional components, such as safety valves and instrumentation feedthroughs. The residual gas pressure in the cryostat was 10^{-3} Pa and nominal temperatures on the cryogenic lines have been obtained with the following mass flows: 0.5 g/s at 50-75 K, 0.2 g/s at 4.5-20 and the 0.08 g/s at 1.9 K. Under steady-state conditions at 50-75 K the longitudinal temperature gradient in the thermal shield was less than 0.3 K/m. At 1.9 K the thermal gradient between the pressurized and the saturated helium was 100 mK and the longitudinal thermal gradient on the cold mass was below 50 mK under nominal operating conditions.

The mass-flow at each temperature level 4.5-20 K and 50-75 K and the inlet and outlet temperatures have been measured and the heat inleak on each of these cryogenic lines calculated from enthalpy balance. Maintaining the nominal residual gas pressure value the temperature of the circuit E-F has been varied from 50 K up to 150 K in steps of 10-15 K and the temperature of the circuit C-D from 4.5 K to 35 K in steps of 5-10 K. Off-design measurements were particularly difficult to control since the mass flows were low and as a consequence longer time was required to reach steady-state conditions.

Heat inleak to 1.9 K was determined firstly by measuring the steady-state mass flow-rate of vapour boil-off at 1.9 K, and secondly by evaluating the temperature drift with time of the quasi-isothermal helium II bath over the interval between 1.9 K and the lambda point, and calibrating it with an electrically applied heat source of known value.

Under nominal temperature conditions the vacuum has been degraded in steps from 10^{-3} Pa to 10^{-1} Pa by introducing dry helium gas into the cryostat insulation volume.

Single-magnet tests and string test

The single-magnet test heat load measurements have been carried out at zero magnet excitation under nominal steady-state conditions with the equipment for “warm” magnetic measurements in the apertures maintained at 1.9 K. The residual gas pressure was 10^{-4} Pa and the lines E and F were cooled by saturated nitrogen at 80 K.

String test heat loads have been measured at all the three temperature levels without current in the superconducting magnets. The temperature of the nitrogen circulating in the lines E and F varied between 85 K at inlet and 100 K at outlet.

CRYOSTAT THERMAL PERFORMANCE

Cryostat thermal model

Heat inleak measurements from the CTM are in agreement with those calculated. Table 2 lists the measured and the calculated heat inleaks of the cryostat in steady-state conditions without the contribution of the end boxes (which amounts to 40 W at 50-75 K, 4.2 W at 4.5-20 K, 0.1 W at 1.9 K).

The cryostat instrumentation permits the heat inleak contribution at 4.5-20 K and at 50-75 K from the end boxes to be separated from those of the cryostat.

Table 2. Measured and calculated heat inleaks under steady-state conditions

Heat inleak	50-75 K		4.5-20 K		1.9 K	
	Measured	Calculated	Measured	Calculated	Measured	Calculated
[W]	47.8±3	45.8	2.3±0.15	2.4	1.82±0.1	1.92
[W/m]	4.66±0.29	4.47	0.23±0.01	0.23	0.18±0.01	0.19

Heat flux, from 300 K to 50-75 K through the superinsulation only, was estimated to 32 W, corresponding to an average of 1.2 W/m^2 . Radiation heat inleak from 50-75 K to 4.5-20 K confirmed the value of 90 mW/m^2 already found during tests of multilayer reflective insulation¹⁰. The heat inleak to the cold mass from the support posts¹¹ has been maintained low by two heat intercepts at 10 K and at 85 K.

The cold-mass heat inleak is given by radiation from the thermal shield (line F) and conduction through the support posts (line C). Fig. 3 and fig. 4 show the heat inleak at 1.9 K as a function of the line C and thermal shield temperatures.

Heat inleak to 4.5-20 K depends on line E and line C temperatures by conduction through the support posts and line F temperature by radiation from the thermal shield. Fig. 5 shows the heat inleak at 4.5-20 K as a function of the thermal shield temperature.

Radiation from the vacuum vessel (line F) and conduction through the support posts (line E) constitute the main contributions to the heat inleak to 50-75 K. Fig. 6 shows the heat inleak to 50-75 K as a function of the thermal shield temperature.

Following a vacuum degradation the 1.9 K level is the most affected since in nominal steady-state conditions the heat transfer through the radiative insulation represents 80 % of the total heat inleak. Fig. 7 shows the heat inleak to 1.9 K as a function of the residual gas pressure.

Single-magnet tests and string test

Table 3 lists the heat inleaks at the three temperature levels measured in the single-magnet tests and in the string test under steady-state conditions. Heat inleak contribution from auxiliary components (end boxes, quench valves, warm bore anticryostats and current leads) largely exceed those from the cryostat and renders their measurements difficult. This justifies a posteriori the interest of the CTM for proper validation of cryostat design. The heat loads below were measured with a precision of around ± 5 %.

Table 3. Measured heat loads on single-magnet and string tests

Heat load	80 K [W]	4.5-20 K [W]	1.9 K [W]
Single-magnet tests (1 dipole+auxiliaries)	150	40	10
String test (2 dipoles+1 quadrupole+auxiliaries)	250	15	20

CONCLUSION AND FUTURE PROGRAM

Good agreement has been obtained between measured heat loads and those calculated over a large range of variation of parameters and all results lie within the limits imposed by the refrigeration capacity foreseen for the LHC project.

Future work will include evaluation of new types of superinsulation with a hard screen at 4.5-20 K and the performance of different thermal contacts will be investigated.

Figure 3. Heat inleak at 1.9 K versus line C temperature (residual gas pressure= 10^{-3} Pa, thermal shield temperature=75 K)

Figure 4. Heat leak at 1.9 K versus thermal shield temperature (residual gas pressure= 10^{-3} Pa, line C temperature=5 K)

Figure 5. Heat leak at 4.5-20 K versus thermal shield temperature (residual gas pressure= 10^{-3} Pa)

Figure 6. Heat leak at 50-75 K versus thermal shield temperature (residual gas pressure= 10^{-3} Pa)

Figure 7. Heat inleak at 1.9 K versus residual gas pressure (thermal shield temperature=75 K, line C temperature=5 K)

ACKNOWLEDGMENTS

The authors would like to thank the String Team, in particular B. Gaillard-Grenadier, Th. Goiffon and L. Serio for their support during the string heat load measurements.

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