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DESIGN OF THE SECOND SERIES 15 m LHC PROTOTYPE DIPOLE MAGNET CRYOSTATS

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Abstract

A first series of six LHC 10 m long prototype dipole magnets and cryostats have been manufactured in European Industry and the assembled cryo-magnets tested singly and connected in series in a test string at CERN between March 1994 and December 1996. During the same period, an evolution in the requirements for LHC cryogenics distribution has lead the project management to adopt a separate cryo-distribution line running parallel to the LHC machine¹. The former standard LHC half-cell, made up of a short straight section unit and four 10 m dipoles, has been discarded and replaced with one composed of a short straight section unit and three 15 m dipoles. The new 15 m LHC dipole magnet cryostats are described. These units house the dipole magnet cold mass standing on three low heat in-leak support columns, and enclosed within an actively cooled radiation screen operating at 4.5-20 K and an actively cooled thermal shield operating at 50-75 K.

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INTRODUCTION

Following project approval in December 1994, CERN is undertaking the design and construction of the Large Hadron Collider (LHC)² as the next important step in its future scientific program. This new facility, enabling the collision of protons at energies in the multi-TeV range, will mainly consist of a double ring of advanced technology super-conducting magnets which will be installed in the existing LEP tunnel of 27 km circumference. The dipole magnets are of a twin-aperture design and about 15 m long producing bending fields in the 8 to 9 T range. For this purpose, they use Nb-Ti superconductors and operate at temperatures below 2 K. In order to test these magnets, the related cryogenics and the other components of the LHC under realistic operating conditions, CERN has ordered a number of full scale super-conducting dipole cryo-magnets from European industry and will install and operate them in a prototype 107 m long String representing an LHC full cell.

The cryo-magnet operates in a bath of pressurised super-fluid helium at a pressure close to atmospheric and at temperatures below 2 K. The magnet String will allow the verification of magnetic performance as well as the thermal and mechanical behaviour of a long cryogenic system operating with super-fluid helium.

The cryostat must provide a stable platform for the cold mass while maintaining heat in-leaks at a level matching the stringent heat load budget of the LHC. It must survive the thermo-mechanical transients associated with rapid cool-down or warm-up, with a magnet resistive transition (quench) and due to a loss of insulation vacuum and must be simple and economic to manufacture in large numbers.

The *Dipole Magnet*³ enclosed in its all welded *Helium Vessel* with heat exchanger and cold-bore tubes, forms the *Dipole Cold-Mass*. The *Cryostat* of the dipole magnet consists of three *Support Posts* to position the cold-mass, a *Radiation Screen* and a *Thermal Shield* both equipped with multi-layer super-insulation, and a *Vacuum Vessel*.

The dipole cold-mass assembled into the cryostat forms the *Cryo-Dipole Magnet*.

Figure 1 shows a cross-section of the LHC 15 m dipole cryo-magnet in the plane of an extremity support post.

Similar cryostats have been designed for the LHC Short Straight Section (SSS) units.⁴

Figure 1. Cross-Section of the LHC 15 m Dipole Cryo-magnet Assembly

DIPOLE COLD MASS

The cylindrical LHC dipole cold mass of length 15.2 m and diameter 0.57 m, weighs about 25000 kg and during manufacture is curved about a vertical axis to a radius of 2700 m leading to a horizontal sagitta from end to end of 11.3 mm. Inside the cryostat, it is supported at three points along its curved axis, one at the mid length, the others being positioned as a compromise between minimizing vertical sagitta, rendering the cold mass approximately horizontal at its ends to ease interconnect assembly and minimizing overhang outside the end supports to simplify magnet to magnet alignment. Maintaining the vacuum vessel wall thickness and mid length deformation under load within reasonable limits was also taken into account. These conditions require three internal supports located 5.4 m apart. The cold mass applies loads through the support posts to the vacuum vessel of 7800 kg at each end and 9400 kg at the mid-plane.

To minimize heat transfer by radiation the outer surface of the cold mass is closely wrapped with one foil of double aluminized polyester Mylar™, reflective material.

INTERCONNECT

The electrical, cryogenic and vacuum circuits of successive dipole cryo-magnets are linked across the interconnect via stainless steel flexible bellows, which compensate for maximum thermal contractions between room and operational temperatures of about 48 mm between the longitudinally fixed central supports of neighbouring units. To permit cryo-magnet alignment in the LHC tunnel, the flexible components of each interconnect allow displacements of up to ± 4 mm in any direction perpendicular to the particle beam axes.

Table 1 lists the interconnect temperatures and pressures associated with various operating modes.⁵ All pipe-work installed in the interconnect region is in austenitic stainless steel with the exception of that linking the 15 mm internal diameter radiation screen cooling circuits, which at present terminates at one end with an Al 6060 single turn expansion loop instead of an aluminum to stainless steel transition and conventional bellows.

The finally adopted design will depend on the results of process validation, currently underway at CERN, for the helium leak-tight butt welding of these aluminum tubes in the tunnel.

A specified fatigue life of 500 cycles combined with the operational pressure and temperature fluctuations has often imposed the use of multi-wall bellows. This leads to an overall interconnect stiffness of 890 N/mm longitudinally and 800 N/mm radially.

To avoid further complicating the interconnect, both the radiation screen and the thermal shield are attached to, and fixed laterally and vertically by, the two support posts at the cold mass extremities. On each side of the interconnect, these fixing points lie about 2.2 m inboard from the flexible bellows located in the thermal shield cooling circuit. Under the most unfavorable operating conditions, lateral and vertical stiffness with a safety factor of six to resist buckling instability of the flexible bellows has been incorporated into the thermal shield lower tray.⁶

As short as possible to maximize bending magnet occupancy in the LHC, each interconnect requires 20 stainless steel and 1 aluminum tube welds and relies on compact orbital tube cutting and welding equipment for initial assembly and maintenance.

Table 1. Operational pressures and temperatures

Component	Dipole cold mass					Interconnect			
	DN	T ₀	P ₀	P _Q	P _C	T ₀	P ₀	P _Q	P _C
	[mm]	[K]	[bar]	[bar]	[bar]	[K]	[bar]	[bar]	[bar]
50/75 K Circuit	80					50/75	19	19	19
He-He heat exchanger	54	1.8	0.016	1.3	1.3	1.8	0.016	1.3	1.3
Bus bar tubes	80					1.9	1.3	19	10
5/20 K Circuit	15					4.6	3	3	20
He vessel	570	1.9	1.3	19	10				
Beam tubes	49	1.9	1e-14	1e-14	1e-14	1.9	1e-14	1e-14	1e-14
Vacuum vessel	914	293	1e-9	1e-9	1e-9	293	1e-9	1e-9	1e-9

Where T₀ is the normal operating temperature, P₀ the normal operating pressure, P_Q the pressure during quench, P_C the pressure during cool-down and DN the nominal tube diameter.

VACUUM VESSEL

To contain the dipole stray field and reduce costs, the vacuum vessel shell is based on standard straight pipeline elements of outer diameter 914 mm (36") and wall thickness 12 mm in construction steel with end and auxiliary flanges in stainless steel AISI 304L. In case of a sudden loss of insulation vacuum, local cooling of the vessel shell to about 230 K may occur.⁷ A minimum energy absorption of 28 J/cm² according to ISO standards during a Charpy impact test at 240 K is specified to qualify the vacuum vessel steel against low temperature embrittlement.

These standard tube dimensions are chosen as a compromise between providing adequate resistance to bending under the cold mass loads, keeping the total cryo-dipole mass less than

35000 kg and leaving sufficient space beneath the vacuum vessel to locate three adjustable floor mounted jacks to permit cryo-magnet alignment.

Three vertical through-penetrating flanges are positioned to locate the support posts, support the cold mass and maintain its maximum static deflections to less than 0.3 mm. On each side of these three flanges two welded annular reinforcements strengthen the vacuum vessel shell against ovalization. Lower 'U' shaped reinforcing elements, welded between the annular reinforcements provide hard points for external supports and carry lateral lifting plates for handling. Upper support angles locate alignment fixtures.

A captive flange behind the front end flange permits connection to a de-mountable sliding sleeve which encloses the interconnect region. This sleeve consists of two flanges separated by a tube incorporating two bellows, each of three corrugations.

Four ISO DN100 and one ISO DN160 standard flanged ports are distributed around the vessel circumference at one end. During normal operation, the vessel contains a static insulating vacuum below 10^{-6} mbar and, in the event of a cryogenic leak, serves as a containment vessel up to a pressure of 0.4 bar above atmosphere at which point a pressure relief valve on the vessel wall opens.

SUPPORT SYSTEM

The cold mass to vacuum vessel vertical eccentricity of 80 mm together with the vacuum vessel inner diameter of 890 mm leads to an overall support column height of 210 mm. As a compromise between minimizing heat in-leaks and providing adequate stiffness, the support column consists of a glass-fiber/epoxy long fiber lay-up tube of 4 mm wall thickness and outer diameter 240 mm. Top and bottom flanges interfacing to the cold mass and the vacuum vessel are molded as an integral part of the composite column. These dimensions and composite technology have been selected to minimize shear and bending deflections and consequent cold mass lateral and tilt displacements due to parasitic forces induced by the interconnect bellows.

Each column is designed to withstand a worst case combined loading due to cold mass weight and unbalanced interconnect and vacuum forces of 125 kN in axial compression and 40 kN in shear. The column, when equipped with two intermediate heat intercept plates, becomes a support post. The upper and lower plates support and are thermalized to the radiation screen and the thermal shield respectively. The support system⁸ consists of three identical support posts fixed to the cold-mass along its curved median plane, the middle post is blocked longitudinally and slides laterally on closely toleranced guiding devices located in the vacuum vessel, the other two, located in a similar manner, are free to slide longitudinally.

THERMAL INSULATION SYSTEM

The thermal insulation system consists of two actively cooled shields, the thermal shield operating at 50-75 K and the radiation screen operating at 4.5-20 K.

THERMAL SHIELD

The thermal shield lower tray is extruded from Al 6060 in one 15 m length complete with two 80 mm diameter channels for the passage of helium coolant. One only of these channels is used for cooling and requires an aluminium to stainless-steel pipe transition at each end for connection to

interconnect expansion bellows. The other provides vertical bending stiffness. Three machined features in the extrusion allow it to be blocked to the central support post lower flange and constrained to slide longitudinally on the end support lower flanges. Each support post lower flange is thermalized to the lower tray via flexible aluminium straps welded at each end.

Divided into a minimum of five longitudinal sections, the roughly circular upper shell part allows ease of assembly and during asymmetric cool-down and warm-up, it limits overall deflections and reduces stresses on the support posts. Industrially pure aluminium sheets 2.5 mm thick to ISO Al 99.0, (equivalent to AA 1100), for the upper sections provide adequate thermal conductivity. The upper sections are slotted into the bottom tray and then intermittently welded in place over 20 % of the total length, to ensure adequate circumferential heat conduction under steady state conditions whilst limiting thermo-mechanical transient deflections during rapid cool-down and warm-up.⁹

The thermal shield together with extension pieces covering the interconnect region are covered with multi-layer reflective super-insulation, made of 30 layers of double aluminised polyester Mylar™, or equivalent film with an adequate spacer material.

RADIATION SCREEN

Very similar to the thermal shield, the radiation screen is attached and thermalized to the upper flanges of the three support posts and is completed in the same manner, with at least 5 roughly circular upper sections 2 mm thick slotted into place and welded intermittently.

These upper sections envelop the cold mass, leaving only a small (around 6mm) radial gap which under normal circumstances should remain at all times. As a precaution, each upper section is equipped with carbon composite studs to promote point contacts and minimise thermal shorts between the radiation screen and the cold mass.¹⁰

During a magnet quench, the close proximity of the radiation screen means that the rapid collapse of the dipole field will induce short term forces and displacements in its structure. The integrity of the radiation screen under this loading has been verified.¹¹

The radiation screen together with extension pieces covering the interconnect region are covered with multi-layer reflective super-insulation, made of 10 layers of double aluminised polyester Mylar™, or equivalent film with an adequate spacer material.

THERMAL PERFORMANCE

Heat in-leak measurements¹² on a full scale cryostat thermal model of previous prototype LHC dipole cryo-magnets¹³ indicate that heat in-leaks to the cold mass at 1.9 K can be reduced by including a second “hard” radiation screen manufactured in high thermal conductivity aluminium alloy and actively cooled to temperatures between 4.5 K and 20 K.¹⁴

Table 2 shows estimated heat loads for the cryostat configuration as shown in Figure 1 incorporating a thermal shield and a radiation screen both actively cooled. The thermal performance of this cryostat will be fully measured under both nominal and accidental LHC operating conditions towards the end of 1997.

Table 2. Heat load estimates for one 15 m LHC dipole cryostat and interconnect

Component	Average heat loads (Watts)		
	300 K to 50/75 K	50/75 K to 4.5/20 K	4.5/20 K to 1.9 K
<u>Cryostat</u>			
Thermal shield	43.7		
Radiation screen		1.57	
Cold-mass			0.058
Support System	17.3	2.58	0.069
Total Cryostat	61.0	4.15	0.127
<u>Interconnect</u>			
Thermal shield	3.3		
Radiation screen		0.12	
Cold-mass interconnect			0.004
Diagnostic feed-through			0.39
Total Interconnect	3.3	0.12	0.394
Total	64.3	4.27	0.521

STATUS

In December 1996, orders were placed with three firms in European Industry for the manufacture of five 15 m LHC dipole cryostats. These cryostats will be assembled with dipole cold masses and delivered to CERN between October 1997 and March 1998 for performance tests on the magnet test bench.

CONCLUSIONS

Incorporating experience gained during the manufacture and testing, both on the single magnet test bench and when assembled into a half cell, of the first series of 10 m LHC prototype dipole cryo-magnets, a new generation of 15 m LHC dipole cryostats has been designed.

This new design is fully adapted to the 15 m curved dipole cold-mass specified for the LHC machine and is compatible with the revised LHC cryogenic distribution scheme.

To simplify the industrialization process that must precede the series production, a full quality control procedure has been established for the five units currently under manufacture and emphasis has been placed on the selection of standard industrial components and materials.

LHC dipole and short straight section cryostat designs have evolved in parallel and have been constrained to use common components wherever possible.

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