Fermi National Accelerator Laboratory

Cryostat Design for the Superconducting Super Collider *

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ABSTRACT

The cryostat of an SSC dipole magnet consists of all magnet components except the cold mass assembly. It serves to support the cold mass accurately and reliably within the vacuum vessel, provide 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 manufacturable at low cost.

The major components of the cryostat are the vacuum vessel, thermal shields, multilayer insulation (MLI) system, cryogenic piping, interconnections, 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 their 25 year expected life.

This paper describes the design of the current SSC collider dipole magnet cryostat and includes discussions on the thermal, structural, and dynamic considerations involved in the development of each of the major systems.

INTRODUCTION

Fermilab has been involved in the design and production of cryostats for all prototype Superconducting Super Collider (SSC) dipole magnets built since 1986. That work is very well documented in the literature[2-7]. Late in 1989 a fundamental change in the dipole coil design; increasing the physical aperture from 40mm to 50mm, resulted in the need to redesign the dipole cryostat. The larger aperture gave rise to an increase in diameter of the overall cold mass assembly of approximately 25% and a weight increase of approximately 50% both of which impact the cryostat design significantly.

Cryostat designs for superconducting magnets are largely driven by thermal and structural considerations. Designers must continually be cognizant of the heat load to the helium system and of the structural loads imposed on the cryostat systems from static weight, shipping and handling, quench loads, and ambient ground motion. These two considerations are generally at odds with one another. Low heat load implies a minimum of structural material conducting heat from the environment. Sound structural design implies material with sufficient strength to resist both static and dynamic forces.

This paper attempts to summarize the results of the design effort to date on the collider dipole cryostat for the 50mm magnet. Thermal and structural aspects of the design of each of the major cryostat systems will be described in detail. The 40mm dipole cryostat purposely served as the starting point for this design work. Wherever possible, development work on that and other similar cryostats was borrowed in order to take advantage of proven technology. References to the 40mm cryostat will be made for comparison wherever appropriate. Each of the cryostat systems will be addressed in turn; vacuum vessel, 80K and 20K thermal radiation, multilayer insulation (MLI), cryogenic piping, suspension system, and magnet interconnect.

In order to begin the design process, one needs a good handle on the pertinent allowable heat loads to each thermal station as well as a good definition of the structural environment to which the magnet will be subjected. Table 1 summarizes the thermal and structural design criteria for the 50mm dipole which affect the cryostat design[1]. Figure 1 illustrates a cross section through the 50mm cryostat.

VACUUM VESSEL

The vacuum vessel is the outermost cryostat component and, as such, serves to contain the insulating vacuum. In addition, it functions as the major structural

Table 1. Thermal and Structural Design Criteria

	4.5K	20K	80K
Static Heat Loads			
Infrared	0.053 W	2.335 W	19.1 W
Support conduction	0.160 W	2.400 W	15.8 W
Interconnect	0.150 W	0.320 W	2.1 W
Total static	0.363 W	5.055 W	37.0 W
Dynamic Heat Loads			
Synchrotron rad	2.169 W		
Splice IR heating	0.140 W		
Beam microwave	0.195 W		
Beam gas	0.136 W		
Total dynamic	2.640 W		
Total Dipole	3.003 W	5.055 W	37.0 W

Structural load summary
Cold mass weight:	11,360 kg	
Shipping and handling:	2.0g	vertical
	1.5g	axial
	1.0g	lateral

element to which all other systems are ultimately attached to the accelerator tunnel floor. Furthermore, it serves as a pressure containment vessel in the event of a failure in an internal cryogen line. The vessel is 685.5 mm OD, 7.92 mm wall with an overall length of 14922.5 mm. Its 40mm counterpart was 609.6 mm OD, 6.35 mm wall and had an overall length of 16306.8 mm.

The vacuum vessel has five penetrations at which the internal cold mass supports are attached. The internal supports are positioned to minimize the deflection of the cold assembly due to its own weight and are spaced on 3179.76 mm centers starting at the center of the magnet. Two external supports serve to tie the vessel to the tunnel floor. The external supports are spaced to minimize the deflection of the vacuum vessel due to its own weight and to the weight of the internal components. They are located 4154.17 mm on either side of center.

The 7.92 mm wall of the vessel is not sufficient to transfer suspension system loads to ground immediately around the internal support locations. At these positions a 19.05 mm thick, 559 mm long reinforcement transfers internally generated loads, primarily from shipping and handling, from the magnet support system to the vacuum vessel. Figure 2 illustrates the major features of the vacuum vessel and notes applicable dimensions. The vacuum vessel material is low carbon steel. Ordinarily one would like to use a material with greater fracture toughness in the event of a major cryogen spill inside the cryostat, however, cost mandated a more readily available material. In addition, failure analysis indicated that a high fracture toughness material was not required.

THERMAL RADIATION SHIELDS

Like its 40mm counterpart, the 50mm dipole cryostat uses two thermal radiation shields. The outermost shield is cooled by LN$_2$ and operates at 80K.
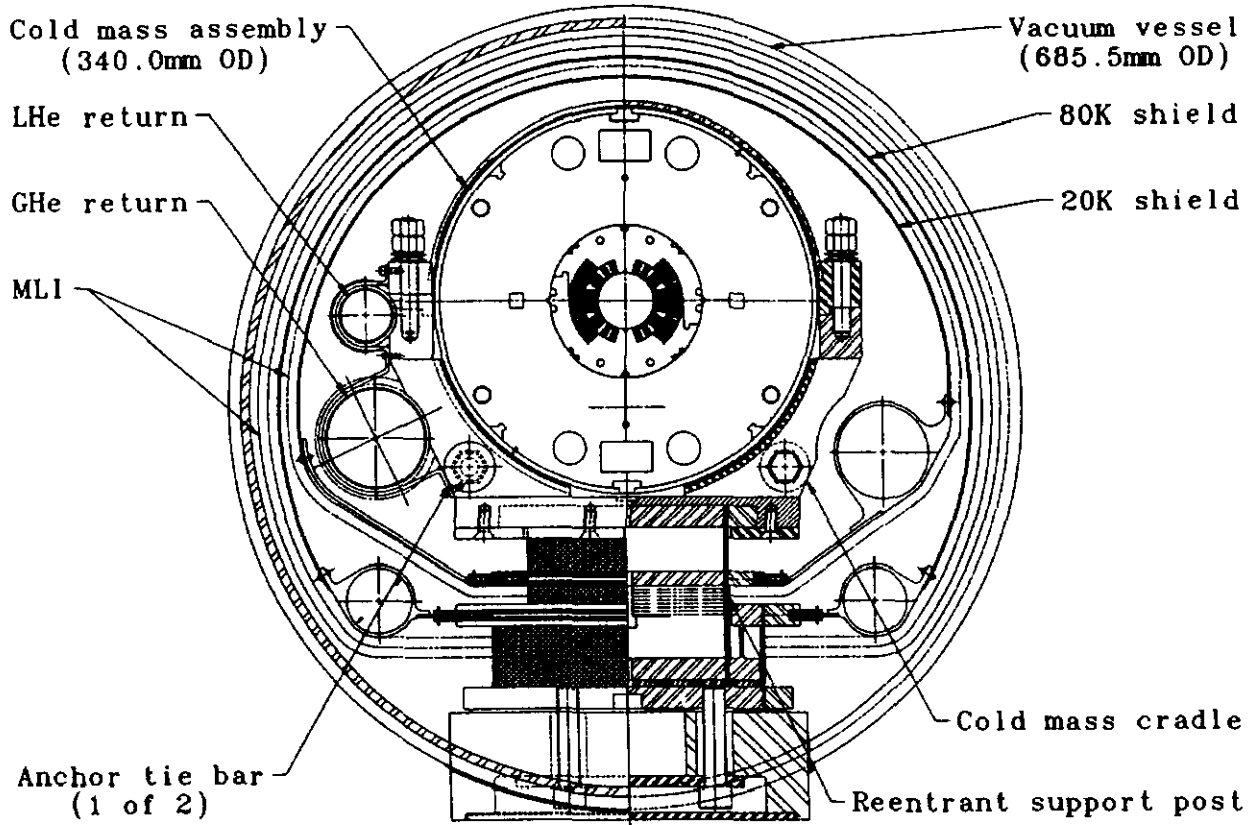

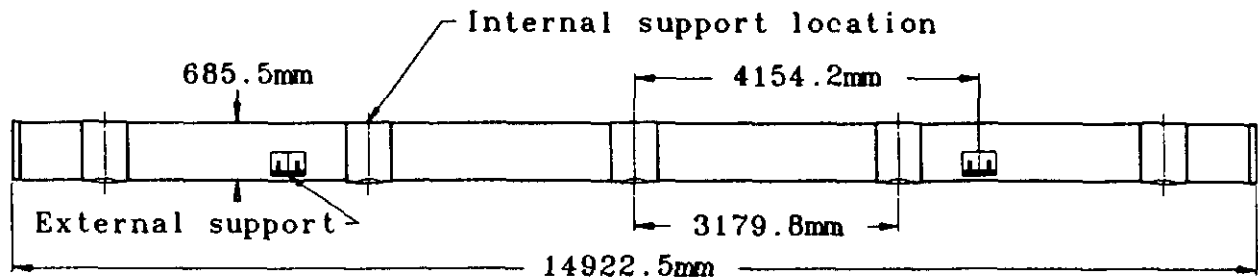Fig. 1. 50mm collider dipole cryostat cross section

Fig. 2. 50mm collider dipole cryostat vacuum vessel

The innermost shield is cooled by helium gas returning to the refrigerator and operates nominally at 20K.

Each shield is cooled by discrete pipes connected to formed shells which totally encompass the internal cold assembly. The 20K shield uses a single extrusion attached to the shell. The 80K shield uses two; one serving as the shield supply, the other as the return. This scheme requires that the shells have high thermal conductivity to minimize thermal gradients around their circumference. Copper and aluminum are the materials of choice for this application. Thermal analyses on both shields were performed using both materials. The results from these analyses indicate there is no significant difference in the thermal performance of either shield between these two materials. Material cost dictated the ultimate material choice. Copper and aluminum are approximately the same cost per unit weight, however, with a density over three times that of aluminum, the use of copper as the shield material would result in an assembly cost three times higher than an aluminum shield. The selected material for both 80K and 20K shields is 6061-T6 aluminum, 1.59 mm thick. The shields are segmented along their length to minimize the effect of bowing during cooldown caused by the asymmetry of the cooling tubes with respect to the shield shells.

MULTILAYER INSULATION

The design requirements for the thermal insulation system in the SSC dipole cryostat dictate that heat load from thermal radiation and residual gas conduction be limited to the values listed in Table 1. Essential to meeting these requirements is an insulation system design that addresses transient conditions through high layer density for improved gas conduction shielding, has sufficient mass and heat capacity to reduce the effects of thermal transients, and is comprised of materials suitable for extended use in a high radiation environment. Finally, the system design must be such that fabrication and installation techniques guarantee consistent thermal performance throughout the entire accelerator.

The insulation system must have a mean apparent thermal conductivity of 0.76 x 10^{-6} W/cm-K in order to meet the design heat load budget. This is achieved by using a multilayer insulation (MLI) system comprised of reflective layers of aluminized polyester separated by layers of spunbonded polyester spacer. The reflective layers consist of flat polyester film aluminized on both sides to a nominal thickness not less than 350 angstroms. The spacer layers consist of randomly-oriented spunbonded polyester fiber mats. The mean apparent thermal conductivity of an MLI blanket comprised of these materials has been measured to be 0.52 x10^{-6} W/cm-K [6,7]. The MLI system for the SSC 50mm collider dipole cryostat will consist of full cryostat length assemblies of MLI fabricated and installed as blankets on the 80K and 20K shields.

The MLI system for the 80K thermal shield consists of two 32-reflective-layer blanket assemblies, for a total of 64 reflective layers. The stack height of each 32-layer blanket is 8.86 mm, with a mean layer density of 3.61 layers per mm. The blanket design incorporates 32 reflective layers of double-aluminized polyethylene terepthalate (PET) film. The reflective layers are separated by single spacer layers of 0.10 mm spunbonded PET material. Single layers of 0.23 mm spunbonded PET cover the blanket top and bottom and serve to position the polyester hook and loop fasteners at the blanket edges. The fasteners are affixed to the cover layers by sewing. A third 0.23 mm PET layer is located midway through the blanket assembly and separates the upper and lower 16 reflective layers of MLI. The multiple blanket layers are sewn together as an assembly along both edges of the blanket. Non-lubricated polyester thread is used in all sewing operations.

The MLI system for the 20K thermal shield consists of two 16-reflective-layer blanket assemblies, for a total of 32 reflective layers. The blankets are designated as the inner 20K and outer 20K blanket, respectively. The basic design geometry and component materials for the 20K MLI blankets are the same as for the 80K blankets; the principle differences being the overall width of each blanket and the sewn seam configuration. The blanket design incorporates 16 reflective layers of double-aluminized PET film separated by single spacer layers of 0.10 mm spunbonded PET material. Single layers of 0.23 mm spunbonded PET cover the blanket top and bottom and serve to position the polyester hook and loop fasteners at the blanket edges. The fasteners are affixed to the cover layers by sewing. The multiple blanket layers are sewn together as an assembly along both edges of the blanket. The 20K blankets are sewn straight through from the upper cover layer to the bottom cover layer.

CRYOGENIC PIPING

In addition to providing the necessary structural support and thermal insulation for the cold mass assembly, the cryostat serves to contain the piping for all of the cryogenic services required for magnet and magnet

system operation. Table 2 provides a summary of the pressure and flow parameters for each of these services. Table 3 lists the pipe sizes for each of the cryostat pipes. Each pipe is anchored at the center of the magnet assembly, and is free to slide axially at the remaining support points to allow for thermal contraction during cooldown.

Table 2. Cryogenic System Pressure and Flow Parameters

System	Pmax (atm)	Fluid	Poper (atm)	v (cm³/g)	T (K)	Flow (g/s)	ΔP (psi)
20K shld	18	He	2.5	163.4	20	100	0.016
80K shld	18	LN₂	5.0	1.286	84	750	0.012
Single phs	18	He	4.0	7.255	4.25	100	0.010
LHe retn	18	He	3.0	7.609	4.425	85.6	0.010
GHe retn	9	He	0.9	73.07	4.3	26.8	0.00053
Vacuum	2	He	0.0	na	300	na	na

Table 3. Cryostat Pipe Sizes (mm)

System	Pipe ID	Pipe OD	Flow Area	Material
20K shield	82.55	88.90	5352	Alum
80K shield	57.15	63.50	2565 x 2	Alum
LHe return	45.14	47.62	1600	Stn stl
GHe return	86.41	88.90	5864	Stn stl

SUSPENSION SYSTEM

The suspension system in any superconducting magnet serves as the structural attachment for all cryostat systems to the vacuum vessel which in turn anchors them to the accelerator tunnel floor. Conventional suspension systems were effectively reinvented during early SSC magnet development [2,3,5]. The intention in development of the 50mm dipole cryostat was to take advantage of that earlier work tailoring it only for the revised thermal and structural design parameters.

Schedule requirements for the redesign work did not allow continued suspension R&D and, in fact, the thermal and structural performance of the 40mm design did not indicate it to be necessary.

Using the thermal and structural parameters outlined in Table 1 the suspension system for the new design was extrapolated from its 40mm counterpart. The emphasis was on meeting the allowed suspension system conduction heat load, satisfying the structural requirements, and maximizing the lateral suspension stiffness. This latter constraint is not explicitly defined in the design criteria but arose out of concerns during testing of 40mm prototypes that the lateral natural frequency was too closely coupled with resonances found in an over the road shipping environment.

As shown in figure 3, the suspension system consists of two major components; reentrant style support posts and anchor tie bars. There are five support posts located along the length of an SSC cold mass assembly spaced 3179.76 mm apart centered about the middle of the cold mass. Five being the number which limits the cold mass sag due to self weight to the allowed 0.25 mm. The support posts resist vertical and lateral loads imposed during shipping and handling. The cold mass is allowed to slide axially with respect to all but the center post to allow for thermal contraction of the cold assembly during cooldown. This implies that, given no other restraint, the center support would need to resist axial loads. A single support is not capable of resisting this potential 1.5g load. Using a special support at the center which could handle this load would impose inordinately high heat loads on the refrigeration system. Rather, a means was developed to distribute axial loads to all five supports without impacting the conduction heat load. Axial tie bars are used to connect the top of each support post to its neighbor(s). In this scheme, an axial load acts first at the center support and then is distributed to all five supports.

The tie bars must be dimensionally stable when cooled from their assembly temperature of 300K to their
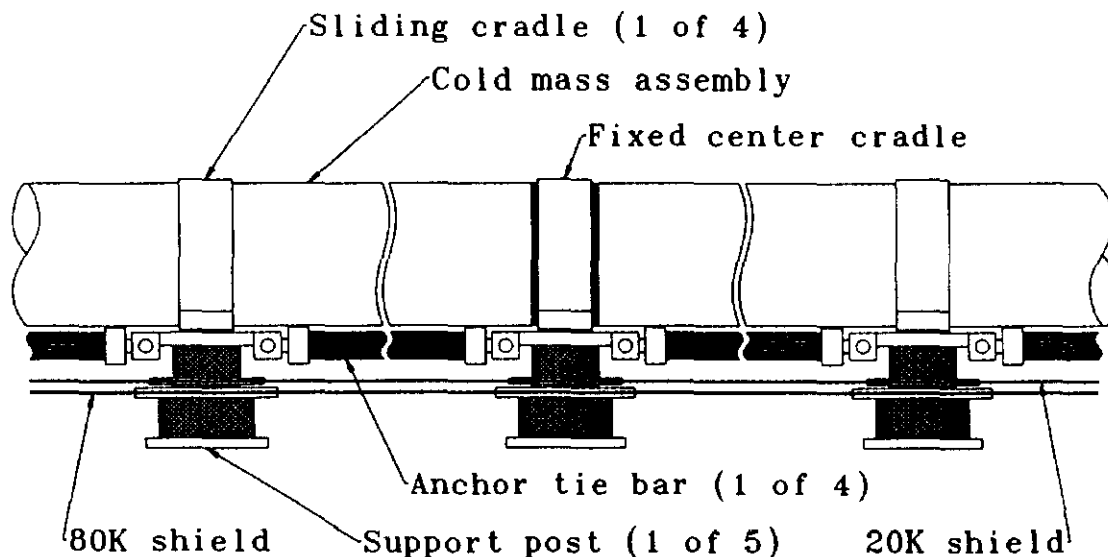

Fig. 3. 50mm collider dipole cryostat suspension system components

operating temperature of 4.5K, otherwise their contraction would impose high bending loads on the support posts. Uniaxial graphite fibers in an epoxy matrix provides the solution. This material is extremely stiff and yet exhibits virtually no change in length during cooldown. An elastic modulus of 82.5 GPa can be achieved in such a composite even with relatively low modulus fibers.

The configuration of the support posts for the 50mm cryostat is shown in figure 4. The outer composite tube is 2.16 mm thick and is filament wound using S-glass in an epoxy matrix. The inner tube is 3.18 mm thick and is filament wound using graphite fibers in an epoxy matrix. The ability of this design to use two different materials allows each material to be used in its optimum temperature range.

INTERCONNECT

As its name implies the magnet interconnect serves as the connection area between magnets at which each of the cold mass and cryostat pipes between magnets are connected. Each pipe is anchored axially at the center of the magnet which means they contract between approximately 25 mm and 32 mm depending on whether they are stainless steel or aluminum. The relative contraction at the interconnect is then 50 mm to 64 mm, i.e. twice the single magnet value. Bellows are required on each cold mass, shield, and cryogenic pipe to allow for this expansion. All bellows are hydroformed stainless steel. For the aluminum extrusions on the 80K and 20K shield pipes an aluminum to stainless steel transition joint is required for the bellows connection. Joints using diffusion bonding or brazing between these two materials have been successfully employed in 40mm prototypes. Lateral instability is a concern for interconnect bellows and requires the use of internal squirm protectors on each bellows.

Radiative heat transfer must also be minimized in the interconnect area. This is accomplished by shield bridges which span the 80K and 20K shield gap between adjacent magnets. These bridges are little more than extensions to the magnet shields, modified to contain their respective bellow OD's if necessary. A sliding joint between bridge sections on adjacent magnets accommodates contraction during cooldown. Each is covered with the same MLI scheme used throughout the body of the magnet. These shield bridges also contain pressure reliefs for each shield to prevent pressure buildup within either shield in the event of an internal piping failure. The reliefs are located in the upper half of the shield sections in order to prevent liquid spills from impinging directly onto the vacuum vessel wall.

SUMMARY

The SSC development program has afforded us the opportunity to extend the design of cryostats for superconducting magnets far beyond the state of the art present at the end of the Fermilab Tevatron program. Advances in new materials technology have opened up options for cryostat designers in both thermal and structural materials. Strict limits on allowable heat load have forced us to develop new mechanisms for structural support and thermal shielding. The end result is a cryostat design which meets the demands of the SSC and which will serve as the starting point for the development of other magnet systems far into the future.
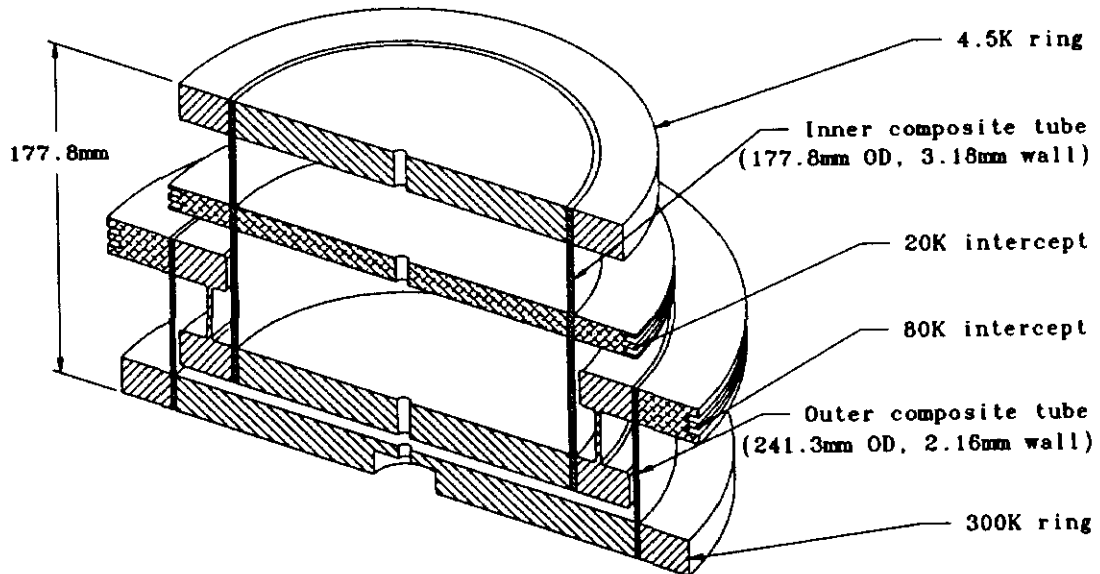

Fig. 4. 50mm collider dipole cryostat support post

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