LHC Interaction Region Quadrupole Cryostat Design and Fabrication

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***Abstract*--The cryostat of a Large Hadron Collider (LHC) Interaction Region (IR) quadrupole magnet consists of all components of the inner triplet except the magnet assembly itself. It serves to support the magnet accurately and reliably within the vacuum vessel, to house all required cryogenic piping, and to insulate the cold mass from heat radiated and conducted from the environment. It must function reliably during storage, shipping and handling, normal magnet operation, quenches, and seismic excitations, and must be able to be manufactured at low cost. The major components of the cryostat are the vacuum vessel, thermal shield, multi-layer insulation system, cryogenic piping, and suspension system. The overall design of a cryostat for superconducting accelerator magnets requires consideration of fluid flow, proper selection of materials for their thermal and structural performance at both ambient and operating temperature, and knowledge of the environment to which the magnets will be subjected over the course of their expected operating lifetime. This paper describes the current LHC IR inner triplet quadrupole magnet cryostats being designed and manufactured at Fermilab as part of the US-LHC collaboration, and includes discussions on the structural and thermal considerations involved in the development of each of the major systems.**

***Index Terms*--Cryostat, LHC interaction region, quadrupole, superconducting magnet.**

I. INTRODUCTION

THERE are four interaction points (IP) in the LHC, two high-luminosity and two low-luminosity IPs. Two magnet triplets will be installed at each IP, one on each side, mirrored about the IP. Each triplet consists of four superconducting quadrupole magnets in three individual cryostats. The magnet assemblies are designated Q1, Q2a, Q2b, and Q3. Q2a and Q2b are assembled in to a single cryostat designated Q2. As part of their contributions to the LHC, Fermilab and KEK will each provide half of the triplet quadrupoles. Fermilab will build all the Q2a and Q2b magnet assemblies. KEK will build all of the Q1 and Q3 magnet assemblies and ship them to Fermilab where all of the magnets will be installed into their respective cryostats prior to shipping to CERN. The cryostat consists of the vacuum vessel, structural support system, insulation, thermal shield, and internal piping, that is, essentially all of the complete magnet components except the magnet assembly itself. The cryostat design for both Fermilab and KEK magnets has been developed at Fermilab. This report documents that design development work. A schematic layout of a complete triplet is shown in FIG. 1.

II. CRYOSTAT DESIGN

As a rule, many of the constraints facing the design of cryostats for superconducting magnets are at odds with one another. This design is no different. The final assembly must be structurally strong to resist loads imposed by shipping and handling and, in this case, overseas shipment. The suspension must be stiff enough to resist long-term degradation in alignment and yet must be thermally efficient to minimize heat input to the 1.9 K helium system. The design shipping loads in the vertical, lateral, and axial directions are 2 g, 1 g, and 4 g respectively. These loads are those expected as input to the shipping container and are not necessarily seen by the magnet assembly. A combination of shock isolation systems and removable shipping restraints is planned to minimize input to the mechanical structures in the magnets themselves. Table 1 shows the current alignment criteria. The figures in this table illustrate requirements for final alignment in the tunnel, not necessarily for the magnet inside the cryostat. Finally, Table 2 contains the heat load estimates for a complete triplet. The estimates reflected here assume the cold bore is passively cooled. Insertion of a cold bore liner in all or part of the triplet would redistribute estimates of the 1.9 K and 4.5 K heat loads.

The design of this cryostat is the first of its kind at Fermilab to make exclusive use of 3-dimensional solid modeling and analysis software. The original design development and the structural and thermal analyses were done using a combination of SolidWorks and I-DEAS for modeling and ANSYS for analysis. The final fabrication drawings were produced from the I-DEAS solid models.

A. Vacuum Vessel

The primary purpose of the vacuum vessel is to maintain the insulating vacuum environment for the cold mass and other internal piping. Additionally, it serves as a secondary containment in the event that an internal pipe or bellows failure releases cryogens inside the vacuum space. Finally, it provides the mechanical connection of the cold mass and piping to the accelerator tunnel floor. Each of the different quadrupoles, Q1 through Q3, requires a different vacuum vessel design, differing mostly in length. The dominant features however are the same. Each is constructed from rolled and welded sections of carbon steel pipe connected at heavier-walled reinforcing sections. The reinforcing sections are coincident with the internal supports and transfer the weight and any mechanical loads to ground. The end flanges allow the insulating vacuum bellows to be "parked" over the outermost section while connecting the interconnect piping during installation in the tunnel.

While ordinarily at room temperature, there are failure modes in which the vacuum vessel might experience lower operating temperatures for short periods. This could occur in the event of an internal failure that spills cryogens inside the vessel. It can also occur during a loss of insulating vacuum in which the vessel would be cooled by conduction from the cold mass and internal piping. These conditions require a material with higher fracture toughness at low temperature than normal construction-grade carbon steel. CERN has developed a material specification adopted by all collaborating laboratories that defines the toughness in terms of a minimum Charpy impact strength at –50°C [2]. Several domestic and foreign materials commonly used in the gas pipeline industry have been shown to meet this specification. Stainless steel and aluminum were considered for fabrication of these vessels early in the design process, but were dropped from consideration due to their high cost. FIG. 2 shows a vacuum vessel assembly typical of those used in all LHC triplet magnets.

B. Structural Support System

The suspension system for this cryostat design represents a departure from systems used in similar magnets over the course of the last several years. SSC collider dipole cryostats, Tevatron low-beta quadrupole cryostats, and LHC arc dipole and quadrupole cryostats all employ composite support posts to support the weight of the cold assembly and to resist loads experienced during shipping and handling [3-5]. Early in the design phase of this project we elected to place the He II heat exchanger outside the cold mass, but inside the vacuum vessel. This precluded the use of a support post scheme like these other magnets since it would have necessitated a vacuum vessel much larger in diameter than could have been transported into the LHC tunnel. Rather, we opted to use a composite "spider" to support the cold mass and internal piping similar to structures used in the construction of cryogenic transfer lines. These structures are very strong and stiff in the radial direction and make good use of radial space. One of their weaknesses is in resisting axial loads encountered during shipping, handling, and cooldown. To better distribute these loads to all the support spiders each pair of spiders has a set of axial tie-bars to tie them together. The tie-bars are made from Invar tube to minimize axial forces imposed on the supports during cooldown.

FIG. 3 illustrates a complete two-support suspension system including the support spider axial tie-bars. Q1 and Q3 cryostats use two supports and Q2 uses three. The cold mass is attached to the support at the bearing blocks located at the horizontal plane. These are Garlock-DU® sleeve bearings and allow the cold mass to slide axially during cooldown to accommodate up to 14 mm of thermal contraction. The holes through the composite are clearance holes for the internal piping. The band around the outer perimeter is stainless steel and serves as an axial stiffener and as the thermal intercept when attached to the 70 K shield. The composite material is G-11CR.

C. Multi-Layer Insulation System

Multi-layer insulation is installed on the outside of the 70 K thermal shield, the cold mass, and around the internal helium pipes. The insulation is made in blankets consisting of alternating layers of 6 µm to 12 µm reflective Mylar and nylon spacer. The reflective aluminum coating thickness is 300Å minimum on each side. The edges of the blankets are terminated with Velcro strips to ensure a good seal and easy, repeatable installation. The thermal shield uses two blankets of 15 layers each (15 layers of reflector, 14 layers of spacer) for a total of 30 reflective layers. The cold mass and internal piping each have single blankets of 10 reflective layers each. The expected performance of the thermal shield blankets based on earlier testing at CERN is 1.2 W/m^2 from 300 K to 70 K for all thirty layers [6]. Similarly, the expected performance below 70 K is 50 to 100 mW/m^2 for ten layers. Aluminized Mylar is almost transparent to infrared radiation below 20 K and so is nominally not effective on the cold mass or internal piping. It is used as protection from residual gas conduction in the event of a spoiled insulating vacuum and to reduce the transient heat load on the cold mass and piping in the event of a catastrophic loss-of-vacuum accident.

D. Thermal Shield

A single thermal shield operating nominally at 70 K intercepts heat radiating from room temperature at the inside surface of the vacuum vessel. The temperature of the shield varies from about 60 K at the beginning of the triplet to 75 K at the end. The shield consists of an aluminum shell surrounding the entire cold assembly, attached at the horizontal plane to two aluminum extrusions. The annular shell is constructed in segments to minimize the effects of bowing due to longitudinal temperature gradients during cooldown. Each extrusion has an aluminum to stainless steel transition welded to the end to allow welding to stainless steel interconnect bellows. FIG. 4 illustrates a complete shield assembly. The holes through the shell allow the lugs on the support spider shown in FIG. 3 to pass through for connection of the suspension system to the vacuum vessel.

E. Internal Piping

The internal piping consists of the He II heat exchanger, pumping line, cooldown line, and 4.5 K intercept lines. The He II heat exchanger is a corrugated copper tube inside a stainless steel shell. Helium in the outer shell is common with the magnet volume. It operates at 1.9 K and 1.3 bar. The inside of the corrugated copper operates at 1.8 K and 16 mbar. A complete test of a full-scale mockup of this heat exchanger is described in [7]. The cooldown line is used only during initial filling of the magnet volume. The 4.5 K intercept lines will be used to cool absorbers located at each magnet interconnect and potentially any cold bore liner that might be installed at CERN. Pipe supports are positioned at both ends of the cold mass and at one or two places along the cold mass length. These supports position the ends of the pipes accurately to facilitate magnet interconnections and stiffen the ends to preclude interconnect bellows failure due to elastic instability caused by high internal pipe pressures. Since the pipe supports have no direct connection to anything other than the cold mass, there is no additional heat load associated with any of the internal piping. FIG. 5 shows the completed internal assembly and includes the cold mass, suspension system, piping supports, and all the internal piping.

F. Final Assembly

After the assembly is completed to the stage shown in FIG. 6, the multi-layer insulation blankets are installed over the cold mass and internal piping, the thermal shield and its insulation is installed, and the entire assembly is rolled into the vacuum vessel. The lower support blocks on each support spider contain a series of four cam rollers that allow the assembly to roll on the inside surface of the vacuum vessel. A close-up of this block and its associated rollers is shown in FIG. 6.

A rail system that is part of the final assembly tooling being fabricated for the production magnets helps to effect the transition from the assembly table to the vacuum vessel. A cable and winch system is used to pull the assembly into the vessel on the rollers shown in FIG. 6. Guides installed inside the vacuum vessel and assembly tooling help to ensure the final alignment of the internal assembly with respect to the vacuum vessel. Mechanical fasteners are inserted into the support blocks from outside the vacuum vessel to anchor the internal assembly. Fine tuning the rough alignment mentioned earlier takes place at this stage through an adjustment mechanism built into the vacuum vessel penetrations. Finally, Conflat gaskets and flanges are installed to effect the final vacuum closure. FIG. 7 shows a model of the completed first prototype assembly.

III. SUMMARY

One prototype magnet and cryostat have been completed. The prototype is half of a final Q2 assembly. The next complete assembly will be two cold mass assemblies identical to the prototype, joined into a complete Q2 in a full-length cryostat. Aside from small cosmetic changes to some of the components and minor changes in some styles of mechanical fasteners employed in the assembly the only significant change indicated by the experience gained building the first prototype is in the design of the MLI blankets on the internal piping. The prototype used a single blanket around all the internal piping, including the cold mass. Production magnets will use the separate cold mass and piping blankets referred to earlier. In spite of the use of temporary tooling, the alignment of the cold mass inside the vacuum vessel was very encouraging. The roll angle of the cold mass with respect to gravity varied from 1.84 to 2.13 mrad, with a maximum uncertainty of 0.03 mrad, over the course of three thermal cycles [8]. Adjusting for the roll of the vacuum vessel of 1.3 mrad gives a maximum roll angle inside the vacuum vessel of 0.8 mrad. The maximum warm-to-cold displacements were 77 μ laterally and 260 μ vertically. Opposite ends of the magnet did not move together so some work remains to understand these measurements. It is important to note that these roll and displacement values are measures of the alignment of the cold mass with respect to the vacuum vessel. The final alignment also relies on the precision of the installation of the vacuum vessel in the tunnel.

Although it is difficult to quantify it seems clear that the extensive use of solid modeling in all phases of this design have made the overall assembly much more straightforward. The fit and finish of all phases of the assembly are far superior to those in past projects. Rework of parts at final assembly was almost non-existent and mounting on the Fermilab test stand required no rework of piping to effect electrical or cryogenic connections.

IV. ACKNOWLEDGMENTS

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V. REFERENCES

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TABLE 1
CURRENT IRQ ALIGNMENT TABLE

Magnet	Transverse displacement	Longitudinal displacement	Roll angle	Pitch / Yaw
Q1	300 µm	~1 mm	200 µrad	130 µrad
Q2	300 µm	~1 mm	100 µrad	130 µrad
Q3	300 µm	~1 mm	100 µrad	130 µrad

TABLE 2
INNER TRIPLET ESTIMATED HEAT LOADS (ONE COMPLETE TRIPLET)

Temperature level	50 to 75 K	4.5 K	1.9 K	Notes
Static heat loads (W)	220	0	18	1,2
Dynamic heat loads (W)	0	17	184	3
Total heat loads (W)	220	17	202	

Notes

1. Static heat load to outer shield: 140 W conduction through supports + 80 W radiation and gas conduction.
2. Static heat load to 1.9 K: 12 W conduction through supports + 6 W radiation (assume emissivity=0.1).
3. Dynamic heat loads based on nominal luminosity [1].

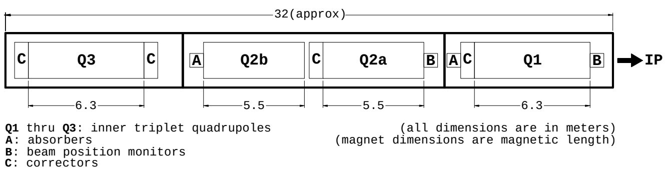

Fig. 1. Schematic layout of a typical LHC interaction region triplet.

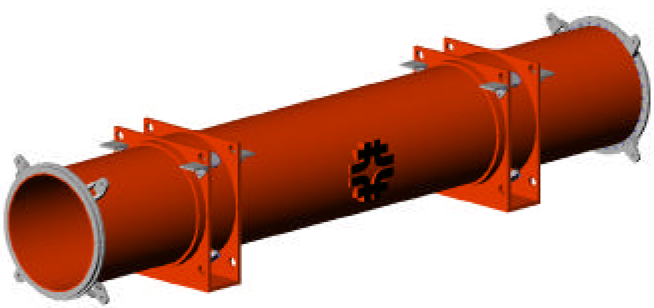

Fig. 2. Vacuum vessel assembly.

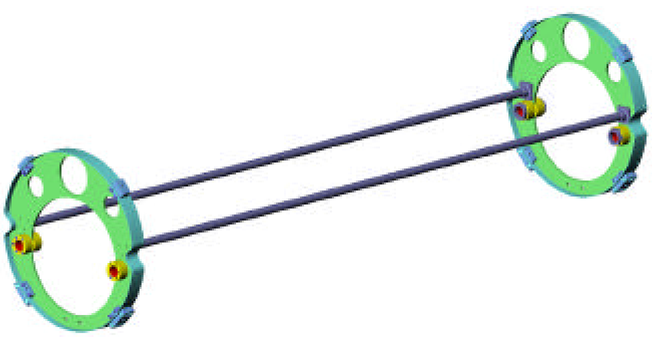

Fig. 3. Suspension system assembly.

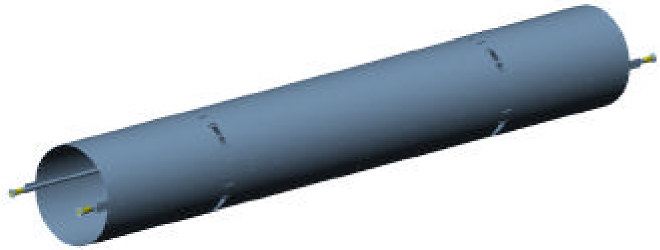

Fig. 4. 70 K thermal shield assembly.

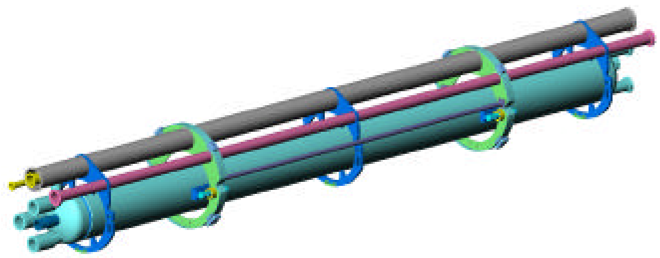

Fig. 5. Internal piping assembly.

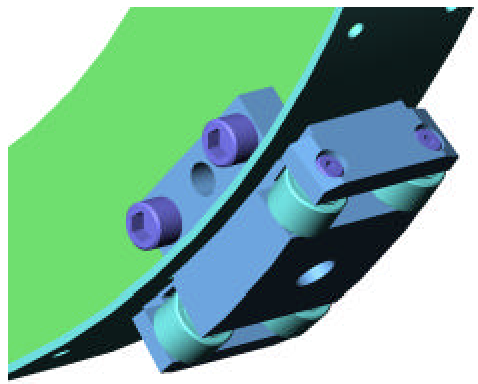

Fig. 6. Close-up of support block and rollers.

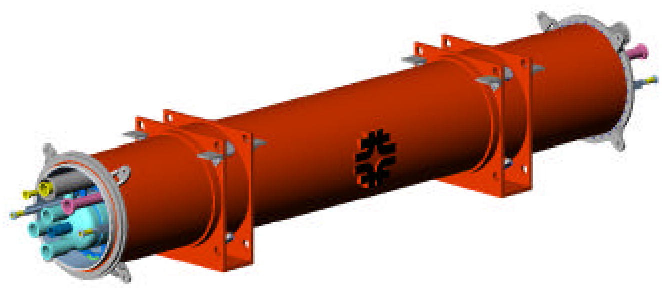

Fig. 7. Complete magnet assembly.