EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 335

THERMAL PERFORMANCE OF THE SUPPORTING SYSTEM FOR THE LARGE HADRON COLLIDER (LHC) SUPERCONDUCTING MAGNETS

M. Castoldi,[1] M. Pangallo,[2] V. Parma,[1] and G. Vandoni[1]

Abstract

The LHC collider will be composed of approximately 1700 main ring super-conducting magnets cooled to 1.9 K in pressurised super-fluid helium and supported within their cryostats1,2 on low heat in-leak column-type supports3. The precise positioning of the heavy magnets and the stringent thermal budgets imposed by the machine cryogenic system, require a sound thermo-mechanical design of the support system. Each support is composed of a main tubular thin-walled structure in glass-fibre reinforced epoxy resin, with its top part interfaced to the magnet at 1.9 K and its bottom part mounted onto the cryostat vacuum vessel at 293 K.

In order to reduce the conduction heat in-leak at 1.9 K, each support mounts two heat intercepts at intermediate locations on the column, both actively cooled by cryogenic lines carrying helium gas at 4.5-10 K and 50-65 K.

The need to assess the thermal performance of the supports has led to setting up a dedicated test set-up4,5 for precision heat load measurements on prototype supports.

This paper presents the thermal design of the support system of the LHC arc magnets. The results of the thermal tests of a prototype support made in industry are illustrated and discussed. A mathematical model has been set up and refined by the comparison with test results, with the scope of extrapolating the observed thermal performance to different geometrical and material parameters. Finally, the calculated estimate of the heat load budgets of the support system and their contribution to the total cryogenic budget for an LHC arc are presented.

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Presented at the 1999 Cryogenic Engineering and International Cryogenic Materials Conference
(CEC-ICMC'99), 12-16 July 1999, Montreal, Canada

Administrative Secretariat
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Geneva, 1 December 1999

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ABSTRACT

The LHC collider will be composed of approximately 1700 main ring super-conducting magnets cooled to 1.9 K in pressurised super-fluid helium and supported within their cryostats[1,2] on low heat in-leak column-type supports[3]. The precise positioning of the heavy magnets and the stringent thermal budgets imposed by the machine cryogenic system, require a sound thermo-mechanical design of the support system. Each support is composed of a main tubular thin-walled structure in glass-fibre reinforced epoxy resin, with its top part interfaced to the magnet at 1.9 K and its bottom part mounted onto the cryostat vacuum vessel at 293 K.

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INTRODUCTION

Accurate supporting and stable positioning of the LHC super-conducting magnets within their cryostats (Figure 1) is essential for the machine alignment which is carried out through surveying and aligning of cryostat-mounted fiducials. High stiffness (mainly flexural) of the supports is therefore the basic mechanical requirement to guarantee that magnets are stable

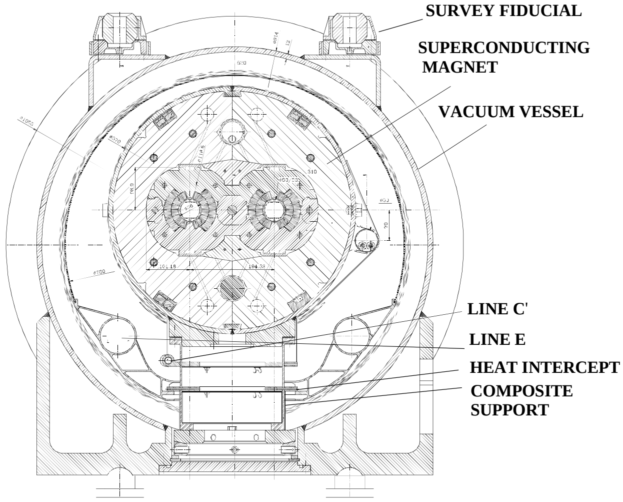

Figure 1. Cross-section of an LHC super-conducting magnet within its cryostat

within 0.3 mm under variation of external forces (magnet interconnection forces, weight components due to cryo-magnet inclination, etc.). A three-point support configuration is adopted for the 1300 15 m-long, 25,000 kg dipole magnets, whereas two points of support are sufficient for the 400 quadrupoles which are shorter (6 m-long) and lighter (6,000 kg).

To limit conduction heat in-leaks from the cryostat vacuum vessel at room temperature to within specified maximum values per support (<0.05 W to the magnets at 1.9 K, <0.5 W to the cryogenic line C' at 4.5-10 K, <5 W to the cryogenic line E at 50-65 K), materials featuring a low thermal conductivity-to-stiffness modulus ratio are required.

CHOICE OF THE MATERIAL

A wide variety of low thermal conductivity plastic materials, ranging from charged thermo-plastics to carbon or glass fiber reinforced epoxies, were tested at CERN during several years of R&D[6]. For tubular thin-walled structures of a given diameter, as for LHC supports, both conduction and flexural stiffness are proportional to the wall thickness therefore the merit figure can be expressed in terms of the conductivity-to-flexural modulus ratio. Figure 2 compares this ratio, in the 300-4 K range, of two among the best performing candidate materials, ULTEM 2300® (a short glass-fiber reinforced PEI resin) and G-10 (a long glass-fiber reinforced epoxy) with a more conventional material such as stainless steel.

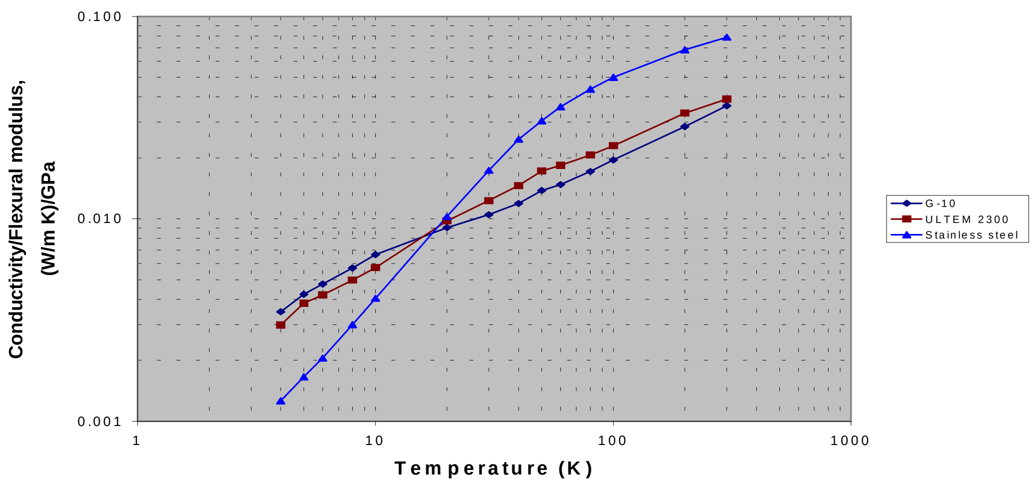

Figure 2. Thermal conductivity/flexural modulus versus temperature

Although stainless steel exhibits the best performance at very low temperatures, high thermal conductivity above 20 K limits its range of application for LHC supports. ULTEM 2300®, featuring very low thermal conductivity across the full temperature range, is however penalised by a low stiffness; when compared with glass-fiber reinforced epoxy composites, whose stiffness is more than twice as high, the resulting conductivity-to-stiffness ratios are of the same order across the temperature range of interest. However, the higher sensitivity of thermo-plastics to creep, unlike the more stable thermo-sets, limits the allowable stress for ULTEM supports, leading to higher thickness of the columns thus thermally less performing.

Therefore, glass-fiber epoxy composite is the material retained for the LHC supports. The wide availability of manufacturers in European industry, should assure a competitive market for the mass production of supports. Among all manufacturing processes, industrialisation experience suggests the use of hand lay-up of pre-preg material processed in autoclave or Resin Transfer Moulding (RTM). The latter presents the advantage of being highly automated reducing production costs, despite a large initial investment in tooling, and improving the quality control over the production of some 5000 supports required for LHC. Testing on prototypes at CERN confirmed that long glass-fiber in epoxy, with a 50-60% volume fraction of fiber, allows the required stiffness properties to be achieved.

However, thermal conductivity in composites is characterised by a wide dispersion depending on the properties of its constituents (fiber and resin) and on the composition of the material (lay-up, volume fraction of constituents, fibre orientation, etc.). Figure 3 reports data for glass-fiber epoxy composites available in literature and the estimated thermal conductivity for an LHC prototype support, reconstructed from test measurements as explained in this paper. The stringent cryogenic budgets demand a precise characterisation of the thermal performance of the supports, which requires qualification testing of prototypes at CERN.

THERMAL DESIGN

The maximum available vertical space between magnet and vacuum vessel, together with compatibility with integration and assembly constraints, limits the support height to 213 mm, whereas

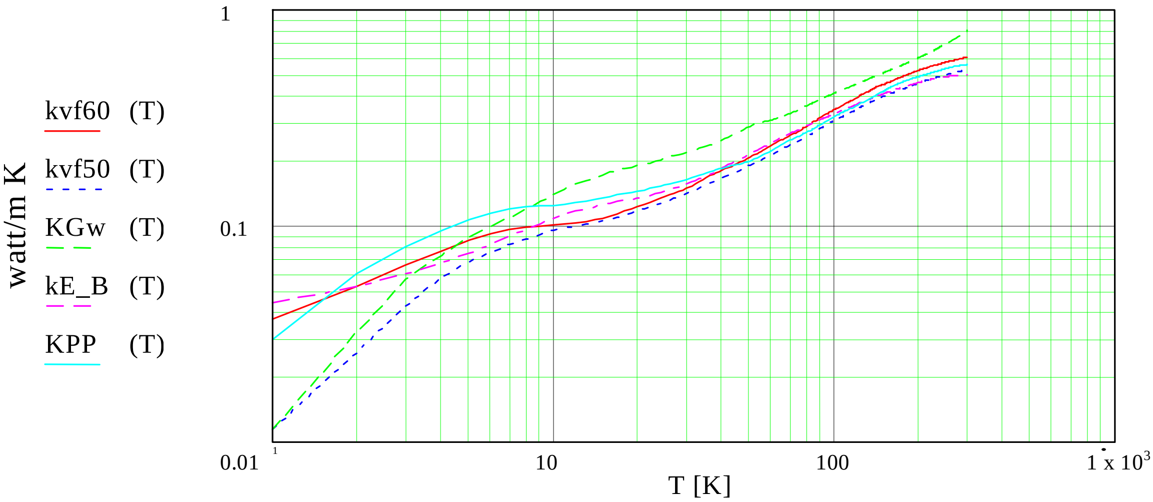

Figure 3. Thermal conductivity for various epoxy based composites versus temperature:

Gw:	G-10
E_B:	Glass fiber, E glass and B resin
vf50:	Glass fiber Vf = 50%
vf60:	Glass fiber Vf = 60%
PP:	Extrapolated conductivity for prototype dipole support

the diameter and thickness of 240 mm and 4 mm respectively, are defined by the stiffness constraints already discussed.

Cryogenic lines C' and E, run through each LHC cryogenic sector of 3.3 km length providing cooling capacity to the cryostat and the supports by helium gas flow. Line C' provides cooling between 4.5 K and 10 K whereas line E operates between 50 K and 65 K, depending on the location considered along the sector.

A reduction of conduction heat to the magnet, to meet the cryogenic requirement at 1.9 K, is obtained by extracting heat at two intermediate sections of the support, by so called *heat intercepts*, cooled by the lines C' and E. For the thermal design of the supports, the C' and E lines are considered at average temperatures of 7.5 K and 57.5 K, respectively.

The optimal spacing of the heat intercepts along the support is chosen to minimise the cryogenic cost function expressed by equation 1, which uses weight factors, suitably chosen for LHC, expressing the power required for extracting heat at 1.9 K, 5-10 K and 50-65 K:

$$Q_{tot} = (Q_{1.8K}\cdot 1000+Q_{5\text{-}10K}\cdot 125+Q_{50\text{-}65K}\cdot 15)\ \ [\mathrm{W}] \tag{1}$$

The heat intercepts are 10-mm thick aluminium plates externally glued to the composite column, and connected to the cryogenic lines by an all-welded solution for the aluminium line E, and a low-thermal-impedance aluminium-to-stainless steel transition for line C'. The heat intercepts shrink fit onto the composite column during cool down assuring an improved heat exchange due to contact pressure. However, an unavoidable thermal impedance exists at this interface, resulting in a not fully efficient heat extraction. This effect was measured during testing and mathematically modelled as explained in the following sub-section.

Aluminised Mylar foils, between the line E heat intercept and the vacuum vessel, are used to insulate the composite material from radiation in-leaks from the vacuum vessel at room temperature. With the same purpose, aluminium foil disks are also mounted inside the support column at the level of the heat intercepts.

Calculation Model and Results

With the aim of supporting and checking the measurements campaign on a prototype dipole support, a mathematical model has been set up[7]. This is a lumped-parameter model for a simplified geometry of the supports, which takes into account non linear solid conduction through the composite column and its aluminium heat intercepts, and radiation heat transfer at temperatures above 50 K. An analytical and non linear formulation for the steady state heat transfer was used, leading to a system of equations of an equivalent electrical network, as shown in Figure 4. An iterative finite difference algorithm applied to a step-wise linearized system of equations, leads to the simultaneous solution of the heat loads at the nodes.

The model also allows, by simple parameter changes, to estimate heat loads for supports having different geometry (as for the quadrupole magnets) or having different boundary condition temperatures. This last feature permits the extrapolation of the heat loads for a support in any point of a cryogenic sector, or the heat loads induced by a faulty heat intercept operating at a higher temperature. Moreover, the model also yielded a useful tool for tuning of the thermal design of the supports.

Due to the lack of data on the thermal conductivity of the composite material used in manufacturing the prototype support, the conductivity curve (see Figure 3) was reconstructed and fine-tuned to meet reliable measurement results obtained from the test set-up. 10 measurement points, covering most of the operating temperature range of a support in a cryogenic sector, were used with the aim of minimising the error between calculated and measured heat loads. The values for some of these working points are displayed in Table 1.

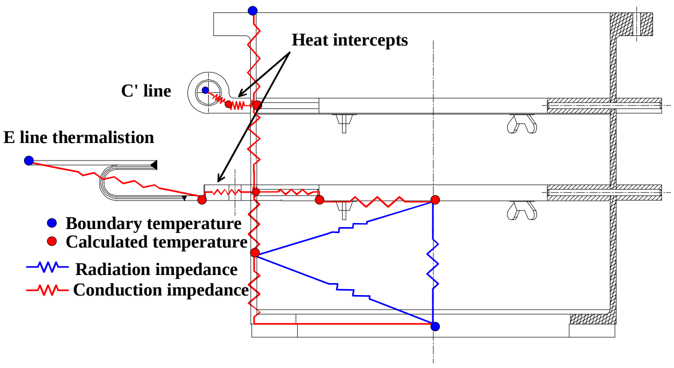

Figure 4. Equivalent electrical network of the calculation model

Table 1. Measured and calculated heat loads for the dipole support post.

		Measurements				Calculation			
		Magnet	C' line	E line	Vacuum Vessel	Magnet	C' line	E line	Vacuum Vessel
1	T [K]	1.63	6.8	76	288	1.63	6.8	76	288
	HL[W]	**0.051**	**0.716**	**6.69**		**0.056**	**0.639**	**6.90**	
2	T [K]	2.19	19.6	94	289	2.19	19.6	94	289
	HL[W]	**0.171**	**-**	**7.09**		**0.159**	**0.688**	**6.61**	
3	T [K]	1.67	6.55	53.3	295	1.67	6.55	53.3	295
	HL[W]	**0.036**	**0.379**	**7.82**		**0.046**	**0.433**	**7.75**	
4	T [K]	1.87	17.43	52.0	296	1.87	16*	52.0	296
	HL[W]	**0.112**	**-**	**8.01**		**0.116**	**0.312**	**8.04**	
5	T [K]	1.83	7.33	95.3	299	1.83	7.33	95.3	299
	HL[W]	**0.070**	**0.880**	**7.14**		**0.068**	**0.876**	**7.29**	

It appears that the model remains affected by a residual error which, for the majority of the measurements, is below 10% and for only few cases, when the magnet temperature in the test set-up is below 1.9 K, is up to 25%, due to the uncertainty of the conductivity curve in that temperature range.

The measurements demonstrate the imperfection of the heat intercepts. Working points 1, 3 and 5 show similar temperatures on the magnet and C' line, however, the heat load to the magnet are quite different, and corresponds to the scaling between the temperatures on the E line, indicating that the C' line intercept is not fully effective in intercepting the heat.

Figure 5 shows the temperature profiles along the column with or without heat intercepts, whereas Table 2 presents the corresponding calculated heat loads breakdown and the total required cryogenic power. It can be concluded that the double heat intercept solution

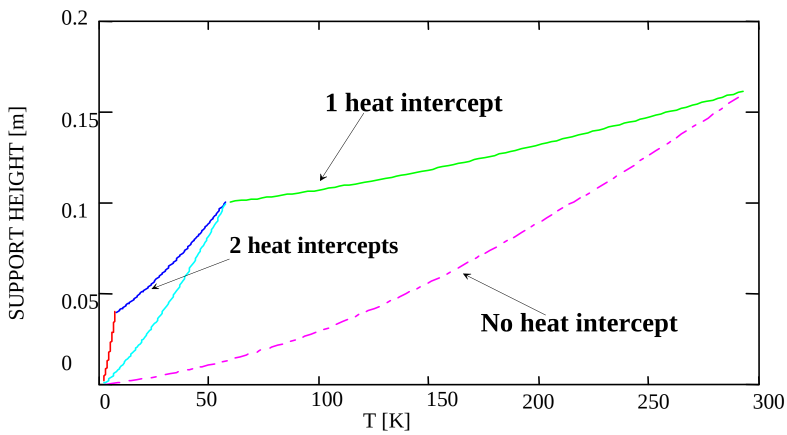

Figure 5. Temperature profiles along the support

Table 2. Calculated heat loads for various heat intercept configurations

	Q_{magnet} [W]	$Q_{c'line}$ [W]	Q_{Eline} [W]	Q_{tot} (exergetic) [W]
No heat intercept	2.06	-	-	2060
1 heat intercept	0.27	-	7.1	378
2 heat intercepts	0.049	0.45	7.1	212

provides a cost reduction by a factor 1.8 and 10 as respectively compared to the simpler alternatives of having only one heat intercept at the C' line, or no heat intercepts at all.

Figure 6 shows the calculated heat loads to the magnet over the full temperature range of the cryogenic lines, underlining the importance of having an efficient C' line thermalisation, to limit these heat loads. The somewhat weak correlation of heat loads with the temperature of line E, for a given C' line temperature, visible in the diagrams, is due to the partial efficiency observed for the heat intercept. Finally, calculation indicates that the effect of radiation at temperatures higher than 50 K up to the ambient temperature of the vacuum vessel, is responsible for approximately 50% of the total heat leak.

Cryogenic Test Set-up

In order to simulate the thermal behaviour of the support posts, the test set-up should reproduce as closely as possible their working environment in the dipole cryostat. Unavoidably, the measuring device perturbs this working environment, hence a compromise has to be made between measurement precision and perturbation induced on the working conditions. In the present set-up, illustrated schematically in Figure 7, heat-flow measuring devices, so called heat-meters, are mounted between the heat intercepts of the support and the heat sinks, representative of cryogenic lines E and C'. A heat-meter is a calibrated thermal impedance which measures a temperature difference induced by the heat flow. This additional thermal impedance inserted between the intercepts and the heat sinks slightly shifts the working temperature of the support intercepts, so a correction of this effect needs to be taken into account.

The support is mounted into a vertical cryostat consisting of a central cylindrical vessel which is surrounded by two annular concentric vessels; the internal one is the saturated HeII vessel, the other two are filled with HeI and with LN2 or with gaseous helium. Two radiation screens are suspended from the bottom of the two annular vessels. They can be cooled by conduction, or actively by a gaseous helium flux taken from the HeI vessel.

Each heat intercept of the support post is connected to the shields through two heat-meters. The bottom flange of the support post is bolted to an aluminium plate, which is maintained at 293 K by a resistive heater. Adequately tightened bolts and use of vacuum grease reduce thermal contact impedance. The comparison between the power applied to the

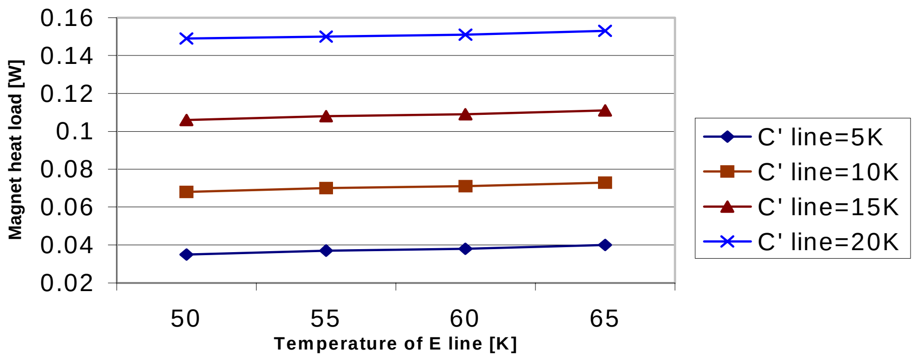

Figure 6. Magnet heat loads as a function of C' and E line temperatures

heater and the sum of the heat flows measured on the heat-meters provides a crosscheck of the the measurement precision, helping in detecting parasitic thermal leaks. The temperature sensors are mounted on the shields at the connection of the aluminium straps, or on the plate closing the support towards the 1.9 K heat sink. Tests were made with temperatures ranging from 7 K to 20 K, and from 50 K to 95 K at the C’ and E line shields respectively, while the magnet and vacuum vessel interfaces were kept at around 2 K and 293 K, respectively.

Some problems were encountered during the tests. The heat-meters at the C’ line level are equipped with carbon resistor sensors, whose sensitivity at 20 K is very low ($dR/dT = 5.5\ \Omega/K$). The error on their reading at this temperature is therefore very high, and their calibration not reliable. Also, the time required by the support posts to reach thermal equilibrium is very long (~10 h) and comparable to the operating time of the cryostat itself, raising stability problems. Nevertheless, data points show a very good reproducibility (1%). The heat-meter error varies between 2 and 10%, depending on the temperature range. Parasitic thermal leaks could be kept below 1%, and the error arising from non-equilibrium conditions is also smaller than 1%. Globally, the relative error on one data point can fluctuate between 4 and 15%.

HEAT LOAD BUDGETS FOR AN LHC ARC

The heat load budget, for the supports of an LHC arc, are calculated using the model presented, calibrated on the tested prototype support, and on the basis of average temperatures of the C’ and E lines. Their contribution over the total budget for an LHC arc is shown in Table 3.

Some design improvements were introduced to the dipole supports since the measurements were made, namely an increase by 3 mm of the composite column height and a change in the position of the E line heat intercept. The values presented include these changes.

It can be observed that the heat loads at 1.9 K represent only 4% of the total at this temperature, which is however compensated by the heat intercepted at the cryogenic lines where cooling cost is lower. Globally the corresponding cost of total heat extraction is around 60 kW per arc.

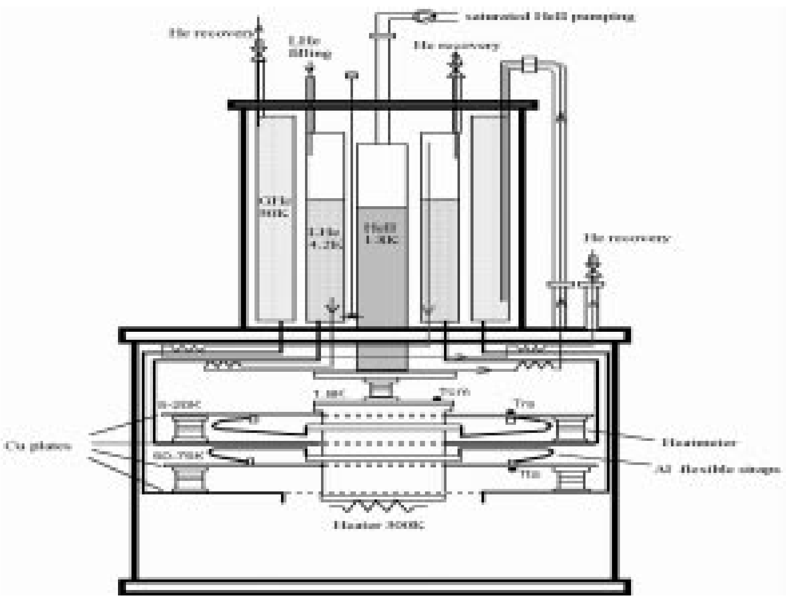

Figure 7. Schematic of a support in the cryogenic test set-up

Table 3. Calculated heat loads for an LHC arc

	No of units	Heat Load to magnet (1.9 K) [W]	Heat Load to C' line (4.5-10 K) [W]	Heat Load to E line (50-65 K) [W]
Heat Load per Dipole support	462	0.049 ±10%	0.45 ±10%	7.1 ±5%
Heat Load per Quadrupole support	108	0.047 ±10%	0.42 ±10%	7.2 ±5%
Totals	570	27.7 ±10%	253 ±10%	4057 ±5%
% of total arc static heat loads		4%	35%	31%

CONCLUSIONS

The LHC magnet supports are designed to fulfil minimum stiffness requirements to guarantee stability of the magnets within their cryostats. The achievement of the stringent cryogenic requirements imposes the use of low thermal conductivity-to-stiffness ratio materials for the tubular thin-walled supports. An intense R&D phase has led to the selection of glass-fiber epoxy resin composite. The thermal performance of each support is improved by two optimally spaced heat intercepts, obtained by aluminium plates shrink fitted onto the composite column, extracting conduction heat to cryogenic lines at intermediate temperatures.

Precision measurements on a dedicated test bench have been carried out on a prototype dipole support, allowing the characterisation of its thermal properties. A calculation model, tuned on test results from a prototype support, is used to estimate the heat loads of the supports across the full range of operating temperatures in an LHC arc, allowing the estimate of heat load budgets. Over the total heat loads of an arc, the support system contributes by only 4% at 1.9 K, but 35% and 31% of the total loads at 4.5-10 K and 50-65 K respectively, is the cost of heat extraction through the intercepts.

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