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Second Generation Superconducting Super Collider Dipole Magnet Cryostat Design*

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DIPOLE MAGNET CRYOSTAT DESIGN

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ABSTRACT

The Superconducting Super Collider magnet development program includes the design, fabrication and testing of full length (17.5m) model dipole magnets. A result of the program has been the development of an improved design for the magnet cryostat, whose subsystems include suspension, thermal shields, insulation, vacuum vessel and interconnections. The details of the design are presented along with experimental evaluations and magnet model fabrication experiences.

INTRODUCTION

The SSC Magnet Development Program is developing accelerator dipole magnets in successive iterations. The initial iteration[1] is complete with six full length model magnets and a thermal model having been built and tested. This initial experience along with the evolving SSC Magnet System Requirements have resulted in the second generation magnet cryostat design. It is this configuration that will be employed for the near term ongoing magnetic, thermal, string and accelerated life testing and will be the design considered for Phase I; i.e., Technology Orientation, of the SSC Magnet Industrialization Program.

CRYOSTAT

The cryostat features are critical to the SSC since they must allow proper magnetic function, impose low refrigeration loads, operate with very high reliability and be manufacturable at low cost. The cryostat must function reliably during transport, transient, steady state and upset conditions. The major components of the cryostat are the cold mass, cold mass connection-slide, suspension system, piping, thermal shields, insulation, vacuum vessel and interconnections. The magnet assembly is as shown by Figures 1 and 2.

COLD MASS CONNECTION-SLIDE

The cold mass is supported by five cold mass-suspension system connections. The connections must withstand transportation and seismic loads, accommodate axial contraction of the cold mass during cooldown and warmup, accurately position the magnetic axis and fit within the compact geometry of the cryostat. Four of the connections must allow for relative axial motion, while an anchor connection fixes the cold mass axially to ground. The connections are attached to the support posts and transfer load to the suspension system.

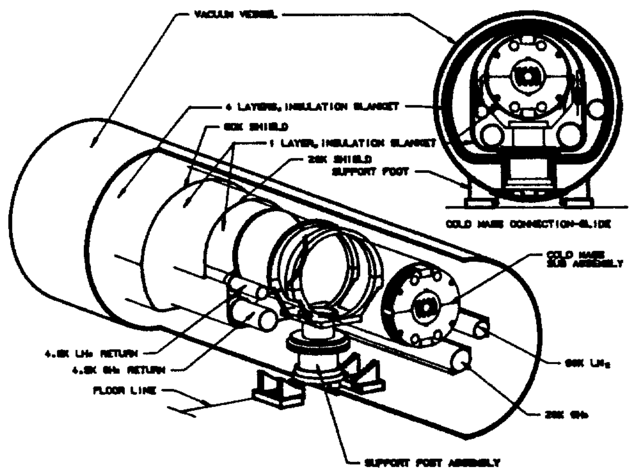

Fig. 1 Second generation cryostat

The connection-slide was developed with the experience of the initial iteration and focused on improving performance in the following areas:

- Reduced cold mass outer shell welding.
- Provide angular position adjustment of the cold mass about its axis.
- Increased dynamic load structural capacity.
- Improved bearing performance and lower contact stresses to avoid stick-slip binding and to reduce wear.
- Increased simplicity and fewer parts.
- More conducive to accurate alignment procedures.

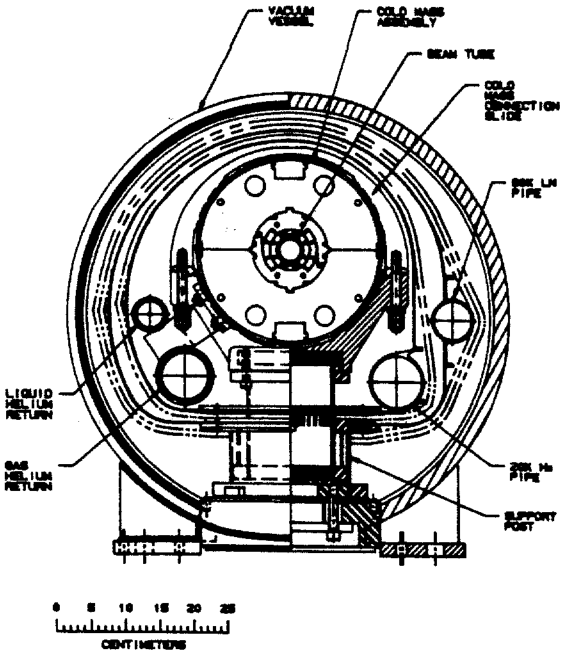

Fig. 2 Cryostat cross section

The cold mass-suspension connection-slide[2] is as shown by Figure 2. Four bearing blocks, containing removable bearing pads, contact the cold mass outer shell and establish its position. The bearing pads are supported by upper and lower cradles, the latter is secured to the support post 4.5 K cold end ring. The outer surface of the cold mass is used for locating the magnetic axis.

To function properly, the cold mass outer shell, or skin, must be precise in nature relative to its thickness and form and must be installed with intimate contact to the outside of the cold mass iron yoke at the bearing contact points. The degree of precision required is dependent on the skin's functional requirements. If the only functional requirement of the skin is to provide a shaft that meets the requirements of the sliding journal bearing, the OD of the installed skin must be within ±0.51 mm (0.020 in) of the nominal value. If the function of skin is to provide a journal bearing shaft as well as being the principle cold mass fiducial, the OD of the installed skin must be within ±0.03 mm (0.001 in) of the nominal value.

The connection-slides allow rotational adjustment for final alignment during magnet assembly. By measuring the average vertical magnetic plane and determining its offset, the cold mass can then be rotated to compensate for this offset and fixed at the center anchor connection. The cold mass remains rotationally free at all but the center support.

The upper half of the connection retains the cold mass during transportation and seismic loading. Conical spring washers act as tensioner springs on the bolts which connect the two halves of the connection-slide. The spring action maintains uniform loading during thermal cycling and minimizes radial differential thermal contraction effects. The connection has been tested at design loads.

Evaluations of the connection-slide's sliding characteristics were made using a full length model at ambient conditions and a short model at cryogenic conditions. The test results are as follow:

- The 3.3 mm (0.13 in) cold mass horizontal sagitta has little effect on the sliding characteristics.
- Cooling the assembly to 80 K increases the sliding resistance 2.5 times over ambient test runs. The results are as shown by Figure 3. The imposed loads are well within the capacities of the suspension system.
- The slides performed acceptably for a number of cycles that greatly exceed the specified twenty cooldown - warmup cycles for the magnets.

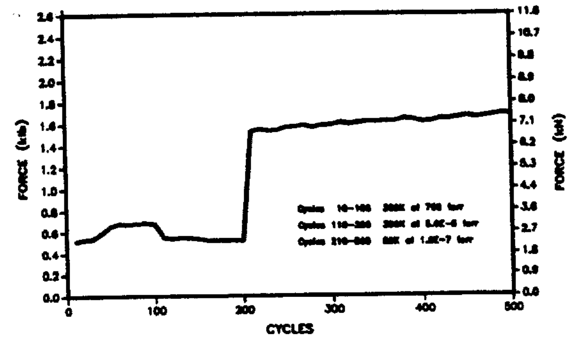

Fig. 3 Cold mass connection-slide sliding test results

SUSPENSION SYSTEM

The cryostat suspension system performs two essential functions. It resists internally and externally generated structural loads imposed on the cold mass assembly ensuring that the position of that assembly is stable over the operating life of the magnet and it insulates the cold mass from heat conducted from the environment.

To satisfy the first function, the normal operating stresses in the suspension system must be low enough to avoid creep in the component materials yet sufficient reserve strength must exist to handle loads imposed during shipping and handling, seismic excitations and internally generated axial quench loads. To satisfy the second function in some optimal way, the suspension components must be sized to meet the structural requirements and must utilize materials that offer a good compromise between mechanical strength and thermal impedance. Table 1 summarizes the design structural and thermal loads.

Table 1. Suspension Design Structural and Thermal Loads

Shipping and handling:	vertical	±2.0 g
	lateral	±1.0 g
	axial	±1.5 g
Seismic:	Nuclear Regulatory Guide 1.61 vertical and horizontal spectra scaled by 0.3	
Axial quench:	111,200 N (25000 lb)	
Suspension conduction heat load budget per magnet:	80 K	7.20 W
	20 K	0.82 W
	4.5 K	0.12 W

Support Post

A reentrant support post assembly[3] as shown by Figure 2 is employed.

The second iteration support post is similar to the initial version. The differences being due to better understanding of the effects of seismic and shipping and handling loads and from the increased estimates of potential axial quench loads. The outer tube is 178 mm (7 in) OD, 2.77 mm (0.109 in) wall, fiberglass reinforced composite. The inner tube is 127 mm (5 in) OD, 3.28 mm (0.129 in) wall, graphite reinforced composite. The heavier walls and the graphite inner tube increase the strength and stiffness of the post assembly. The use of graphite for the inner post partially offsets the increased heat load incurred from the heavier wall. The change to a graphite material is only applicable for the inner tube. Glass is a better thermal choice for materials operating between 300 and 40 K while graphite is the better thermal choice below 40 K.

Table 2 lists the heat load values. The post has been measured in a Heat Leak Test Facility[4]. A heat load to 4.5 K of 0.020 W was measured. This value does not include the resistance of the cold mass connection-slide.

Table 2. Support Post Heat Loads

	Heat Load (W)	
Thermal Station	Predicted	Measured
80 K	2.10	1.670
20 K	0.32	0.414
4.5 K	0.015	0.025

Anchor System

The five support posts share vertical and lateral loads. Thermal contraction of the cold mass assembly during cooldown and warmup necessitates axial sliding between the cold mass and each of the four outer posts and thus they do not contribute to axial load restraint. The center post is rigidly attached to the cold mass to ensure correct axial position within the vacuum vessel. Given no other axial restraint, the center post would carry the total axial load. A single post is incapable of handling these loads alone. Utilizing a 'strong' post at the center would impose intolerable heat loads on the cryogenic system. Thus a separate means of affecting axial restraint is required.

Due to the sliding cold mass-suspension system connections, the fixed center post is the only one capable of resisting axial loads. In order that the bending strengths of all five posts be combined to effectively act as a single axial restraint[5], the 4.5 K end of each post is connected to that of each adjacent post with tie bars. Figure 4 illustrates the post-tie bar anchor system.

The tie bar is a filament wound graphite reinforced epoxy 51 mm (2 in) OD, 6.4 mm (0.25 in) wall, 3.05 m (120 in) long tube. Graphite filaments were chosen for their thermal expansion properties. When cooled from 300 to 4.5 K, the fibers tend to grow and the epoxy tends to shrink. The net effect is a tube which changes length by only a small amount over the operating range of the anchor assembly. Tests indicate that a complete tie bar shrinks only 0.025" mm (0.001 in) when cooled to 80 K. Graphite reinforced material has the added benefit that it is stiff and thus tends to distribute axial loads among all five support posts more evenly than a less rigid material. Figure 5 illustrates the deflection at the tops of the five support posts and provides an indication of load sharing between posts.

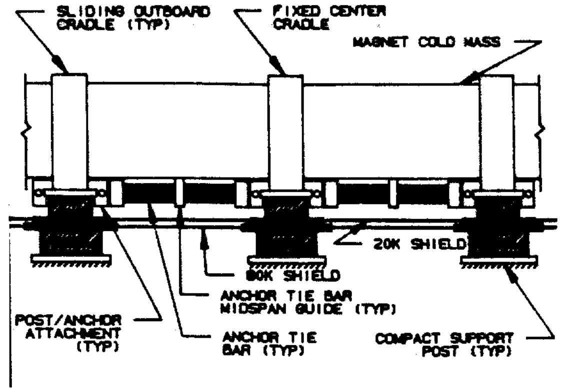

Fig. 4 Post-tie bar anchor system

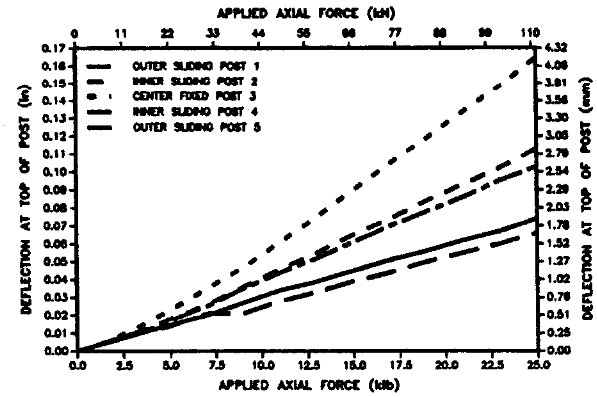

Fig. 5 Post-tie bar anchor post deflection vs. load

The importance of the tie bars is their impact on the thermal performance of the anchor system. The tie bars have both ends at 4.5 K thus contribute no conductive heat load. They lie completely inside thermal shields and require no penetrations through the shields.

Ambient temperature structural testing has been done on a complete post-anchor system. Figure 6 illustrates the cold mass deflection vs. applied load and provides an indication of the total anchor stiffness.

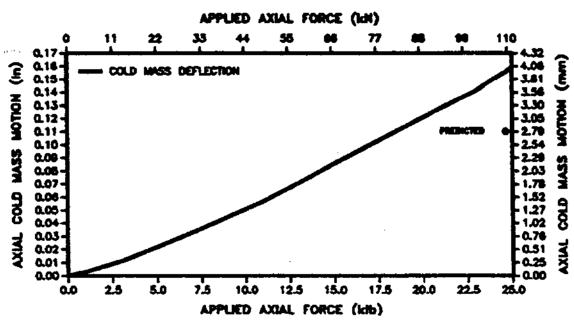

Fig. 6 Post-tie bar anchor coldmass deflection vs. load

Comprehensive testing of a complete magnet assembly will be done to verify analytical simulations of the magnet system when subjected to dynamic loads.

THERMAL SHIELDS

The cryostat incorporates two thermal shields that intercept radiant heat flux from the environment and provide heat sinks for the suspension system. The shields surround the cold mass and are operated at 20 and 80K.

The shields are aluminum, which has high thermal conductivity, forms easily and remains strong and ductile at cryogenic temperatures. The shields are supported by the five support posts. The post-shield interface permits relative axial motion to permit the shields to move as the cryostat is cooled down and warmed up. The shields are thermally connected to the post heat intercept rings by copper cables. Extruded aluminum pipes carry the cooling fluids; i.e., 20K helium gas and liquid nitrogen.

The initial iteration shields performed well. However, the design was costly to produce and time consuming to assemble. Changes have been made to reduce component fabrication and assembly time. The primary motivation being to reduce cost rather than to improve performance.

The second iteration shield is different from the initial iteration in the following ways:

- There are two components instead of five. Fewer connections result in reduced assembly time and cost.
- The shields are thinner, resulting in reduced material and forming costs.
- The heat sink straps are crimped to their lugs at assembly rather than soldered. The temperature rise across the crimped connection heat sink straps has been determined experimentally and found to be less than 3% more than across equivalent geometry straps with soldered connections.
- The shields are assembled and fastened by spot welded connections rather than fusion welding.
- The lower half of the shields are pulled up along the support posts from the bottom during assembly instead of being split and welded. The longitudinal bottom weld has poor accessibility and is time consuming to make and can result in considerable shield distortion.

Predictions and measurements of shield bowing during cooldown and warmup will be made to establish the structural integrity and elastic nature of the bowing.

The effects of cyclic relative motion between the shields and the post intercept rings will be evaluated experimentally.

INSULATION

The insulation system consists of multilayer assemblies of aluminized polymer film, fabricated and installed as blankets on the cold surfaces. Each blanket covers the entire surface in a one-piece application.

The second iteration blanket materials are thermal radiation reflective layer made of double aluminized polyester film and a spacer material consisting of spunbonded polyester used to separate the reflective layers.

Each blanket is an assembly of 16 layers of reflector and 15 double layers of spacer, alternately stacked.

Thermal evaluation of the blanket between 300 and 80K indicated that 59 layers of are required to meet the 80K heat leak budget. Subsequently, the insulation system for the 80K shield was specified to be an assembly of four blankets. Two blankets was specified for the 20K shield. Insulation will be installed directly onto the cryostat cold mass to impede gas conduction heat transfer to the cold mass by residual gases and from desorbed gases released from cryostat surfaces during thermal upset conditions. The intent of the insulation is to act as a heat absorbing buffer surrounding the cold mass; to slow the effects of transient heat loads by reducing the rate of heat transfer to the cold mass, thereby dampening the response time of the cold mass to the upset condition and providing more time for system operation to recover from the upset condition. Given that the purpose of the insulation on the cold mass is only to impede gas conduction, this function can be accomplished with minimal labor by draping the cold mass with a full length blanket, and cutting and spiral wrapping the blanket width circumferentially around the cold mass to form a series of sleeves of insulation around the cold mass. A single blanket consisting of 5 reflecting layers and 4 spacer layers is used. At a higher installation cost, a more restrictive application with better performance can be obtained by assembling multiple blankets of fewer layers.

Insulation development continues.[6] The performance of candidate insulation systems between 80 and 4.5K will be measured. Blankets with alternate or no spacer materials and of a hybrid nature will be evaluated on the basis of radiation resistance, pumpdown, compactness, cost, etc. Blanket fabrication and installation techniques will be refined during the fabrication of the balance of the long magnet models.

VACUUM VESSEL

The vacuum vessel provides the insulating vacuum required for the control of heat transfer to the internal components by residual gas conduction and provides for the transfer of the loads of the cryostat internal structure to ground. The vacuum vessel is circular in cross section, is equipped with bellows at its ends for interconnection and is connected to ground by means of foot assemblies.

The cold mass is supported at five points. The number of supports was determined such that the maximum cold mass deflection between supports was limited to 0.25 mm (0.010 in). The spacing between supports was determined to minimize the sag of the cold mass, given five supports.

The shell is 610 mm (24 in) in diameter and is 6.4 mm (0.25 in) thick.

A reinforcing ring is welded to the vacuum vessel at the mounting positions of the internal supports. These reinforcing rings reduce bending stresses in the vacuum vessel when loads are imposed on the cold mass assembly. Reinforcing rings are also required at the external foot locations.

The completed internal cryostat assembly is inserted, by sliding, into the vacuum vessel by means of a tow tray-plate assembly installed at the bottom of the vessel shell.[7]

The initial iteration vacuum vessel has been incorporated into one short (4.5m) and six long (16.6m) model magnets and one full length thermal model with good success. The vessel is buildable and the slide-in insertion method works well for both assembly and disassembly.

The second iteration vacuum vessel will be different from the initial iteration in several ways:

- For installation and alignment reasons, five external supports overconstrain the installed position of the vacuum vessel. Two external supports suffice to fix the location of the magnet assembly. However, two supports are not sufficient to support the cold mass. The static sag of a cold mass supported only at two points is nearly 12.7 mm (0.5 in). The solution selected is to retain five internal support posts between the cold mass and vacuum vessel and to eliminate three of the five external feet.

  Figure 7 shows the second iteration vacuum vessel. The vessel is built with a vertical precurve to reduce its static deflection when loaded by the magnet's internal assembly. The average cold mass deflection is -0.25 mm (-0.010 in). The maximum deviation from the average is 0.41 mm (0.016 in). The sag of the vacuum vessel at the ends of a magnet assembly is 5.0 mm (0.196 in) which is considered to be within the range which facilitates magnet interconnection.

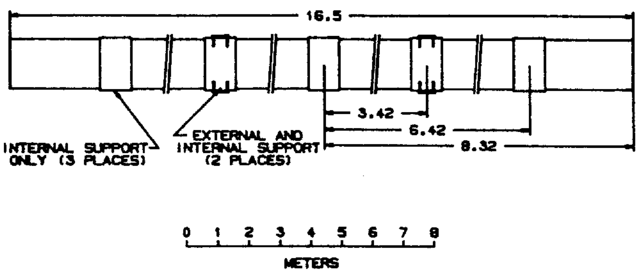

Fig. 7 Vacuum vessel assembly

- The vacuum vessel is fabricated from pre-fabricated, full section reinforcing rings connected by short sections of tubing. The full rings are more mass producible as subassemblies and reduce final vessel assembly time and cost. Since the support locations are determined by assembly tooling which controls the position of the rings, short lengths of tubing are used to interconnect and fix the relative ring positions. This segmented assembly scheme also facilitates the vertical pre-curving of the vacuum vessel assembly.

- The material is SA516 steel. This material provides improved reduced temperature ductility over mild steel with a minor cost penalty.

INTERCONNECTIONS

The cryostat interconnection consists of seven pipes, having bellows which accommodate the axial motion due to cooldown and warmup, that must be connected. All pipes are stainless steel except the vacuum shell connection, which is carbon steel. All will be welded when the magnet is installed and will be cut apart when the magnet is removed.

All connections will be welded with automatic welding units and will be cut apart with orbital pipe cutters. The units are specially designed for the cryostat's small clearances.

The interconnection is developed radially outward from the cold mass centerline. The first connection to be made is the beam tube. The cold mass outer helium containment shell connection is then made. The next pipes to be welded are the four small pipes surrounding the cold mass. The interconnection shield bridges are made of two pieces of aluminum. They assemble with hinge arrangement on one side and rivets on the other. Small welds attach the magnet shield to the interconnection shield on one side, primarily for thermal contraction. The other side is unattached but overlaps enough for the magnet to contract upon cooldown. The shields are insulated as they are on the body of the magnet. The final connection to be made is the vacuum vessel shell.

The second iteration interconnection is different from the initial iteration in several ways:

- For the cold mass connection, the welding unit will be mounted on the cold mass end flange, requiring less radial clearance. A lower clearance pipe cutter which feeds axially is employed. The cutter does not need to cut radially beyond the fillet to remove the weld penetration. Therefore the weld can be removed without damaging the cold mass end flange. The area inside the cold mass is accessible without having to remove any of the other pipes. The 4.5 K helium return pipes, which are near the tunnel wall are accessible without having to reach around the cold mass. This greatly reduces the time needed to connect and disconnect a magnet. The four cold piping bellows will not need to be removed from one end of the magnet. These bellows become part of the magnet and will only be welded and cut off on one end. This eliminates 4 welds and 4 cuts per end.

- For the helium return and shield pipe connections a sleeve is used instead of a consumable washer.

- 316L stainless steel bellows are used to improve cold extension-compression cycle life.

- The bellows do not need to be compressed at assembly and are self aligning. Longitudinal tolerances in pipe position are taken up by the gap between pipes, allowing a smaller bellows travel to be specified which results in longer bellows life.

MODEL MAGNET EXPERIENCE

The initial unit of the second iteration cryostat design has been incorporated as part of the SSC Magnet Model Program. The unit was extensively instrumented to monitor cryostat performance as compared to that predicted and measured for individual components and subassemblies. Details of the cryostat measurements will be reported later. This cryostat design will be employed for the balance of the FY88 and for all of the FY89 model magnet program.

CONCLUSIONS

- The second iteration SSC dipole magnet cryostat is a logical extension of the successful initial version cryostat. Its development incorporated model magnet experiences in the areas of analysis, design, material properties, component fabrication and assembly, transient and steady state performance and construction costs. The design effort was and continues to be heavily augmented by laboratory evaluations of components and assemblies. Components included are the cold mass connection-slide, support post, anchor, insulation, shield vacuum vessel and interconnections. The cryostat has been evaluated as an assembly in the areas of handling and installation, thermal performance and magnetic performance.

- The design satisfies most of the needs of the SSC Magnet System Requirements. Areas that require continuing resolution include allowable composite material stresses, radiation resistance, dynamic response, alignment and reliability.

- The design is appropriate for the FY88-89 Long Magnet Model Program and for the Technology Orientation phase of the SSC Magnet Industrialization Program.

- A continuing and timely development effort is required in support of the second iteration cryostat program and the following iterations leading to the mass production design. Of particular importance are evaluations that consider the response of the entire cryostat assembly to non steady state conditions. The evaluations will consist of analysis confirmed by measurement. Such evaluations include the following:

  - Handling and installation
  - Transportation and seismic loading
  - Vacuum vessel pumpdown
  - Cooldown and warmup
  - Quench
  - Operation in strings
  - Life testing

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