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TM-1410
(SSC-N-204)
0102.000

SUPERCONDUCTING SUPER COLLIDER MAGNET CRYOSTAT*

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July 1986

* To be presented at the 6th Intersociety Cryogenic Symposium, Miami, Florida, November 2-7, 1986

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ABSTRACT

The proposed Superconducting Super Collider high energy physics research facility will entail one of the major cryogenic system undertakings of the next decade. The two 30 Km diameter accelerator rings contain an integrated system of ≈10,000 superconducting devices that must have low capital cost and operate reliably and efficiently over the lifetime of the machine.

The design for the ≈8,000 superconducting dipole magnet cryostats has been developed and evaluated by both component and systems tests. The details of the design are presented along with summaries of the experimental evaluations of the suspension system, insulation, transient phenomena, systems' performance, etc.

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The proposed Superconducting Super Collider (1) (SSC) is an advanced high energy physics research device. The machine will consist of two 30 km diameter rings that will accelerate protons to energies up to 20 TeV prior to their collision in particle physics detection facilities. For reasons of both performance and cost, the rings will incorporate superconducting magnets to bend (dipole) and focus (quadrupole) the particle beams. Approximately 10,000 superconducting devices will be utilized in the SSC.

The superconducting magnet cryostat is a critical SSC component. The cryostat must facilitate proper magnetic function, provide low refrigeration loads, be highly reliable and be mass producible at low cost.

The development of the cryostat utilized the extensive experience gained in the design, construction and operation of the Fermilab Tevatron superconducting magnet system (2). The Tevatron is an operational 0.8 TeV proton-antiproton accelerator that consists of a single 1.6 km diameter ring that utilizes ≈1000 superconducting devices. Also utilized were earlier SSC cryostat design efforts of the ironless cosθ dipole magnet (3) and the cold iron cosθ dipole (4) programs.

Conditions that control and affect the cryostat design include magnet assembly; transportation and installation; as well as transient, steady-state and upset operating conditions. Component design considerations include fluid flow, material performance, structural integrity, position stability, thermal performance and thermal contraction. Functional design trade-offs were used to optimize the effectiveness of each component as it relates to the overall, long-term performance of the integrated magnet-cryogenics system.

CRYOSTAT GENERAL ARRANGEMENT

The cryostat general arrangement is as shown by Fig. 1 and 2. The major elements are the cryogenic piping, cold mass assembly, suspension system, thermal shields, insulation, vacuum vessel and the interconnection region.

CRYOGENIC PIPING

The cryostat assembly contains all piping that interconnects the magnet refrigeration

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system throughout the circumference of the accelerator ring. A five pipe system has been selected for cryogenic and magnet safety reasons:

- Pipe 1: The complete cold mass helium containment subassembly that delivers the supply of 4.5K single phase liquid helium that flows around the beam pipe and through the magnet's superconducting collared coil assembly.

- Pipe 2: The 5K liquid helium recooler return pipe.

- Pipe 3: The 5K helium gas return pipe. The 5K gas is generated in the helium recooler assemblies spaced around the accelerator ring to regulate the temperature of the single phase helium that cools the magnet coils. The 5K gas line reduces the pressure drop across the magnet and thus reduces the associated temperature gradient.

- Pipe 4: The 20K thermal shield cooling pipe. This pipe connects to the helium relief header during system cooldown or to the return or supply headers during operation. The 20K line provides quench buffering.

- Pipe 5: The 80K thermal shield cooling pipe. This pipe connects to the liquid nitrogen return or supply header.

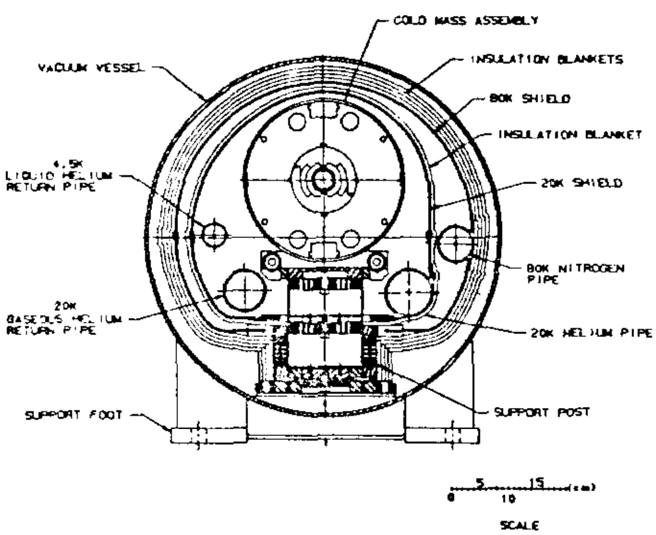


Figure 1 Cryostat Cross Section at a Suspension Point

COLD MASS ASSEMBLY

The cold mass assembly consists of the accelerator beam tube in which the protons circulate, the superconducting cosΘ wound collared coils, stacked iron yoke laminations, outer helium containment shell and alignment fiducials; all joined together to provide a leak tight and structurally rigid welded assembly. The helium containment shell is the principle structural element of the cold mass assembly and provides the required flexural rigidity between suspension points.

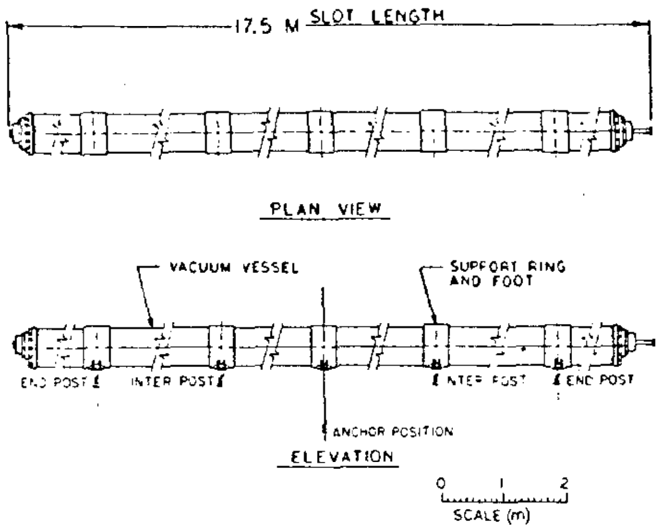


Figure 2 Cryostat Plan and Elevation Views

SUSPENSION SYSTEM

The cold mass assembly (4.5K) and thermal shields (20 & 80K) with their distributed static and dynamic loads are supported relative to the vacuum vessel (300K) by the suspension system. The system functions under conditions that include assembly; transportation and installation; magnet cooldown and warmup; magnet steady-state operation and upset conditions. Required attributes are: low heat leak, high reliability, dimensional stability, installation and adjustment ease, and low cost.

The cold mass and shields are supported at five points along their length. The number and location of the support points were determined by the analysis of the deflection of the cold mass assembly as a beam and the need to minimize the number of support points for reasons of magnet fabrication ease and low heat leak.

After consideration of tension member, compression member, elliptical arch and post type suspension systems; a cylindrical post type support (5) was selected. The significant features of a post support are as follow:

- Load Carrying Versatility - The cylindrical section results in a versatile support member that can carry tension, compression, bending and torsional loads.

- Thermal Contraction Structural Insensitivity - The post configuration provides connections to the cold mass and thermal shields that permit axial motion relative to the post as they contract and thus reduces load changes due to thermal transients.

- Low Heat Leak - The use of fiber reinforced plastic (FRP) materials with effective heat intercepts results in predictably low heat leaks. A minimum number of penetrations through the shields and their insulation are required, which reduces the potential thermal radiation heat flux.

- Integral Restraint - The hollow, central region of the post permits the installation of an integral restraint member that connects the warm and cold ends. The restraint is employed during transportation and handling and is removed prior to operation.

- Installation and Adjustment Ease - The post, involving a single support member at a suspension point, simplifies installation and adjustment.

The details of the reentrant post support are given by Fig. 3. The insulating sections are tubing with metallic interconnections and heat intercepts. The geometry was determined by simultaneous consideration of stress, deflection, heat leak, creep effects and installation requirements.

Shrink fit junctions between the FRP tubing and the metallic connections are employed to permit effective transmission of tension, compression, bending and torsional loads. To understand the long term stability and thus reliability of shrink fit junctions for FRP materials, creep tests of representative junctions have been made. Creep extrapolations to the machine life (20 yr) predict no significant loss in joint strength.

A post support is subject to internal axial and radial thermal radiation that can significantly affect thermal performance. Control of such radiation is achieved by the use of multilayer insulation.

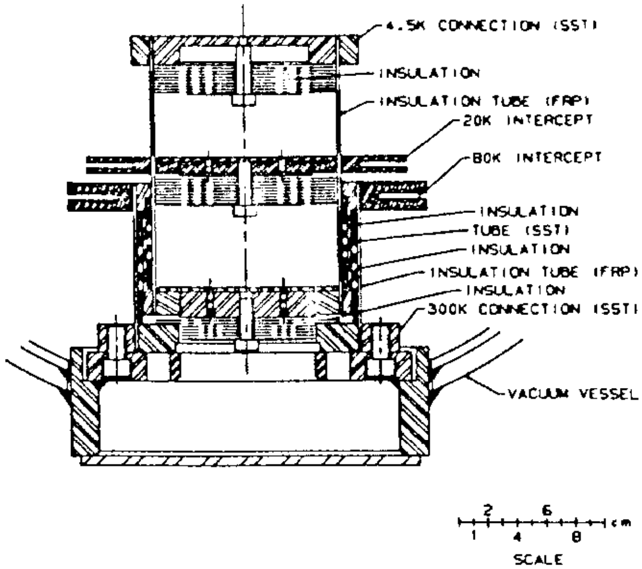


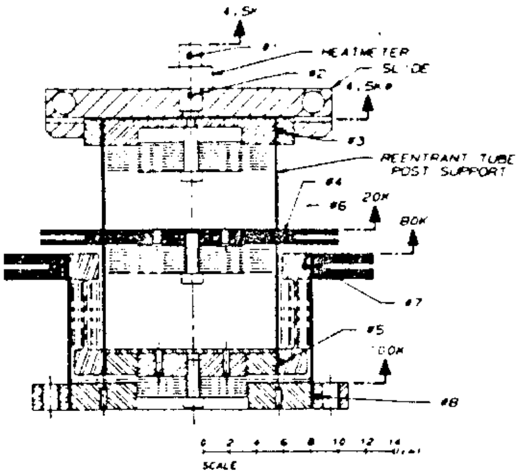
Figure 3 Reentrant Support Post Cross Section

Proper design of the thermal connections between the support's 20K and 80K intercepts and the thermal shields is essential to minimize heat leak. A 5K temperature rise at 80K and a 1K temperature rise at 20K were budgeted. The corresponding heat leak increases are 10% to 20K and 8% to 4.5K.

The support post is fixed at its 300K end and incorporates a slide at the 4.5K end to accommodate the axial differential contraction between the mid-span anchored cold mass assembly and the vacuum vessel.

Significant transient bowing of the cold mass assembly is not expected due to its structure, location of helium flow paths and cooldown and warmup procedures to be employed. The shields will undergo transient bowing and the shield-post interfaces are designed to allow the relative motions while providing support.

Straight post type supports were employed successfully in SSC ironless cosθ magnet development program (6). The posts performed to design, both structurally and thermally. A reentrant tube post support, instrumented with temperature sensors, was installed and evaluated in a specially configured heat leak measurement dewar (7). The heat leak and temperature distribution results are as shown in Table 1. The measured vs. predicted temperature profiles and heat leaks are in good agreement.



TEMPERATURE PROFILE		
SENSOR NO.	DESIGN (K)	MEASURED (K)
1	4.5	5.0
2	—	6.0
3	4.5*	10.4
4	20.0	18.1
5	79.1	81.5
6	80.0	85.8
7	80.0	84.5
8	300.0	284.3

HEAT LEAK		
DT (K)	DESIGN (mW)	MEASURED (mW)
4.5	—	12
4.5*	23	13
20	105	123
80	1276	1132

Table 1 Thermal Performance of a Representative Reentrant Post

Inorder to permit the post support to withstand the high lateral handling loads without incuring a severe operational heat leak penalty, the post design incorporates an integral, coaxial, removable shipping restraint. The restraint is installed at the time of magnet assembly and is removed when the magnet arrives at tunnel level.

Inorder to permit symmetrical axial thermal contraction at both magnet ends, the internal components are anchored at mid-span. The anchor consists of a pair of FRP struts that connect the base of the mid-span support post to the cold mass assembly.

Inorder to allow the mid-span anchor to survive axial transportation and handling loads without incuring a severe heat leak penalty, the cryostat incorporates a removable axial shipping restraint. The restraint provides a strong structural axial connection between the cold mass assembly and the vacuum vessel shell. The restraint is installed at magnet assembly and is removed when the magnet arrives at its specified tunnel location.

THERMAL SHIELDS

Thermal shields, operating independently at 20 and 80K, surround the cold mass assembly to absorb the radiant heat flux and to provide heat sink stations for suspension intercepts. The shields are constructed from aluminum and are fabricated from a combination of extruded flow channels and rolled shapes.

The 5K liquid and gaseous helium return pipes are supported from the cold mass assembly by hangers. The 20 and 80K shields are supported by and are thermally anchored to the cold mass assembly suspension system.

A program to study thermal bowing (8) was developed and carried out as a part of the SSC ironless cosΘ magnet development program. The inner thermal radiation shield was studied. The thermal and structural response of the shield, when subjected to a 100K differential across the section, was modeled and predicted by finite element methods. Good agreement was achieved between the predicted and measured performance. The refrigeration system design limits the transient shield thermal excursions to 100K.

During steady state operation, the temperature difference across the shield is 1K.

INSULATION

Insulation is installed between the 300 and 80 and 20K surfaces.

The insulation system employs blankets that consist of layers of flat, reflective aluminized plastic film radiation shields with random oriented fiberglass mat spacers. Four blankets are installed on the 80K surface and one blanket is installed on the 20K surface. Prefabricated transition pieces and well defined installation procedures are utilized to eliminate insulation system voids due to assembly and differential thermal contraction.

The insulation system's plastic substrate and the fiberglass mat should not suffer performance degradations when subjected to the estimated radiation environment of 1×10^8 rad over the machine life.

The design cryostat insulating vacuum is 10^{-6} Torr with the cold mass assembly and shield at operating temperature. The insulating vacuum will not have a permanent pumping system. A vacuum pumpout space equal to the thickness of each insulation blanket is provided around one boundary of each insulated assembly.

The insulation system has been successfully employed in two, full section model cryostats; i.e., 6 m Magnetic Effects Model and 12 m Heat Leak Model of the ironless cosΘ magnet development program. The radiation heat transfer factors employed for the design were 6.1×10^{-1} Wm^{-2} to 80K, 7.5 x

10^{-2} Wm^{-2} to 20K and 2.7 x 10^{-4} Wm^{-2} to 4.5K. The insulation system was readily manufactured and performed well during heat leak measurements at good; i.e., 10^{-6} Torr, and poor, i.e., 10^{-2} Torr, vacuums.

VACUUM VESSEL

The vacuum vessel provides insulating vacuum and cold mass connection to ground. The magnet assembly procedure incorporates a slide-in insertion of a completed internal assembly into the vacuum vessel. The support post-vacuum vessel connection provides for the alignment of the cold mass assembly relative to the vacuum vessel after insertion. There is no capability for adjustment after manufacture.

Since the vessel has no magnetic requirements, candidate materials were carbon steel, stainless steel, 9% nickel steel and aluminum. Carbon steel was selected on the basis of cost. The composition of the steel will be a compromise between the material's mechanical properties and fabrication cost.

INTERCONNECTIONS

Mechanical and electrical interconnections are required at the magnet ends. It is essential that the connections be straightforward to assemble and disassemble, compact, reliable and low cost. The mechanical connections are beam tube vacuum, cold mass assembly helium containment, helium lines, liquid nitrogen shield lines, insulating vacuum, thermal radiation shield bridges and insulation. The electrical connections are magnet current bus bars, quench bypass bus bars, quench protection diodes, instrumentation leads, quench detection voltage taps, correction coil leads, etc.

The interconnection design stressed assembly and disassembly operations in the SSC tunnel. The resulting geometry permits the use of automated welding and cutting equipment that is esssential for installation efficiency and interconnection reliability.

For the Tevatron magnets, a large fraction of the dipole cost was for the ends. Therefore, the ends of the SSC magnet have been greatly simplified by using straight pipe connections between magnets. All pressure tight connections are circular and incorporate bellows for assembly and disassembly and to allow for axial thermal contraction. For piping, two bellows are employed in series to increase the tolerance to offset.

The interconnection region incorporates 20 and 80K heat shield bridges to maintain radiation heat transfer barriers. The bridges are attached to the magnet shields by riveting, with thermal connection by means of conductive braids. A single blanket of multilayer insulation is installed on the 20K shield bridge.

Four blankets of multilayer insulation surround the 80K shield bridge.

HEAT LEAK

The cryostat heat leak consists of two major elements, thermal radiation and solid conduction. The budgeted cryostat heat leak totals, determined in conjunction with the design of the refrigeration system, are 25 watts to 80K, 2.5 watts to 20K and 0.3 watts to 4.5K. Other contributions to the total heat leak to the refrigeration system include 0.1 watt/magnet to 4.5K due to conductor splice ohmic heating and 2.0 watts/magnet to 4.5K due to synchrotron radiation.

The estimated center section heat leak for the dipole magnet cryostat heat leak model is as given by Table 2.

Table 2

Dipole Cryostat Heat Leak Model
Center Section Heat Leak Prediction

	Watts to Temperature		
	80 K	20 K	4.5 K
. Thermal Radiation	17.68	1.778	.002
. Cold Mass Supports	6.53	.695	.172
. Cold Mass Anchor	0.66	.047	.017
Total	24.87	2.52	0.191
Budget	25	2.5	0.3

In support of the cryostat's thermal design, an extensive program of experimental heat leak measurements has been conducted. The program included the measurements of components; i.e., suspension system elements, multilayer insulation, etc. under both normal and upset; i.e., partial loss of insulating vacuum, conditions. The results of the component measurements program confirmed the ability to accurately predict thermal performance.

The program also included measurements of full length magnet thermal models. A full length 12 m long cryostat model corresponding to the ironless cosθ dipole magnet was constructed and heat leak measurements were made. The cold iron cosθ cryostat development program includes an identical open cycle evaluation of a full length 17.5 m dipole magnet cryostat (9). The model was manufactured in a prototype magnet production facility and used production components, tooling, manufacturing procedures and quality control.

Closed cycle heat leak measurements of a string of five magnet cryostats, with a flowing cryogenic system are also a part of the magnet development program.

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