DESIGN OF LHC PROTOTYPE DIPOLE CRYOSTATS

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The current design of the LHC prototype dipole magnet cryostat is described. An overview of the basic components and their thermal and mechanical behaviour is given. As a first step four of these prototype cryomagnets will be connected in series in a test string to allow detailed cryogenic, mechanical and magnetic measurements to be undertaken at CERN. Each cryostat vacuum vessel houses a dipole magnet cold mass assembly inside its helium vessel, roughly 10 m long, weighing about 16 tonnes and standing on two low heat inleak support posts. All cryogenic piping required for heat interception at intermediate temperature levels and interconnection to adjacent units pass through the cryostat. The cold assembly is enclosed in two thermal insulation systems, the radiative insulation and a gaseous helium-cooled thermal shield, to intercept incoming radiative and conductive heat.

1. INTRODUCTION

CERN is currently undertaking design studies and development work leading towards the future Large Hadron Collider (LHC) project [1]. This multi-TeV range collider will consist of a single ring of twin-aperture magnets using NbTi superconductors operating in pressurized superfluid helium at temperatures below 2 K. Today's prototype dipole magnets [2] are about 10 m long, 560 mm diameter with an interaperture distance of 180 mm and are enclosed and precompressed in a 10 mm thick stainless steel skin which, when closed at the ends forms the cold mass and also becomes the helium vessel.

The **cold mass** is assembled into the **cryostat** consisting of a support system, the cryogenic piping, the radiative insulation and the thermal shield, and the vacuum vessel altogether forming the **cryomagnet**.

While providing a stable mechanical support for the magnet cold mass, the cryostat must limit the heat inleaks to a level matching the tight heat load budget of the LHC. It also incorporates all pipework required for distributing refrigeration in the cryomagnet string. It must withstand the thermal and mechanical transients associated with rapid cooldown and magnet quench and should favour economic straight-forward manufacture on a large scale basis. Fig. 1 shows a cross-section of the LHC prototype dipole cryomagnet assembly. Many design features are based on the twin-aperture prototype (TAP) magnet, currently the only full-scale cryomagnet of this type [3, 4]. Two thermal intercepts at 5 to 10 K and 50 to 70 K insulate the cold mass below 2 K.

Several full scale dipole magnets assembled into their cryostats have been ordered from European industry. Following individual magnet tests, four dipole and one quadrupole cryomagnets will be built into a prototype half-cell string to permit a first simulation of realistic operating conditions. In particular, the cryogenic performance of such a cryomagnet both at individual test and in the string will be carefully investigated [5].

2. SUPPORT SYSTEM

The same support system is envisaged for both dipole and quadrupole magnets leading to a worst case combined design loading on each support post of 90 kN in axial compression and 50 kN in shear. These loads are due to a combination of cold mass weight and reactions due to unequal interconnect forces and vacuum sector valve closure.

As a compromise between minimizing heat inleaks and adequate mechanical strength the support post consists of a six-layer filament wound epoxy glass cylindrical tubular column 240 mm outside diameter 232 mm high and 6 mm wall thickness [6]. Upper and lower stainless steel plates, glued to the support post, interface to the cold mass and vacuum vessel. Two intermediate heat intercept plates, the lower of which supports the thermal shield, are shrink fitted and glued to the support posts. Using a removable assembly trolley however the present LHC design separates the functions of cold mass installation and assembly. Once positioned threaded rings transfer the cold mass weight from the assembly trolley to the vacuum vessel.

The position of one fixed support post is defined by a tight tolerance machined location in the vacuum vessel. Differential contraction between the cold mass and the vacuum vessel is allowed by a sliding plate incorporating low friction polyethylene material and a tightly controlled lateral guidance at the warm end of the second post. Internal elements in stainless steel and external elements in aluminium alloy allow reliable shrink fitting while applying minimal radial stress to the support post at room temperature.

To protect the supports from damage during transport and installation, demountable shipping restraints are inserted inside each support post to transfer the cold mass weight directly to the vacuum vessel. Prototype supports have been ordered from European industry. Mechanical and thermal measurements [7] are currently being undertaken in CERN.

3. CRYOGENIC PIPING AND INTERCONNECT

Table 1 shows the expected pressures and temperatures under various operational conditions. All pipework is made of austenitic stainless steel with the exception of the thermal shield cooling channel which consists of an extruded aluminium alloy profile connected via two aluminium to stainless steel transitions. Cryomagnets are linked together electrically, cryogenically and for vacuum via flexible stainless steel bellows which absorb maximum thermal contractions of about 34 mm between the blocked support posts to which all pipes are fixed.

The interconnect should allow straight forward connection both to the test bench and to neighbouring cryomagnets and easy access for rapid inspection and maintenance. To maximize the bending magnet occupancy of the LHC machine it must be as short as possible. The present interconnect design requires 14 pipe welds to join 11 tubes; extensive use will be made of automated orbital welding machines and tube cutters that must operate in confined space.

The imposed pressure and temperature fluctuations, combined with a fatigue life based on 500 cycles has often dictated multi-wall bellows resulting in overall stiffnesses of 950 N/mm longitudinal and 687 N/mm radial. Consequently the support system will have to withstand unbalanced interconnect forces of the order of 23 kN longitudinally and 3.4 kN radially.

Table 1: Operational Pressures and Temperatures

	DN	T_0	P_0	Pq	Pc	T_0	Pq	Pc
2K He supply	65	2.2	1.3	1.5	6	2.2	1.5	6
2K He return	150	1.8	0.016	0.016	6	1.8	0.016	6
4 K He supply	65	4.5	2.5	2.5	20	4.5	2.5	20
4 K He return	150	10	1.3	10	10	10	10	10
50-70 K He circuit	50	50/70	20	20	20	50/70	20	20
He-He heat exchanger	50	1.8	0.016	20	6	1.8	0.016	6
Bus-bar tubes					10	2	20	10
He vessel	560	1.9	1.3	20	10			
Beam tube	43	1.9	1E-13	20	10	1.9	0	0
Vacuum vessel	960	293	1E-9	1E-9	1E-9	293	1E-9	1E-9
	Dipole magnet					**Interconnect**		

T_0: Normal operational temperature K
P_0: Normal operational pressure bar
Pq: Pressure during quench bar.
Pc: Pressure during cooldown bar
DN: Nominal diameter mm

4. RADIATIVE INSULATION

The radiative insulation serves as an intermediate insulation between the thermal shield at between 50 and 70 K and the low temperature (< 5 K) components. A blanket of 10 layers of 400 Å double aluminized polyester film interleaved with spun-bonded polyester is loosely wrapped and thermalized to the 5 K supply and return pipes but insulated from the 2 K pipes and the cold mass using polyester spacers. The estimated thermal budget for one LHC dipole cryomagnet is shown in Table 2. Calculations indicate that a heat inleak equivalent to the LHC 2 K system budget of 1.6 W is reached for an incident heat load of around 100 mW m^{-2} on this type of MLI only wrap corresponding to 2.5 W total incident heat load.

Recent measurements performed at CERN [8] and at FNAL [9] on superinsulation blankets between 80 and 5 K suggest that under vacuum conditions better than 10^{-6} mbar MLI blanket performance in the 60 to 80 mW m^{-2} range can be reproducibly obtained.

Table 2: Heat Load Estimate (Watts) [10]

	to 70 K	to 5 K	to 2 K
2-D Section			
Radiation	46.29	0.712	1.316
Support posts	12.12	1.683	0.068
(radiation leakage)			(0.014)
Total 2-D Section	**58.41**	**2.395**	**1.384**
End Region			
Radiation			
End plates			0.045
Piping	2.14	0.028	0.076
Relief valve	4.27		0.106
Total End Region	**6.41**	**0.028**	**0.227**
TOTAL ESTIMATE	**64.82**	**2.423**	**1.611**

5. THERMAL SHIELD

The thermal shield must intercept radiation from the inner walls of the vacuum vessel at 300 K. It must perform adequately under all steady state and transient thermo-mechanical conditions [11]. The materials used should present a good thermal conductivity and rigidity to weight ratio at reasonable cost and components should be simple and easy to manufacture and assemble. It should enclose a maximum volume leaving space for lower temperature components.

In commercially pure aluminium alloy (AA1100) the thermal shield is made up of a lower tray 5 mm thick in two longitudinal parts each one fixed to a support post and a roughly circular upper shell 2.5 mm thick divided into four longitudinal sections. These upper parts are clipped to the lower shell and are then tack welded to provide a continuous thermal path and adequate torsional and bending stiffness. This design when subjected to a 2 g vertical acceleration ensures a maximum deflection of 12 mm acceptable during transport and installation.

This multiple section design simplifies assembly and maintains sufficient azimuthal thermal conductivity during the transient asymmetric cooldown and warmup phases so that the deflections of the shield do not cause damage or thermal shorts.

The shell of the thermal shield is covered with a multilayer reflective superinsulation blanket made of 30 layers. The radiative insulation and the thermal shield both continue across the interconnect region as dismountable elements.

6. VACUUM VESSEL

To shield the magnet stray field and reduce costs, the vacuum vessel consists of a cylindrical shell made in construction steel ISO FE430 with end and auxiliary flanges in stainless steel AISI 304L. Reinforcement rings strengthen the shell in the region of two through-penetrating flanges positioned to minimize static deflections of the cold mass to less than 0.3 mm and which locate two support posts. Upper reinforcing elements welded between the rings and equipped with lifting eyes serve for handling. Similar lower elements provide hard points for external support and carry alignment fixtures. The vacuum vessel provides a rigid mechanical support for all components and must remain dimensionally stable to permit accurate cryomagnet alignment.

A captive flange behind the front end flange allows connection to a retractable sliding sleeve which encloses the interconnect region between two cryomagnets. This sleeve consists of two flanges, a corrugated tube and a bellows all in stainless steel. In normal operation, it maintains an insulating vacuum below 10^{-6} mbar and in the event of a cryogenic leak serves as a containment vessel. Viton™ radiation resistant "O" rings are used to seal the insulation vacuum. Inner surfaces are protected with epoxy based varnish with low outgassing properties.

7. STATUS

Following competitive tendering to European Industry, CERN has ordered a total of eight dipole cryostats with three firms to be assembled with their respective cold masses furnished by four separate suppliers.

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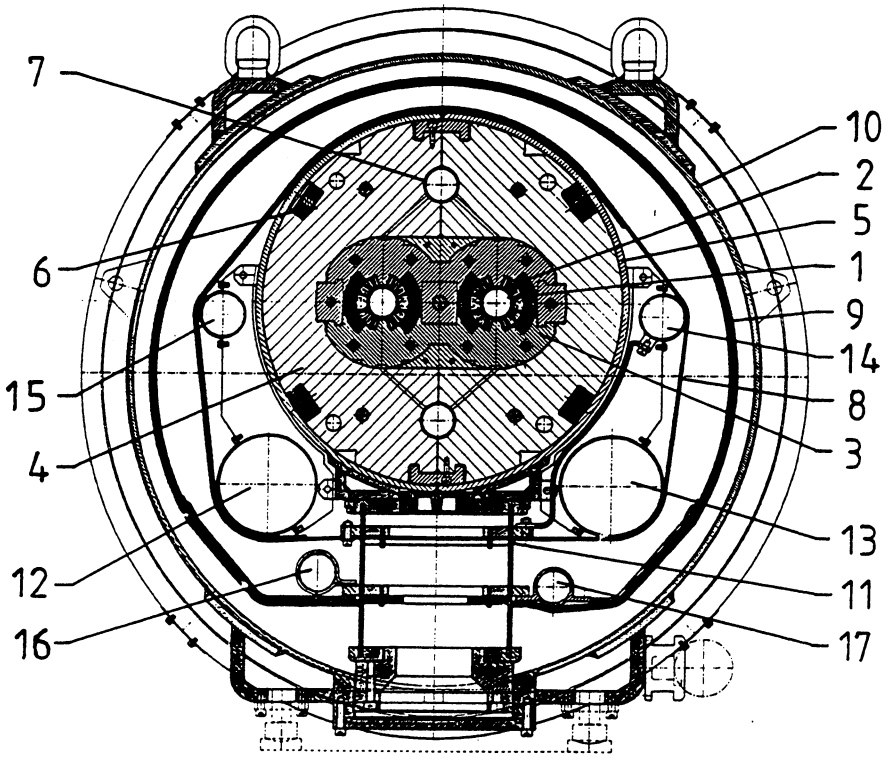

1. Vacuum chamber
2. Coils
3. Al collars
4. Iron yoke
5. Shrinking cylinder
6. Bus bars
7. HeII heat exchanger bore
8. Radiative insulation
9. Thermal shield
10. Vacuum vessel
11. Support system
12. 1.8 K GHe pipe
13. 10 K GHe pipe
14. 4.5 K He pipe
15. 2.2 K LHe pipe
16. 50 K GHe supply
17. 70 K GHe return

Fig. 1: Cross-section of the LHC prototype dipole cryomagnet assembly